Development of Teaching and Training Modules for Higher Education
on Low-Cost Wastewater Treatment, ***Contract VN/Asia-Link/012 (113128) 2005-2008***

Curriculum on Low-Cost Wastewater Treatment

Authors:

Prof. Dimitri Xanthoulis, coordinator, FUSAGx
Jean Tilly, FUSAGx,
Nathalie Fonder, FUSAGx
Marc Wauthelet, FUSAGx
Philippe Bergeron, FUSAGx
Prof. Dr. Wang Chengduan, SWUST
Xu Qingyuan, SWUST
Zhang Qingdong, SWUST
Zhang Zhigui, SWUST
Xiang Yinghong, SWUST
Prof. Dr. Hans Brix, Aarhus Universitet
Dr. Carlos A. Arias, Aarhus Universitet
Dr. Leu Tho Bach, NUCE
Prof. Dr. Tran Hieu Nhue, NUCE
Ass. Prof. Dr. Tran Duc Ha, NUCE
Do Hong Anh, NUCE

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FUSAGx
Faculté Universitaire des Sciences Agronomiques de Gembloux
2, Passage des Déportés
B-5030 Gembloux
Belgium

NUCE
National University of Civil Engineering (NUCE),
Institute of Environmental Science and Engineering (IESE)
55, Gai Phong Road, Hanoi,
Vietnam

SWUST
Southwest University of Science and Technology,
College of Environmental Engineering,
Mianyang, Post code 621010,
Sichuan Province,
China

University of Aarhus,
Department of Biological Sciences, Ole Worms Allé,
Building 1135,
8000 Århus, C,
Denmark

FOREWORD

The overall objective of the project lead with Chinese, Vietnamese, Danish and Belgian universities was to contribute to the improvement of the theoretical capabilities in wastewater treatment in rapidly developing urban and rural areas of China and Vietnam, by means of exchanging and developing new concepts and methods of sustainable sanitation. The urbanisation process is proceeding rather rapidly in Asia, but the water supply and drainage systems in the urban and peri-urban centres remain poor and deficient, with no common facilities for wastewater treatment available. With the increasing pressure on water resources in the world, it is also envisioned that the development and large-scale implementation of low-cost sanitation methods will become crucial for resolving the needs of rapidly expanding cities and suburban areas.

The objective of the project was also to upgrade the skills of current and future Chinese and Vietnamese engineers in low-cost wastewater treatment, as those qualifications are highly demanded on the labour market nowadays. This can be explained by the fact that the human resources capable to work for improving environmental sanitation in China and Vietnam are currently insufficient and the needs in wastewater treatment engineers are expected to increase in the following years.

Another overall goal was to foster the exchange of ideas, concepts, and methods, which will greatly contribute to increase the awareness of European and Asian sanitation technologies in partner countries. Those technologies can later be used and developed by the different institutions involved in the action.

The specific objective of the project was to develop a teaching curriculum for new courses on low-cost wastewater treatment for MSc level students in Europe and Asia. The present course reviews the different low-cost treatment methods existing in the different partner countries and focuses on sharing the experience of processes developed and successfully applied by the partner institutions in their respective countries. Those processes usually use low-cost and light techniques to treat wastewater and reuse the treated wastewater for irrigation or to reduce the pathogens or pollutants. Through teaching and training of postgraduate students, the project raises awareness and strengthens the capacity of the involved professionals in alternative sanitation concepts and methods. The curriculum developed for the MSc level is also used in the European partner universities, which integrate the curriculum in their respective educational programmes.

Prof. Xanthoulis D.

Agricultural University of Gembloux (Belgium)

LIST OF ABBREVIATIONS

Chapter 1 and for the rest of curriculum

BOD: Biochemical Oxygen Demand
BOD_5: 5-day Biochemical Oxygen Demand
COD: Chemical Oxygen Demand
DO: Dissolved oxygen
DS: Dissolved solids
EC: Electric conductivity
EIA: Environmental Impact Assessment
O & M: Operation and Maintenance
Q: flow rate; Q_{18} ; Q_{DW}; Q_m; Q_p
SS : Suspended solids
TDS: Total Dissolved solids
TN or Total-N: Total nitrogen
TP or Total-P: Total phosphorus
TS : Total solids
TSS: Total suspended solids
VS: Volatile solids
WWTS: Wastewater treatment system
WWTP: Wastewater treatment plant

Chapter 2
WWTS: Wastewater treatment system

Chapter 3
WWTP: Wastewater treatment plant

Chapter 4.1
gcd: gram per capita and per day
lcd: liter per capita and per day
O&M: Operation and Maintenance
TWL : Top water level
WSP: Waste stabilisation pond

Chapter 4.2
CWs: Constructed wetlands
HDPE: High density polyethylene
PE: Person equivalent

Chapter 4.3
ISF: intermittent sand filter

Chapter 4.4
ET Systems: Evapotranspirative systems
ET: Evapotranspiration

Chapter 4.5
AF: Anaerobic filter

EGSB: Expanded granular sludge bed
FB: Fluidised bed
GLS: Gas, liquids, solids
HRT: Hydraulic retention time
SRT: Sludge retention time
UASB: up flow anaerobic sludge bed

Chapter 5
HLR: Hydraulic loading rate
NFT: Nutrient Film Technique
PNF: Permanent Nutrition Flow
WSP: waste stabilisation ponds

Chapter 6
OLR: Organic Load Ratio
TST: Traditional Septic Tanks
VIDP: Ventilated Improved Double Pit
VIP: Ventilated Improved Pit

Chapter 7
O&M: Operation and maintenance

Chapter 8
EC: electrical conductivity
EC_w: electrical conductivity of the irrigation water
EC_e: electrical conductivity of the soil saturation extract.
SAR: Sodium Absorption Ratio
SAT: Soil-Aquifer Treatment

Chapter 9
DEHP : phthalates
EQ : exceptional quality
EU : European Union
LAS : linear alkylbenzene sulfonates
NPE : nonylphenols
WWTP: Wastewater treatment plant
Σ PAH : polycyclic hydrocarbons

Chapter 10
AIC: Average incremental cost
CAPEX : Capital expenses
EIA : Environmental impact assessment
ELCA : Environmental life -cycle assessment
IRR : Internal Rate of Return
ISO: International Standards Organization
LCA : Life-cycle assessment
LCA: Life -cycle assessment
LCI: Life-cycle inventory
LCIA: Life-cycle impact assessment
lpcd : litre per capita and day

NPV: Net Present Value
O&M : Operation and maintenance
OPEX : Operational expenses
OWP : Open wastewater planning
PPP : Polluter pays principle
PSP: Private Sector Participation
PV: Present Value
ROI : Return on Investment
WWTP: Wastewater treatment plant
WWTS: Wastewater treatment system

Chapter 11
ADB: Asian Development Bank
BP (World Bank): Bank Procedures
BP (ADB): Bank Policies
EA: Environmental assessment
EC: European Commission
EIA: Environmental impact assessment
EMP: Environmental management plan
EPBs: Environmental Protection Bureaus
GIS : Geographical Information System
IEE: Initial Environmental Examination
NGOs: Nongovernmental organisations
O&M: Operation and maintenance
OM (ADB): organisational manual
OP/BP (World Bank) :Operational Policy/Bank Procedures –
OP (World Bank): Operational Policy
OP (ADB): Operational procedures
SEA: Strategic Environmental assessment
SEPA : State Environmental Protection Agency
TT: Task team
WWTP: Wastewater treatment plant

Chapter 12
EHS: Environment, Health and Safety
EMS : Environmental Management System
EPP: Environmental Protection Plan
ISTS: Individual Sewage Treatment System
RIB: Rapid Infiltration Basins
SEA: Strategic Environmental Assessment
WFD: Water Framework Directive
WWTP: Wastewater treatment plant
WWTS: Wastewater treatment system

Chapter 13
EAP: Economic active population
GDP: Gross domestic products
GIS: Geographic Information System
OWTS: Onsite Wastewater Treatment Systems
ME: Management Entity

O&M: Operation and maintenance
RA: Regulatory Authority
RMEs: Responsible Management Entities
WRS: Water Resources Sustainability
WTS: Waste treatment system
WWTS: Wastewater treatment plant

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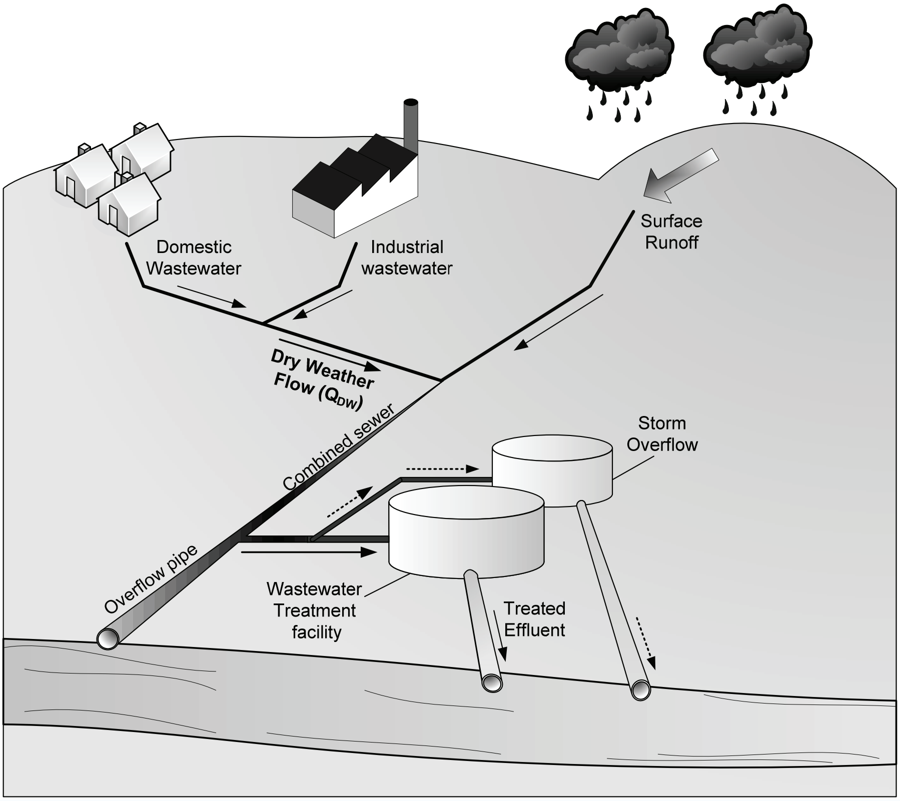
1. INTRODUCTION – GENERAL CONSIDERATION

1.1 Definition of wastewater

Every community produces both liquid and solid wastes and air emissions. The liquid waste or wastewater is essentially the water supply of the community after it has been used in a variety of applications (see Figure 1-1). Any water adversely affected in quality by any anthropogenic influence is wastewater. From the standpoint of sources of generation, wastewater may be defined as a combination of the liquid or water-carried wastes removed from residences, institutions, and commercial and industrial establishments, together with such ground water, surface water, and storm water as may be present (Metcalf and Eddy, 2003).

FIGURE 1-1
SCHEMATIC DIAGRAM OF A WASTEWATER MANAGEMENT INFRASTRUCTURE



There is a wide range of wastewaters and an equally wide range of technologies and techniques for mitigating the impacts of wastewaters on the receiving environment. Depending on the origin, wastewater can be separated into four types:

- Industrial wastewater;
- Domestic wastewater;
- Commercial wastewater; and
- Surface runoff.

Industrial Wastewater: process and non-process wastewater from manufacturing, commercial, mining, and sylvicultural facilities or activities, including runoff and leachate from areas receiving pollutants associated with industrial or commercial storage, handling or processing, and all other wastewater not otherwise defined as domestic wastewater.

Domestic Wastewater: wastewater derived mainly from residences, business buildings, institutions, and the like; sanitary wastewater; sewage. It may also include industrial contributions when domestic and industrial wastewaters are combined in a city sewer system.

Commercial Wastewater: non-toxic, non-hazardous wastewater from commercial facilities which is usually similar in composition to domestic wastewater, but which may occasionally have one or more of its constituents exceeding typical domestic ranges. Included in this definition are wastewaters from commercial and institutional food service operations, commercial laundry facilities with no more than four washing machines, animal holding facilities (such as kennels, veterinary hospitals, and animal grooming facilities), and beauty salons, provided that toxic, hazardous, or industrial wastes are not introduced into the system.

Surface runoff: runoff resulting from rainfall, snowmelt, highway drainage, from urban and industrial areas, etc; it is the portion of water that does not infiltrate into the soil, runs off streets and land, and enters a body of water.

1.2 Characterisation of wastewater

The composition of wastewater varies widely; besides water, it may contain non-pathogenic bacteria, pathogens, organic particles, soluble organic material, inorganic particles, soluble inorganic material, animals, gases, toxins, etc.

1.2.1 Quantitative characterisation

Characterising wastewater quantitatively is essential to choose the type of wastewater treatment plant, design and size the plant, and eventually select a combined or separate sewerage system. Quantitative parameters (wastewater flow rates) are generally the mean daily flow, peak flow and daily, monthly or seasonal fluctuations.

For a combined sewerage system (sewer network + rain), it is generally recommended to use the following parameters (Weber, Vandevenne and Edeline, 2002):

- Q_{DW} or Q_m: mean dry weather flow = daily volume/24 [m^3/h]

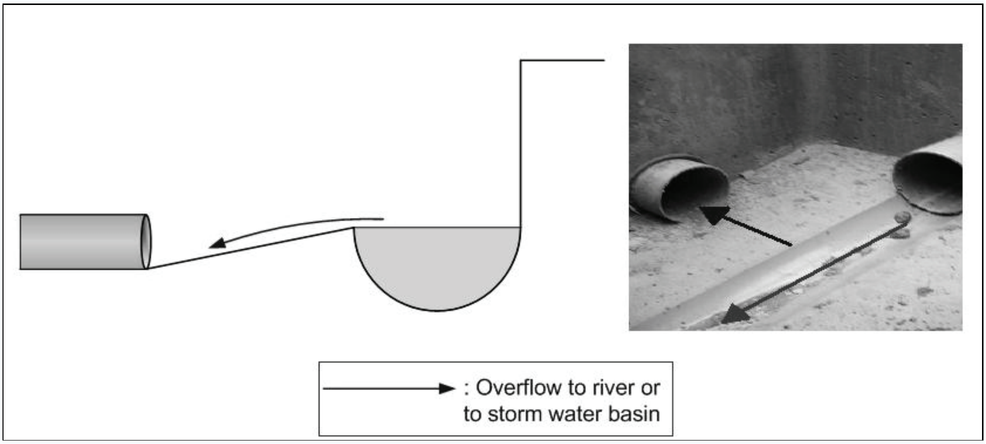
- Q_{18}: dry weather diurnal flow = daily volume/18 [m^3/h]
  - For a wastewater treatment plant bigger than 20,000 population equivalents otherwise, for smaller plants with small volumes during the night, Q_{14} can be used;

- $3Q_{18}$: dry weather peak flow [m^3/h]
  - Biological treatments are often designed considering this parameter (a special attention must be paid to cities with seasonal activity).

- Q_P: wet weather peak flow [m^3/h]: $3Q_{18}<Q_P<5Q_{18}$ (or Q_P =2 to 4 Q_m in Vietnam)
  - Primary treatment has to be designed considering $5Q_{18}$ at least;
  - Combined sewer storm overflow has to be designed considering $6Q_{18}$ or $7Q_{18}$.

Flow restrictions can be obtained by an overflow gutter of an appropriate section (see Figure 1-2).

FIGURE 1-2
OVERFLOW GUTTER AND FLOW RESTRICTION



1.2.2 Qualitative parameters and constituents of wastewater

Physical parameters

Suspended solids (SS): insoluble solid particles that either float on the surface or are in suspension in the water and that can be removed by filtration. *Suspended solids* contribute to turbidity.

Settleable solids: fraction of suspended solids that will settle out of suspension by gravity under laminar regime conditions.

Total Dissolved solids (TDS): organic or inorganic solids that are in solution and that are not removed by filtration. TDS comprises anions, cations, molecules and small colloidal particles. Dissolved solids contribute to conductivity.

Rem: The colloids are classified between SS and DS: $SS<1.10^{-3}mm<Colloids<1.10^{-6}mm<DS$

Turbidity: hazy or cloudy appearance of water, caused by particulate matter in suspension.

Colour: the *colour* (light brown, grey, black, etc.) is an interesting visual indicator because it is directly correlated to the pH and the DO (dissolved oxygen) of the water and allows to assess the condition of wastewater (fresh or septic).

Temperature (°T or °F): an important parameter in the design of treatment facilities because it strongly influences biological processes; the temperature of wastewater varies throughout the year and with location.

Conductivity (EC): *conductivity* or *electric conductivity* measures the ability of water to conduct electric current and is directly correlated to the total dissolved solids content.

Chemical parameters

Total nitrogen (TN): represents all forms of nitrogen. It is the sum of free ammonia (NH4+), organic nitrogen (Org N), nitrites (NO2-), and nitrates (NO3-); the total Kjeldahl nitrogen (TKN) is the sum of organic nitrogen and free ammonia.

Total phosphorus (TP): represents all forms of phosphorus; it is the sum of inorganic phosphorus and organic phosphorus.

pH: measures the acidity or basicity of an aqueous solution.

Alkalinity: measures the buffering capacity of the wastewater; this capacity is due primarily to the presence of naturally available bicarbonate, carbonate, and hydroxide ions.

Chloride (Cl^-): assesses the suitability of wastewater for agricultural reuse.

Sulfate (SO_4^-): assesses the potential for the formation of odours (mainly H_2S, which smells like rotten eggs) and may affect the treatability of waste sludge.

Metals: *metals* such as As, Cd, Ca, Cr, Co, Cu, Pb, Mg, Hg, Mo, Ni, Se, Na, and Zn are tested out to assess the suitability of the wastewater for reuse and for toxicity effects in treatment. Trace amounts of metals are important in biological treatment.

Gases: wastewater contains and produces *gases* such as O_2, CO_2, H_2S, NH_3, and CH_4.

BOD_5: stands for *5-day Biochemical Oxygen Demand* and represents the amount of oxygen required by microorganisms for the biochemical oxidation of biodegradable organic matter over a period of 5 days at 20°C in a unit volume of wastewater. *BOD_5*, expressed in mg/L, is the most widely used parameter to characterise organic pollution of wastewater; it measures the biodegradable organic strength of the wastewater.

COD: stands for *Chemical Oxygen Demand* and represents the amount of oxygen (mg/L) required to chemically oxidise the organic material in wastewater using dichromate (strong chemical oxidant) in an acid solution. From an operational standpoint, one of the main advantages of the *COD* test is that it can be completed in about 2.5 h (at 140°C).

$\underline{BOD_\infty:}$ represents the total amount of dissolved oxygen required by microorganisms for the biochemical oxidation of biodegradable organic matter in a unit volume of wastewater until respiration ends. It measures the total biodegradable organic strength of the wastewater

$\underline{BOD_\infty/COD}$: the ratio BOD_∞/COD indicates the biodegradability of a wastewater sample (i.e., ability of a wastewater sample to be decomposed by biological treatments). A decline of that ratio means an increase of non-biodegradable organic matter (cellulose, lignin, tannins, saw dust, etc.) (Weber, Vandevenne and Edeline, 2002).

- Diary plant: 1.3
- Sugar mill: 0.82
- Slaughterhouse: 0.67
- Domestic wastewater: 0.5
- Laundry: 0.38

Oil and grease: as commonly used, includes the fats, oils, waxes, and other related constituents found in wastewater. The term *fats, oil, and grease* (FOG) used previously in the literature has been replaced by the term *oil and grease*.

Toxic compounds: *s*ome specific toxic compounds may be contained in wastewater and cause adverse effects on living organisms.

Microbiological parameters

Faecal coliform organisms: bacteria in the intestinal tract of warm-blooded animals; used as indicators of fecal contamination in water, they indicate the presence or the absence of pathogen organisms from fecal contamination. Coliforms are not generally pathogenic themselves.

Specific microorganisms: bacteria, protozoa, helminthes, and viruses that are present at the point of disposal indicate the degree of pollution or the toxicity of wastewater. These microorganisms are of concern because many are pathogenic. Some microorganisms that form spores and cysts can survive for long periods and may eventually reach a host. Depending on the type and the degree of treatment, most can be removed. Those parameters are followed up for effluent discharge, for treated wastewater reuse in agriculture –to select crop and irrigation method.

1.2.3 Characterisation of wastewater by type

Domestic wastewater: originates mostly from households, public facilities, and businesses. Table 1-1shows some the typical composition of domestic sewage.

TABLE 1-1
TYPICAL COMPOSITION OF UNTREATED DOMESTIC WASTEWATER

Contaminants	Unit	Concentration		
		Weak	Medium	Strong
Solids, total (TS)	mg/L	350	720	1,200
Dissolved, total (TDS)	mg/L	250	500	850
Suspended solids (SS)	mg/L	100	220	350
Settleable solids	mL/L	5	10	20
BOD_5, 20°C	mg/L	110	220	400
COD	mg/L	250	500	1,000
Nitrogen (total as N)	mg/L	20	40	85
Organic	mg/L	8	15	35
Free ammonia	mg/L	12	25	50
Nitrites	mg/L	0	0	0
Nitrates	mg/L	0	0	0
Phosphorus (total as P)	mg/L	4	8	15
Organic	mg/L	1	3	5
Inorganic	mg/L	3	5	10
Chlorides	mg/L	30	50	100
Sulfate	mg/L	20	30	50
Alkalinity (as CaCO3)	mg/L	50	100	200
Grease and oils	mg/L	50	100	150
Total coliforms	no/100mL	10^6 - 10^7	10^7 - 10^8	10^7 - 10^8

Source: Weber, Vandevenne and Edeline, 2002

In *unsewered areas*, septic tanks are common. Septic tanks accumulate solids known as septage, which must be removed every few years to ensure effective operation of the system. Table 1-2 shows typical pollutant composition of septage taken to wastewater treatment facilities.

TABLE 1-2
TYPICAL POLLUTANT COMPOSITION OF SEPTAGE

Total Suspended Solids (TSS)	10,000 – 25,000 mg/L
5-day Biochemical Oxygen Demand (BOD_5)	3,000 - 5,000 mg/L
Chemical Oxygen Demand (COD)	25,000 - 40,000 mg/L
Total Nitrogen as N (TN)	200 - 700 mg/L
Total Phosphorus as P (TP)	100 - 300 mg/L
Oil and grease	2,500-7,500 mg/L

Source: UNEP, 1998

Industrial wastewater: has a wide range of pollutant concentrations. Industries such as oil refinery, food processing industries, distilleries, and chemical industries produce high BOD concentration, suspended solids, dissolved solids, variable pH, odour, sulphur compounds, and a high level of organic matter (see Table 1-3). Chemical industries frequently produce toxic compounds (e.g., pesticides, insecticides, phenols, etc.) which are dangerous to aquatic organisms at very low concentrations.

TABLE 1-3
TYPICAL POLLUTANT CHARACTERISTICS OF INDUSTRIAL WASTEWATER

Industry	BOD Concentration (mg/L)	TSS Concentration (mg/L)	Oil & Grease Concentration (mg/L)	Metals * Present (mg/L)	Volatile Compounds Present (mg/L)	Refractory Organics Concentration (mg/L)
Oil Refinery	100 to 300	100 to 250	200 to 3,000	Arsenic, Iron	Sulphides	Phenols 0 to 270
Tanneries	1,000 to 3,000	4,000 to 6,000	50 to 850	Chromium 300 to 1000	Sulphides Ammonia 100 to 200	
Bottling Plant	200 to 6,000	0 to 3,500				
Distillery, Molasses, or Sugar Factory	600 to 32,000	200 to 30,000			Ammonia 5 to 400	
Food Processing	100 to 7,000	30 to 7,000				
Paper Factory	250 to 15,000	500 to 100,000		Selenium, Zinc		Phenols 0 to 800
Chemical Plant	500 to 20,000	1,000 to 170,000	0 to 2,000	Arsenic, Barium, Cadmium		Phenols 0 to 5,000

Source: UNEP, 1998 *: Metals +Arsenic+Selenium

1.3 Wastewater collection system

1.3.1 Combined sewer system

A combined sewer system means that sanitary wastewater (domestic and/or industrial wastewater) and runoff water are collected in the same sewer.

1.3.2 Separate sewer system

A separate sewer system means that the carrying of domestic and/or industrial wastewater is operated separately of sewers which carry runoff water. The sewer that collects domestic and/or industrial wastewater is often called a sanitary sewer. The sewer that carries runoff water is often called a storm sewer.

1.4 Importance of treating wastewater

1.4.1 Environment

When untreated wastewater accumulates and is allowed to go septic, the decomposition of its organic matter leads to nuisance, including the production of malodorous gases. All plants and animals living in water require dissolved oxygen, which exists in small amounts. One of the main objectives of wastewater treatment is to prevent as much of “oxygen-demanding” organic material as possible from entering the receiving water. Wastewater also contains nutrients, which can stimulate the growth of aquatic plants and lead to oxygen depletion and eutrophication of the water body. Nutrient salt causes eutrophication in water bodies. Eutrophication process will change water quality. Removing organic and inorganic matter is thus a priority for a sustainable environment, kept clean for present and future generations.

1.4.2 Health

Untreated wastewater contains numerous pathogenic microorganisms that dwell in the human intestinal tract. Some of the more common diseases associated with bathing in contaminated recreational waters or through consumption of contaminated seafood are swimmer's itch, gastro-enteritis, dermatitis, viral hepatitis, wound infections, cholera, typhoid fever, and dysentery. Wastewater may also contain toxic compounds or compounds that potentially may be mutagenic or carcinogenic. For these reasons, removing pathogenic organisms is necessary to protect public health.

1.4.3 Economic considerations

Agricultural use of treated effluents helps to maintain environmental quality and simultaneously furthers other national goals such as providing sustainable agriculture while preserving scarce water sources. Another advantage of irrigation with wastewater is the possibility of decreasing the purification level and the derived treatment costs, thanks to the role of soil and crops in acting as a bio-filter. Using the nutrients available in wastewater may also diminish fertilisation costs.

Water is also a great playground for everyone. The scenic and recreational values of our waters are reasons why many people choose to live where they do.

1.5 How to treat wastewater

Numerous processes can clean up wastewater depending on the type and extent of contamination. The purification objectives determine the type of treatment to be implemented.

In agricultural zones and particularly in semi-arid or arid countries, the main objective can be the wastewater reuse for irrigation. The treatment will be therefore focused on the elimination of pathogens (reduction of health risks) and of sludge (reduction of pipes and irrigation material clogging) for instance by anaerobic decantation followed by sand filter.

In urban zones and in zones where wastewater have to be discharged in rivers or in soils, it's recommended to eliminate the organic matter and sludge. The objective is to avoid the organic overloading (eutrophication) of the rivers and of the groundwater

For households, the most basic treatment of wastewater is the septic tank. For cities, one of the most important aerobic treatment systems is the activated sludge process, based on the maintenance and recirculation of a complex biomass composed by microorganisms able to digest and degrade the organic matter carried with wastewater. Anaerobic processes are also widely used to treat industrial wastewaters and biological sludge.

Individual wastewater treatments concern one household (see chapter 6). Collective treatments concern more than one household and require a sewer system. Some individual treatments can be also applied or included in a collective treatment. In Europe, individual primary treatment (septic tanks) is usually used before the wastewater discharge in the sewer.

Some situations may require or allow other wastewater treatment technologies reproducing natural approaches using reed beds (also known as constructed wetlands) and lagoons (wastewater stabilisation ponds). These light infrastructures and technologies are sometimes more appropriate than modern high cost processes.

Some modern systems may include tertiary treatment such as microfilters or membranes, but this approach has to be justified by the treated wastewater destination or reuse. For instance, treated wastewater can be reused, in artificial recharge of aquifers, in agriculture, in aquaculture, etc.

1.6 Design process decision tree

The design process for wastewater treatment might differ depending on the characteristics of the community producing wastewater. Generally, natural WWTPs are used where it is not possible or economically feasible to connect to a larger WWTP. Actually, not only the size of the community matters, but many other different parameters. Climate, topography, distances between communities, the sewage network community covering ratio and political boundaries are also to consider in choosing an independent natural treatment plant; it is also important to take into account the future and the destination of the treated wastewater. Sometimes, communities are equipped with pre-treatment facilities to lower the waste load before discharging to a collective treatment plant. All these aspects have to be fully considered when choosing a wastewater treatment process.

Treatment is not necessarily easier for small communities. Actually, fluctuations in volume and the characteristics of the wastewater discharges may cause more difficulties for a small than for a large community. Wastewater flows from small communities often have significantly accentuated peaks and minima. Small sources may have effluents varying from heavy to weak loads of suspended solids, organic matter, nitrogen, phosphorus, etc.

Figure 1-3 shows the most important criteria for selecting appropriate technologies and the relevance of each criterion in the decision process. The main factors in choosing a domestic wastewater treatment technology are water availability, presence of a collection system, housing or population density, availability of skilled management and operating personnel, land availability, availability and cost of power, receiving water requirements, hydrogeologic conditions and climate, and availability of opportunities for effluent reuse (UNEP, 1998).

1.7 Treatments classification

Wastewater treatment requires an appropriate removal method for each constituent. These methods may be classified into different levels of treatment:

TABLE 1-4
LEVELS OF WASTEWATER TREATMENT AND SYSTEMS USED.

Treatment level	Definition	Systems
Preliminary	First stage of collective waste water treatment which removes large particles, oil and grease, and other material that may disrupt or affect the performance of downstream operations and processes.	Screening, grit removal, comminution, oil and grease removal, etc.
Primary	Removal of a portion of settleable solids, floatable solids and organic matter from the wastewater.	Primary sedimentation, septic tanks, anaerobic stabilisation ponds, etc.
Secondary	Removal of biodegradable organic matter, suspended solids mainly by biologic processes. Secondary treatment is also called biological treatment.	Facultative stabilization ponds, trickling filters, anaerobic biological treatment, activated sludge, constructed wetlands, , etc.
Tertiary	Removal of dissolved and suspended materials remaining in order to polish the final effluent. Implies the removal of pathogen and nutrients such as nitrate and phosphorus.	Maturation ponds, sand filters, Epuvalisation, etc.

Source : adapted from Crites and Tchobanoglous (1998) and Weber et al; (2002).

1.8 Centralised and decentralised wastewater management

1.8.1 Decentralised **wastewater management**

Decentralised wastewater management (DWM) may be defined as the collection, treatment and disposal/reuse of wastewater from individual homes, clusters of homes, isolated communities, industries or institutional facilities, as well as from portions of existing communities at or near the point of waste generation.

1.8.2 Centralised **wastewater management**

Centralised wastewater management consists of conventional or alternative wastewater collection systems (sewers), centralised treatment plants, and disposal/reuse of the treated effluent, usually far from the point of origin.

Decentralised systems maintain both the solid and liquid fractions of the wastewater near their point of origin, although the liquid portion and any residual solids can be transported to a centralised point for further treatment and reuse.
(Crites, Tchobanoglous, 1998)

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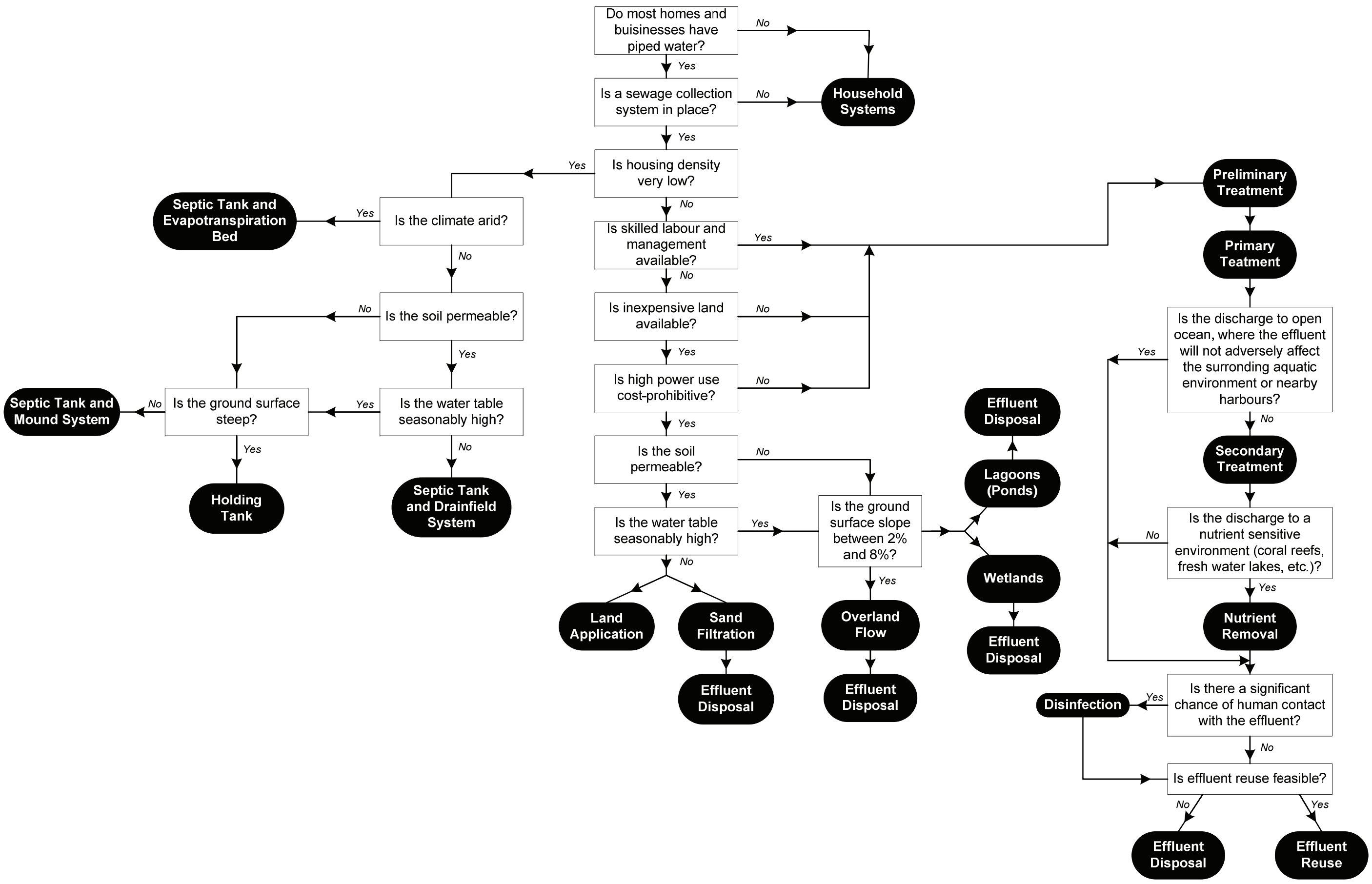
FIGURE 1-3
DECISION TREE FOR APPROPRIATE DOMESTIC SEWAGE TREATMENT



2. DEFINITION OF LOW-COST TREATMENT SYSTEMS

2.1 Definition of Low Cost WWTS

Conventional wastewater treatment combines physical, chemical, and biological processes and operations to remove solids, organic matter, and, sometimes, nutrients from wastewater. General terms used to describe different degrees of treatment, in order of increasing treatment level, are preliminary, primary, secondary, and tertiary and/or advanced wastewater treatment. In some countries, disinfection to remove pathogens sometimes follows the last treatment step.

Low Cost Wastewater Treatment Systems are natural low-rate biological treatment systems that can treat organic wastewaters such as municipal sewage. These systems have significantly lower investment costs as well as less sophisticated and less costly operation and maintenance. Although such processes tend to need more land than conventional high-rate biological processes, they are often more effective in removing pathogens and do so reliably and continuously if properly designed and not overloaded.

All wastewater management processes depend on natural response such as gravity for sedimentation or on natural components such as biological organisms. In typical cases of conventional treatment, however, these natural processes are supported by an often complex array of energy intensive mechanical equipments (pumps, aerators, etc.).

In this curriculum, the term Low Cost WWTS describes nature-near system processes that depend primarily on their natural components to achieve their intended treatment purpose. A Low Cost natural WWTS may include pumps and pipes to convey wastewater, but does not depend exclusively on external energy sources to maintain the major treatment responses (Reed et al., 1995).

Low Cost WWTS are also called natural, nature-near or naturally-based wastewater treatment technologies due to the fact that these treatment systems use natural processes (such as biological, physical or solar elements or else) to achieve a desired level of treatment. Low Cost Treatment Systems are often also defined as:

- Achieving acceptable levels of treatment;
- Requiring low capital investment;
- Requiring low ongoing operation and maintenance costs;
- Requiring less-skilled operator knowledge than many conventional technologies;
- Potentially having longer life-cycles than conventional electro-mechanical technology;
- Minimally relying on civil works and mechanical and electrical equipments;
- Providing robust, reliable, and long-term efficient treatment/conversion technologies/processes;
- Offering plainness of operation and maintenance;
- Achieving self-sufficiency in many respects;
- Providing maximal recovery and re-use of treated water and by-products obtained from the pollution substances;

- Being easily affordable to low and middle income rural beneficiary population; and
- Providing simplicity and universality of design at any scale from very small to very big.

Although several conventional treatment processes (*e.g.*, activated sludge) are also using naturally-based technology because several treatment steps are based on biological processes, these technologies do not fit the definition of “Low Cost” because of the need for high and ongoing energy inputs that make the technology expensive to operate and maintain.

Low Cost WWTS offer the added advantages to have minimal environmental impacts and small ecological footprints. They are available in three major categories: aquatic, terrestrial, and wetlands.

- **Aquatic treatment:** facultative lagoons are the most common form of aquatic treatment technology. The water layer near the surface is aerobic while the bottom layer, which includes sludge deposits, is anaerobic. The intermediate layer is aerobic near the top and anaerobic near the bottom, and constitutes the facultative zone. Aerated lagoons are smaller than facultative lagoons. On the other hand, facultative lagoons usually are deeper than aerated lagoons. Aerated lagoons systems evolved from stabilization ponds after the addition of aeration devices to counteract odours arising from septic conditions.

- **Terrestrial treatment systems** include slow-rate overland flow, slow-rate subsurface infiltration, and rapid infiltration methods. In addition to wastewater treatment and low maintenance costs, these systems may yield additional benefits by providing water for ground-water recharge, reforestation, agriculture, and/or livestock pasturage. They depend upon physical, chemical, and biological reactions on and within the soil. Slow-rate overland flow systems require vegetation, both to take up nutrients and other contaminants and to slow the passage of the effluent across the land surface to ensure maximum contact times between the effluents and the plants/soils. Slow-rate subsurface infiltration systems and rapid infiltration systems are "zero discharge" systems that rarely discharge effluents directly to streams or other surface waters. Each system has different constraints regarding soil permeability.

- **Wetlands** are land where the water table is at (or above) the ground surface long enough each year to maintain saturated soil conditions and the growth of related vegetation. There are essentially two types of constructed wetlands: systems using surface water flows and systems using subsurface flows. Both systems use the roots of plants to provide substrate for the growth of attached bacteria, which use the nutrients present in the effluents to transfer oxygen. Bacteria do the bulk of the work in these systems, although there is also some nitrogen, phosphorus and potassium uptake by the plants. The surface water system most closely approximates a natural wetland. Typically, these systems are long, narrow basins, with depths of less than 1 meter that are planted with aquatic vegetation. The shallow ground-water systems use a gravel or sand medium, which provides a rooting medium for the aquatic plants and through which the wastewater flows.

2.2 Strengths and Limitations of Low Cost WWTS

2.2.1 Advantages

A properly constructed Low Cost WWTS designed to fit the topography has the following advantages:

1. **Provides a relatively high level of treatment;** properly designed, constructed, maintained, and managed natural WWTS can provide very efficient treatment of wastewater. Test results show that phosphorus, nitrate-nitrites, ammonia, BOD_5, and suspended solids can be reduced to very acceptable levels. In general, the removal of BOD, TSS, COD, metals, and persistent organics in municipal wastewaters can be very effective with a reasonable detention time. Removing nitrogen and phosphorus can also be effective with a significantly longer detention time. For many natural WWTS, year-round operation for secondary treatment is possible in all but the coldest climates. Year-round operation for advanced or tertiary treatment is possible in warm to moderately temperate climates.

2. **Can be inexpensive to construct;** Low Cost WWTS may be much less expensive to construct than conventional mechanical treatment systems where sufficient land is available at a suitable price. The absence of sophisticated treatment equipments also contributes to the lowering of the cost. Low Cost WWTS design is site specific, taking into consideration such variables as topography, water supply, soil types, type of wastewater to be treated, etc. Selecting a site with accommodating specifications keeps establishment costs low.

3. **Is inexpensive to operate;** a Low Cost WWTS requires little, if any, energy use and equipment needs are minimal. No chemicals are required. A well-designed wetland transfers water by gravity through the system. If topography limits the use of gravity, pumps will be necessary which increases the cost of operation. Once established, properly designed and constructed natural WWTS are largely self-maintaining. Generally, however, natural WWTS offer effective treatment in a passive manner, minimising mechanical equipment, energy, and skilled operator requirements. Gravity distribution methods consume no energy.

4. **Reduces, if not completely eliminates, odour;** odour can be a serious problem when handling and treating wastewater, especially if the operation is located close to residential housing. Wetlands, unlike perhaps lagoons, have shown that odours from wetlands are of very low intensity or non-existent.

5. **Can handle variable wastewater loadings;** properly-designed Low Cost WWTS have shown great tolerance for varying amounts of wastewater loading. This is important because varying wastewater discharge, changing

climatic conditions, and an evolving number of people connected or modifications of the management of commercial activities connected can alter loading rates significantly.

6. **Reduces the land area needed for application of wastewater;** Low Cost WWTS reduce the concentration of contaminants. Thus, the land area needed for application of water from a constructed wetland is less than the land area needed for direct application of wastewater.

7. **Reduces the quantities of removed material that need further handling;** in Low Cost WWTS, the quantity of removed material is minimal and will be relatively small compared to other secondary treatment processes. Many Low Cost WWTS produce no residual biosolids or sludges requiring subsequent treatment and disposal

8. **Can be aesthetically pleasing;** depending upon design, location, and type of vegetation, Low Cost WWTS especially constructed wetlands can enhance the landscape with colour, texture, and variety in plants. Low Cost WWTS can provide a valuable addition to the "green space" in a community, and include the incorporation of public recreational opportunities.

9. **Provides wildlife habitat;** Low Cost WWTS attract some types of wildlife and can add to the usefulness and attractiveness of the area.

2.2.2 Limitations

Even the best designed Low Cost WWTS has its limitations, in particular,

1. **May have limited ability to remove faecal coliforms;** Low Cost WWTS can remove faecal coliforms by at least one log from typical municipal wastewaters. This may not be sufficient to meet discharge limits in all locations and additional disinfection may be required. The situation is further complicated because birds and other wildlife near the WWTS produce faecal coliforms.

2. **Requires periodic cleaning of settled sludge;** settled sludge and inert material require periodic removal. Low Cost WWTS can fill in with solids or flow patterns can be seriously disrupted when the design does not allow the removal of solids before the wastewater enters the system. Sludge accumulation will be higher in cold climates due to reduced microbial activity. The processes usually require annual removal of accumulated deposits of organic matter on the infiltration surfaces in the basins.

3. **Can be relatively expensive to construct;** just as a desirable topography and other natural factors such as soil type can make a Low Cost WWTS inexpensive to build, undesirable land features can increase construction costs. This is particularly true for constructed wetlands where changing the lay of the land, adding soil amendments, and/or liners, incorporating pumps, etc. can increase the cost of building the WWTS significantly.

4. **Is affected by seasonal weather conditions, which may reduce treatment reliability;** seasonal weather conditions, such as cold and drought, reduce the efficacy of the system. Fluctuation in weather when designing and operating the system is important. The removal of BOD, COD, and nitrogen are biological processes and essentially continuously renewable. The phosphorus, metals, and some persistent organics removed by the system are bound in the wetland sediments and accumulate over time. In cold climates, low winter temperatures reduce the rate of removal for BOD and the biological reactions responsible for nitrification and denitrification. An increased detention time can compensate for this, but the increased wetland size required in extremely cold climates may not be cost effective or technically feasible.

5. **Can have odour problems;** As Low Cost WWTS often uses anaerobic treatment steps, this may give rise especially in warm climate to odour difficulty affecting the neighbouring vicinity. Adequate distance to dwelling units is consequently recommended.

6. **Can be destroyed by an overload of solids or ammonia levels;** in a Low Cost WWTS, the ammonia level may be difficult to control or predict in the effluent. High ammonia levels over time can also destroy the plant life in a Low Cost WWTS.

7. **Removes nutrients for use by crops;** some nutrients removed by a Low Cost WWTS are not available for land application and crop production.

8. **Invites the presence of undesirable animals and insects;** mosquitoes and similar insect vectors can be a problem if emergent vegetation is not controlled. Burrowing animals may also be a problem. The bird population in a large Low Cost WWTS can have adverse impacts if an airport is nearby.

9. **Spatial requirement per habitant can be high;** the land area required for Low Cost WWTS can be large, especially if nitrogen or phosphorus removal are required. Conventional mechanised treatment systems (*e.g.*, activated sludge, trickling filter or rotating bio-contactor systems), are efficient, in terms of their spatial requirements (0.5-1 m^2/Person Equivalent (PE) - compared to natural treatment systems at 5-10 m^2/PE). On the other hand, conventional systems depend on economies of scale to make them economically feasible and viable.

2.3 References

REED, S.C., CRITES R.W., and MIDDLEBROOKS E.J. 1995. *Natural systems for waste management and treatment*. Second Edition, McGraw-Hill, Inc., 433 pp.

3. COLLECTIVE PRE-TREATMENT REQUIREMENTS

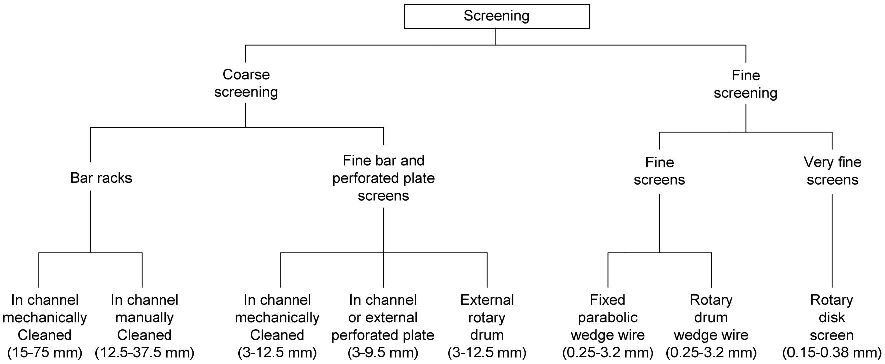
Preliminary treatment removes coarse solids and other large materials often found in raw wastewater. Removing these materials enhances the operation and maintenance of subsequent treatment units. Preliminary treatment operations typically include coarse screening, grit removal and, in some cases, comminution of large objects. In grit chambers, the velocity of the water through the chamber is maintained sufficiently high, or air is used, to prevent the settling of most organic solids. Grit removal is not included as a preliminary treatment step in most small wastewater treatment plants. Comminutors are sometimes adopted to supplement coarse screening and serve to reduce the size of large particles so that they will be removed in the form of a sludge in subsequent treatment processes. Preliminary treatment may include flow measurement devices, often standing-wave flumes (FAO, 1992).

The pre-treatment devices described below are not always present in domestic wastewater treatment plants. Most sewage treatment systems include some form of preliminary treatment, except smaller treatment systems for less than 500-1,000 population equivalent. Some degreasing and de-oiling devices are specifically used on industrial or domestic wastewater discharge just before the sewer pipe.

3.1 Screening devices (bar racks and screens)

Coarse bar racks and screens remove coarse material (rocks, sticks, leaves, and other debris) that would damage pumps and other equipment or interfere with plant operability. The size of holes in the screen will define the function of the screening device (see Figure 3-1).

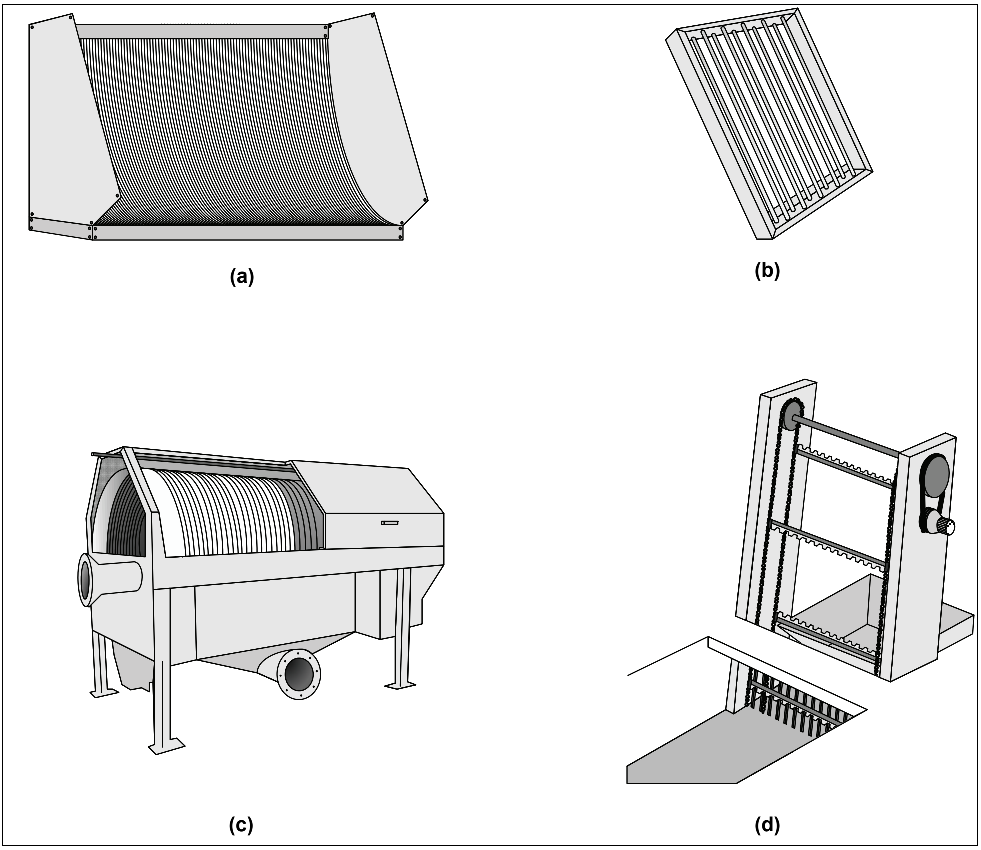
FIGURE 3-1
TYPES OF SCREENS USED FOR WASTEWATER TREATMENT



Source: Adapted from Crites and Tchobanoglous (1998)

There are various types of screening devices from coarse bar racks to finer screens and from manual to mechanical racks (see Figure 3-2). All objects are removed by physical size separation; if they are too small, they pass through the screen and if they are too large, they are caught by the screen.

FIGURE 3-2
SCREENING DEVICES FOR WASTEWATER TREATMENT



(a) parabolic wedge wire screen, (b) bar rack, (c) rotary drum screen, and (d) mechanical bar rack

To treat wastewater at its peak flow (Q_P), the screen must be inclined (sometimes curved or circular) and its total surface (A_{total}) should equal (Weber *et al.*, 2002):

$$A = \frac{Q_P}{v \cdot R_{grid} \cdot (1 - F_{c\log})} \qquad \textbf{(E. 1)}$$

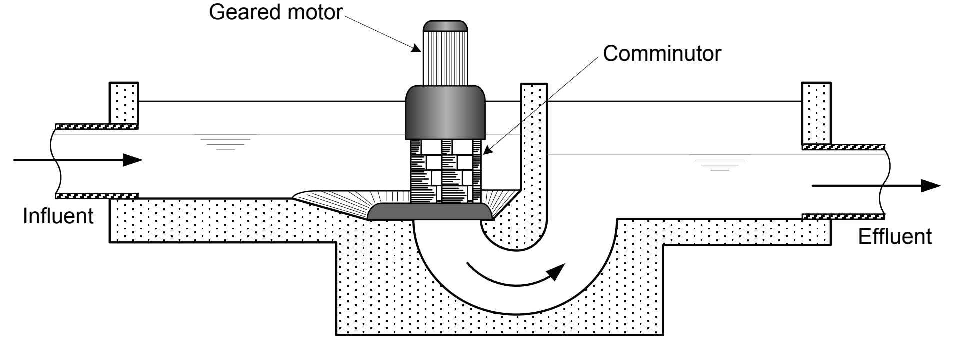
Where:

- The average speed (v) of wastewater into the grid cells:
  - generally 0.6 m/s (up to 1m/s in Vietnam)
  - if v > 0.7 m/s: solid waste may pass through the grid
  - if v < 0.6 m/s: sand deposit
- The clogging factor F_{clog}: 0.4-0.5 for mechanical devices, 0.1-0.3 for manual devices; and
- The grid ratio: $R_{Grid} = \frac{A_{free}}{A_{total}}$ **(E. 2)**

3.2 Comminuting devices

Wastewater solids such as tampons, sanitary napkins, plastic disposables, diapers and other solids are becoming commonplace in wastewater. Screening or reducing in size these solids is necessary to avoid clogging pumps and other processing equipment. To eliminate the problems associated with collecting, removing, storing, and handling the screenings, devices are installed for continuously intercepting, shredding, and grinding into small pieces the large floating material in waste flow. These cutting and shredding devices are called comminutors (see Figure 3-3).

FIGURE 3-3
TYPICAL COMMINUTOR INSTALLATION



Comminutors are commonly used where it is impractical or not economic to remove solids due to the lack of disposal options. Even with screening equipment, some solids inevitably slip through, so a comminutor can be useful as a backup. Alternatively, some plants find it desirable to put the solids through their digestion processes and thus require size reduction equipment and not screening.

3.3 Grit removal systems

Grit is the heavier inert matter in wastewater, which will not decompose in treatment processes. Only grit particles with a diameter superior to 0.2 mm will be held by the installation to avoid holding biodegradable material. Grit removal equipment should be located after bar screens and comminutors and before raw sewage pumps.

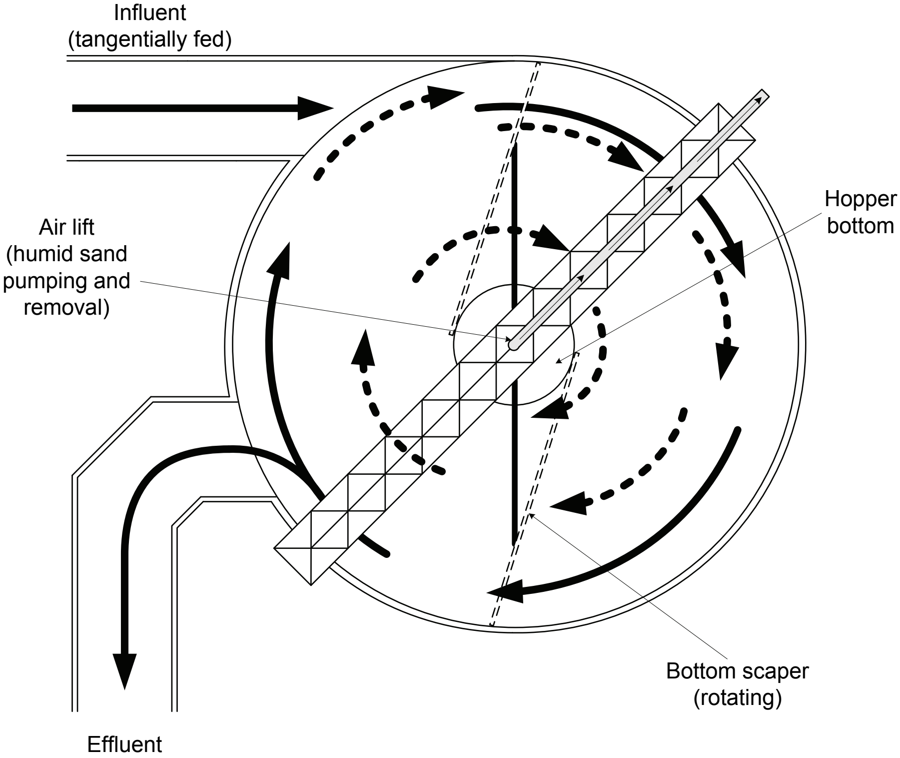
3.3.1 Horizontal flow grit chamber

In small installations, grit is removed by an expansion of the channel that decreases the average fluid velocity to about 0.3 m/s. This reduced velocity allows grit to settle in the channel or tank bottom, while keeping the lighter organic solids in suspension. Grit will settle in a gutter at the bottom of the system. Grit is manually or mechanically collected with a specially shaped shovel (adapted to the shape of the channel).

3.3.2 Circular grit chamber

Circular grit removers are cylindrical-conical devices with a diameter of 3 to 8 m and a liquid depth of 3 to 5 m. The wastewater is fed tangentially into the circular grit chamber to induce a circulatory movement of the water (see Figure 3-4). A mixer supports the circulatory movement and ensures that there is enough flow velocity during low flow periods. The spiral flow pattern and centrifugal force move sand and heavy parts to the peripheral wall and further to the central grit hopper. From there, they can be removed by a centrifugal pump or air lift into a channel or directly into a grit separator. The de-gritted wastewater is discharged via the effluent channel above the influent channel.

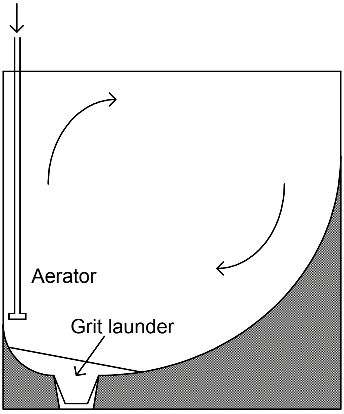
FIGURE 3-4
CIRCULAR GRIT CHAMBER



3.3.3 Aerated rectangular grit chamber

Usually, aerated rectangular grit chambers or aerated channels are used in larger sewage works. Aerated channels are long, narrow, and relatively deep. As the name implies, aerators diffuse coarse bubbles and produce a rolling motion, which is perpendicular to the wastewater flow. The grit, washed free from organic matter by the turbulent flow, is collected in a gutter (see Figure 3-5) at the bottom of the system and can be collected with a travelling bridge for instance. Those systems also allow a pre-aeration of the wastewater and eliminate oils and greases.

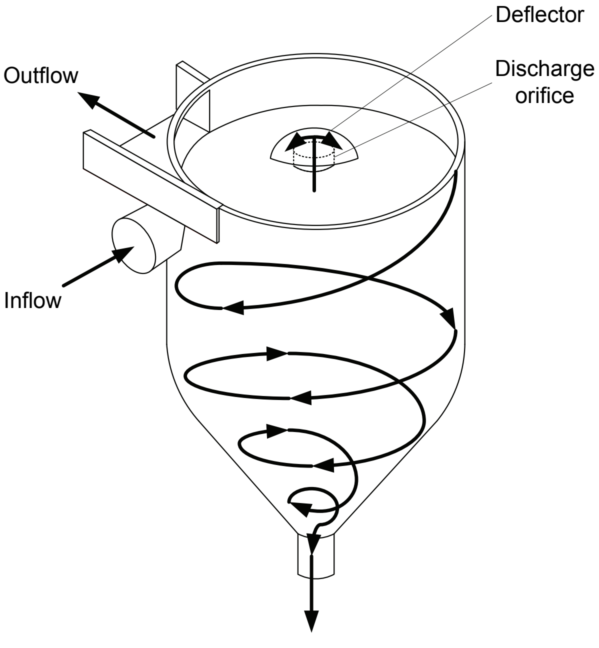
FIGURE 3-5
AERATED GRIT CHAMBER



3.3.4 Hydrocyclone

The hydrocyclone is a vortex type grit chamber and is rather used in industries (see Figure 3-6).

FIGURE 3-6
VORTEX TYPE GRIT CHAMBER (HYDROCYCLONE)



3.4 Oil and grease removal

Oil and grease removal consists in separating products that have a lighter density than water by natural or assisted floatation in large tanks. *Grease* describes solid products or substances that may solidify; they originate from animals or vegetable sources and sometimes they agglomerate with suspended solids. The agglomerations need to be broken down to release grease and allow floatation. This separation technique allows collecting, in addition to grease, some floating products such as vegetal or animal debris, soaps, foams, scum, detergents, plastics, etc. *Oil* describes liquid products such as vegetable oils, mineral oils, and light hydrocarbons.

3.4.1 Operation principle

Grease recovery can be a manual operation (see Figure 3-7). Figure 3-8 shows a more complex grease removal system with an aerated vortex mixer.

FIGURE 3-7
SIMPLE TYPICAL RECTANGULAR GREASE REMOVAL SYSTEM

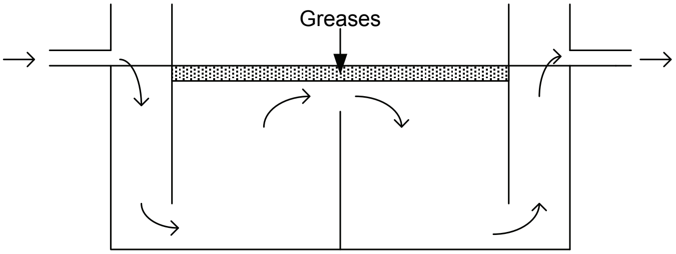
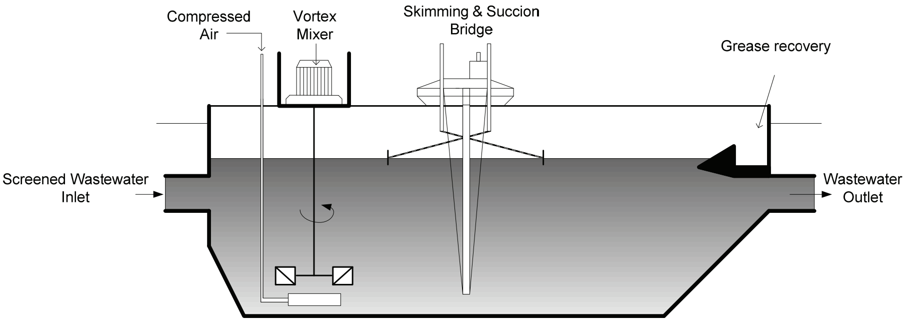
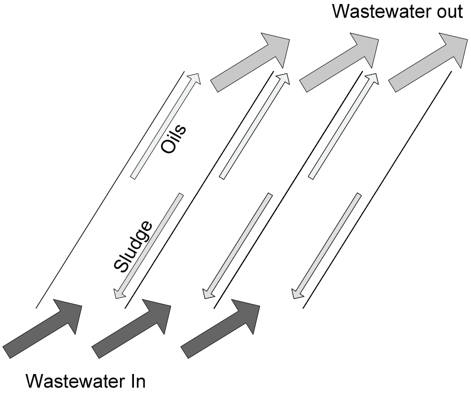


FIGURE 3-8
RECTANGULAR GREASE REMOVAL SYSTEM WITH AN AERATED VORTEX MIXER



In oil separators, lamellar settling is performed by a series of tilted plastic plates vertically spaced of a few centimetres and allows to reduce significantly hold-up times (see Figure 3-9).

FIGURE 3-9
OIL SEPARATOR



3.4.2 Grease removal calculations

The fluid flows with an advancing velocity of $v_f = \frac{Q}{h.l}$ (laminar flow) that carries the particle. Since the particle has a vertical upward velocity, it displaces following a resultant direction. For the second baffle to stop the particle, the time t_p required to travel h must be equal to the time t_f to travel the distance (L) between the two baffles:

$$t_f = t_p \Rightarrow \frac{h}{v_p} = \frac{L}{v_f} = \frac{L \cdot h \cdot l}{Q} \Rightarrow L \cdot l = S = \frac{Q}{v_p} \qquad \textbf{(E. 3)}$$

Where:

- L = distance between baffles [m]
- S = separation surface [m^2]
- h = oil particle located at a certain depth (h) from the first baffle [m]
- h.l = flow section [m^2]
- t_p = required time for the particle to vertically travel h [s]
- t_f = required time for the particle to horizontally travel L [s]
- v_p = vertical upward velocity of an oil particle in the fluid [m/s]
- Q = wastewater flow to treat [m^3/s]

To treat a (maximum) wastewater flow Q, the separation chamber needs a minimum surface (S) equal to the flow Q divided by the vertical velocity of the particle in the fluid v_p. The vertical velocity used in the calculations will be the slowest vertical velocity among all particles to catch. The depth h under the baffles and the relative values of L and l (the general shape) do not *a priori* affect the separation.

Example

Table 3-1 shows the typical pollutants characteristics of industrial wastewater:

TABLE 3-1
TYPICAL POLLUTANT CHARACTERISTICS OF INDUSTRIAL WASTEWATER

Product	Density (Kg/L)	Vertical upward velocity (m/h)	Specific separation surface S’ (m²)	Holding time in separation chamber (min)
Gasoline	0.75	22.5	0.16	2
Petrol	0.80	18.0	0.20	2
Diesel	0.85	13.5	0.27	3
Lubricating oil	0.90	9.0	0.40	4

The specific separation surface S’ is the surface of a chamber able to treat a wastewater flow of 1L/s (10^{-3} m³/s). For instance for gasoline:

$$S' = \frac{Q}{v_p} = \frac{10^{-3}}{v_p} \Rightarrow S' = \frac{10^{-3} \cdot 3600}{22.5} = 0.16m^2 \qquad \textbf{(E. 4)}$$

The specific separation surface for sludge is around 0.1m². The surface of the sludge chamber is bigger than the surface of the separation chamber and thus will be sufficient for sludge to settle in time.

Table 3-2 shows data from a car wash station for particles larger than 0.25 mm diameter:

TABLE 3-2
TYPICAL POLLUTANT CHARACTERISTICS OF A CARWASH STATION

	Per car	Per bus, truck, tractor, …
Oil volume (L)	1	2
Sludge volume (L)	10	20

The car wash station has an area of 60 m² and 4 hydrants (2 x ∅20 mm taps (each 0.6 L/s); 1 x ∅12mm tap (0.4L/s); 1 x wash-water pump with 4 sprays (each 0.5L/s)). That station washes 400 cars and 30 trucks per month. A 100 L safety volume will be taken for the oil collector.

Maximum wastewater flow:

- Rainwater : 60 **.** 0.02 = 1.2 L/s
- 2 x ∅20mm taps : 2 **.** 0.6 = 1.2 L/s
- 1 x ∅12mm tap : 0.4 L/s
- Wash-water pump : 4 **.** 0.5 = 2 L/s
- Total : Q = 4.8 L/s

Separation chamber design:

The separation chamber is designed for the particle having the slowest vertical upward velocity (lubricating oil).

- S = S’ **.** Q = 0.4 **.** 4.8 = 1.92 m²
- Volume = 4.8 **.** 240 = 1152 L or 1.152 m³

- Let us assume a length of 1.9 m a width of 1m and a difference of 0.26 m between the bottoms of the two baffles.
- h' = 1.152/1.92 = 0.6m
- Total height = 0.6 + (0.26/2) = 0.73m

Oil collector design:

- Safety volume = 100L
- 400 cars = 1 . 400 = 400L
- 30 trucks = 2 . 30 = 60L
- Total oil volume = 560L
- Oil collector height = 0.560/(1 x 1.9) = 0.3m

Sludge chamber design:

- 400 cars = 10 . 400 = 4000L
- 30 trucks = 30 . 20 = 600L
- Total volume = 4.6m³
- Height: if inlet and outlet chambers have a width of 0.15 m (operating area of 2.3m²), the resulting sludge chamber height would be equal to 2 m (4.6/2.3). It is thus more appropriate to design a separate sludge chamber that would be located just before the grease removal device and to design a chamber of only 0.15m height inside the grease removal device.

The total height of the grease removal device will thus be equal to 1.18 m (0.73+0.3+0.15).

3.5 Equalization

Pollution due to human activity has rarely a constant flow or concentration. Domestic and industrial wastewater flow and concentration constantly vary. Various wastewater treatments, especially biological treatments, do not tolerate well those variations. Processes for waste treatment work best with uniform conditions. Shocks to the bioprocesses in the form of sudden changes in concentrations of nutrients can cause upsets. If the concentrations or flow rates of the waste vary greatly, dosages for treatment must be constantly be readjusted.

In WWTPs, it is generally recommended to equalize the flow or the concentration or both to:

- Avoid sudden concentration peaks on biological systems;
- Buffer constituents of water and reduce chemicals use;
- Provide a constant wastewater flow for installations even when the initial wastewater flow is equal to zero;
- Avoid by-passing the treatment plant during heavy storms; and
- Discharge a regular effluent into the receiving environment and decrease the risk to be out of discharge standards.

There are two kinds of equalization basins:

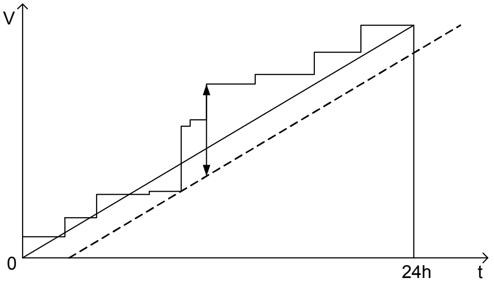
- Variable level (flow equalization)
- Constant level (concentration equalization)

3.5.1 Flow equalization

It is sufficient to accumulate wastewater into a buffer reservoir and to tap wastewater from the reservoir with pump at a constant flow. Cumulating wastewater volumes over a complete production cycle (generally 24 hours or 1 week), then dividing the total amount of wastewater by the period of time can determine the constant flow of the pump. Graphically, it is done by joining the two extremities of the cumulated hydrograph (cumulated volumes as function of time). The slope of the line joining both extremities (Figure 3-10 plain line) equals the flow rate to apply to the pump. This line also represents the emptying of the buffer tank; thus, this line must always be below the hydrograph to avoid the equalization basin from being empty.

The line can be horizontally translated to be tangent to the lowest point of the hydrograph. In Figure 3-10, the tangent line corresponds to the dotted line. The volume of the buffer tank or basin equals the maximum vertical space between the traced line and the hydrograph.

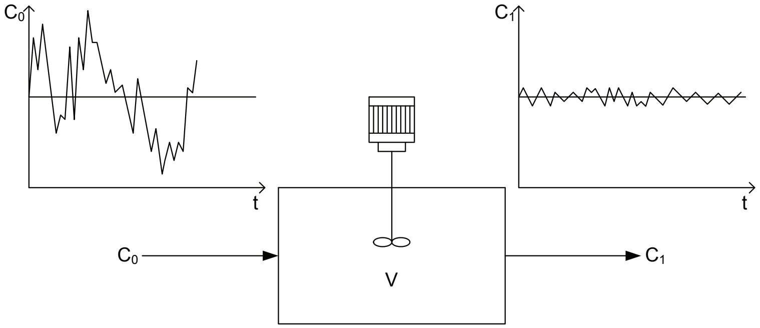
FIGURE 3-10
HYDROGRAPH



3.5.2 Concentration equalization

Figure 3-11 shows the principle of concentration equalization: pH variations can be regulated similarly by “self-neutralizing” sewage (mutual or reciprocal neutralization). Most of the time, however, the pH needs to be followed up by a pH probe and then neutralized into the buffer basin by an appropriate reagent makeup (sodium hydroxide, potassium carbonate, calcium hydroxide, acids, etc.). Such systems only concern industrial wastes.

FIGURE 3-11
CONCENTRATION EQUALIZATION



3.6 Flow measuring devices

Wastewater flow is probably one of the most important parameter for a collective WWTP. Collective WWTP should have an efficient flow measurement device. These devices should at least measure the flow of the plant influent and the plant effluent but should also be considered for equalization tank effluent, recirculation streams, process side-streams, and sludge withdrawal from the wastewater treatment stream.

Common measuring devices for WWTPs are *Parshall* flumes, *Palmer-Bowlus* flumes, venturi tubes, specially shaped weirs in open channels, magnetic meters, etc. Weirs and flumes are the most common devices because they offer a simple way to measure the flow, a couple of them are presented below.

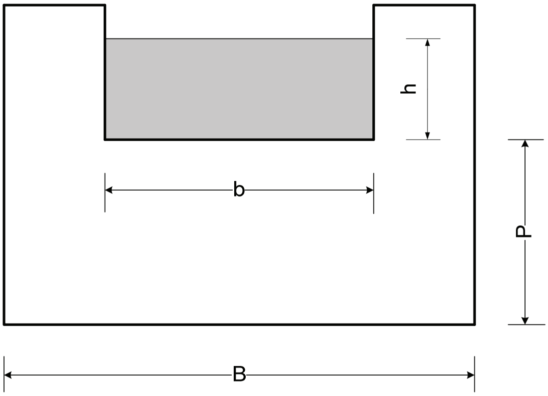
Rectangular shaped weirs: the flow (Q, in m^3/s) into the rectangular shaped weir (see Figure 3-12) relates to the height (h, in m) according to Kindsyater-Carter equation (ISO, 1980) :

$$Q = C_e \frac{2}{3}\sqrt{2g}\ (b + K_b)\ (h + K_h)^{\frac{3}{2}} \qquad \textbf{(E. 5)}$$

Where:

- Q = discharge [m³/s].
- C_e = discharge coefficient [m²].
- g = gravity [m/s²].
- b = notch width [m].
- h = head [m].
- K_b and K_h = corrective parameters due to viscosity and surface tension.

FIGURE 3-12
RECTANGULAR SHAPED WEIR



The sum b + K_b is the effective width and the sum h + K_h is the effective height of the rectangular weir. The discharge coefficient (C_e) is a function of b/B and h/P.

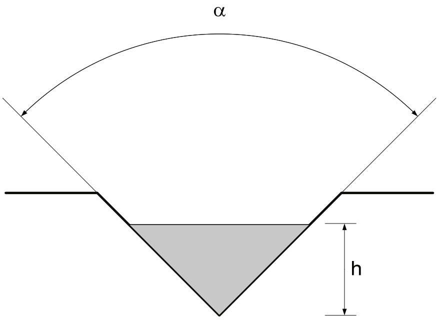
The head (h) should be measured upstream from the weir at a distance of at least equal to 4 times the head. The downstream face of the weir must not be in contact with the water (avoid clinging nappe). According to ISO (1980), the notch width (b) and the channel width (B) should be equal or greater than 0.15 m, the ratio b/B, the ratio h/P should be included between 0 and 2.5,and the height P measured from the bottom of the upstream weir to the notch should be equal or greater than 0.1 m.

Triangular shaped weirs: the flow (Q) into the triangular shaped weir (see Figure 3-13) relates to the height (h) of water as follows:

$$Q = a \cdot h^b \qquad \textbf{(E. 6)}$$

$$Q = 1.32 \cdot tg\frac{\alpha}{2} \cdot h^{2.47} \qquad \textbf{(E. 7)}$$

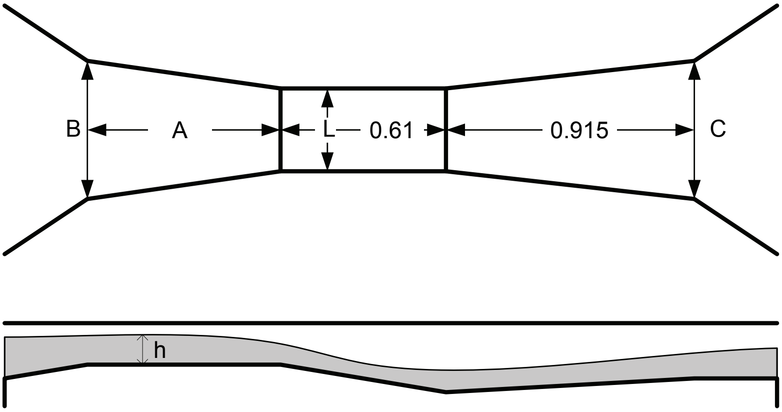
FIGURE 3-13
TRIANGULAR SHAPED WEIR



Equation E.6, where $a = 1.32\ tg(\alpha/2)$ and $b = 2.47$, is a simplified equation which is commonly used to determine the flow of triangular shaped weirs. In practice, it is best to calibrate the weir a few times to determine *a* and *b* in operating conditions (Laborde, 2000).

Parshall flumes: *Parshall* flumes (see Figure 3-14) create a critical flow where the relationship between the flow (Q) and the height (h) is a one-to-one correspondence and only depends on the geometrical dimensions of the device.

FIGURE 3-14
PARSHALL FLUME



The critical flow is created by narrowing the liquid stream or by increasing the depth or both concomitantly. The dimensions of a *Parshall* flume are a function of the throat width (L):

$$A = 0.49L+1.194 \quad \textbf{(E. 8)}$$

$$B=1.196L+0.479 \quad \textbf{(E. 9)}$$

$$C= L+0.305 \quad \textbf{(E. 10)}$$

Where A, B, C, and L are in meters.

The flow (Q in m³/s) is a function of the throat width (L) and of the depth of water (h):

$$Q = 0.372L \cdot (3.28h)^x \quad \textbf{(E. 11)}$$

Where the exponent (x) depends on the throat width of the flume:

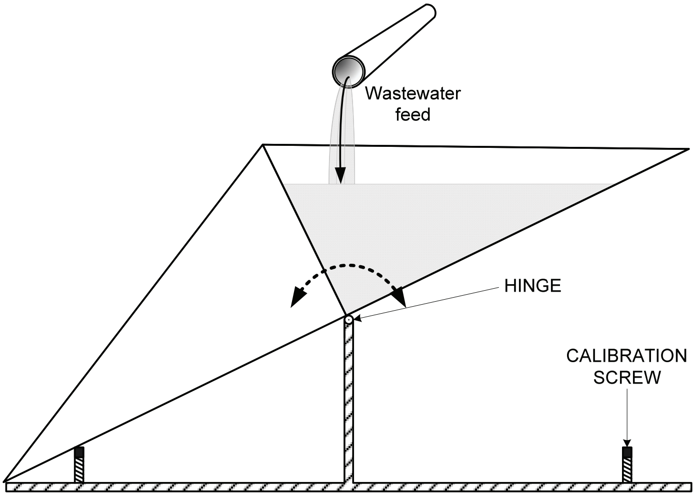
L [m]	0.2	0.6	0.8	1.0	2.6
x	1.506	1.548	1.560	1.569	1.609

In practice, these formulas should often be adjusted because the theory can slightly differ from the operating conditions (Laborde, 2000).

3.7 Flow division

A tipping-bucket (see Figure 3-15) may be used in order to equally split a flow. It consists in two balanced buckets which tip back-and-forth as they are filled in turn by wastewater. The bucket tips once the wastewater it contains reaches a precise volume. A tipping-bucket may also be used to measure small flow rate by counting the number of times the bucket is emptied during a known time interval.

FIGURE 3-15
TIPPING BUCKET



3.8 Storm water basins

In a combined sewer network, during storm events, the storm water basin designates the combination of units which drain the excess water away from the wastewater treatment plant with a limited treatment (settling) into the environment. In general, during heavy rain events, excess wastewater is diverted into a storm water basin and when the basin is totally filled it starts overflowing into the environment. After the rain event, the water stored into the storm water basin may be slowly pumped towards the wastewater treatment plant

3.9 Pumping

Quite frequently, wastewater must be pumped from its point of entry up to the treatment processes. Pumping facilities often form part of the headwork (EPA, 1977). Many different pumps and pumping systems can raise the water level (submersible pumps, vertical pumps, Archimedean screw, etc.). The pumping system selected must meet the varying head conditions caused by differences in level plus all the head losses in the conduit. Head losses in the conduit, which depend on flow variations throughout the life of the pumping system, include wall friction and losses at entrances, outlets, valves, measuring devices, elbows, bends, tees, reducers, and any other location or cross-sectional area where the flow changes direction (EPA, 1977).

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4. COLLECTIVE PROCESSES

4.1 Waste stabilization ponds (WSP)

A WSP system is an arrangement of large, shallow, usually rectangular man-made ponds in which there is a continuous inflow and outflow of wastewater. WSP are widely used in Europe and North America and are often the most appropriate method for wastewater treatment in warm climates of developing countries. The natural action of warmth and sunlight promotes the rapid growth of micro-organisms (principally bacteria and micro-algae), which remove BOD both aerobically and anaerobically. The process that takes place in a pond is a natural cycle, continuous and a living phenomenon.

Treatment usually occurs in two or more ponds. Alternative arrangement of pond sizes and depths can promote either aerobic or anaerobic activity. In the treatment sequence, each pond has its meaning and is designed according to the target or the element to be removed from the wastewater. The resultant effluent will be nutrient rich trough its high algal content but will be low in excreted pathogens and other faecal organisms (Mara et al., 1992; Mara and Pearson, 1987; U.S. EPA, 1977a).

WSP systems are ***easy to build***, ***low cost***, ***tolerant,*** and ***highly efficient.***

Easy to build: earth moving is the main work (other civil work is minimal). It just consists in preliminary treatment, inlets and outlets, pond embankment protection and, if necessary, pond lining (impermeability).

Low cost: because of their simplicity, WSP are less expensive than other treatment processes. They do not need expensive electromechanical equipment and do not use much electrical energy. Unskilled workers, under careful supervision, can easily operate and maintain WSP. Land costs and land requirements may be the only drawback of the technique.

Tolerant: WSP can tolerate high heavy metals concentrations (up to around 30 mg L^{-1}). Ponds can also absorb sudden organic and hydraulic loadings (Mara & Pearson, 1986).

Highly efficient: a series of well designed ponds can remove more than 90% of BOD, 70-90% of nitrogen, and 30-50% of phosphorus.

WSP are particularly efficient in removing excreted pathogens, whereas, in contrast, all other treatment processes are very inefficient at this and require tertiary treatment (such as chlorination, UV, ozone,.....) to destroy faecal bacteria. Actually, well-designed WSP can remove up to five log units and reach WHO guideline values for non-restrictive irrigation (Mara et al., 1992; WHO, 2006; WHO, 1992).

Still, the removal of suspended solids is less than in most of the other treatment processes. This is mostly due to the presence of algae in the final effluent although it is not a cause for alarm since algae are very different from the suspended matter in conventional secondary effluent. High retention times may also be considered a drawback of the process since, coupled with high volumes to be treated, they can lead to high land requirements and land costs.

4.1.1 WSP types and treatment mechanisms

The three successive types of WSP are:

- Anaerobic ponds and/or aerated ponds;
- Facultative ponds; and
- Maturation ponds/Aerobic ponds.

In essence, anaerobic and facultative ponds remove BOD and maturation ponds remove pathogen (for which faecal coliform bacteria are commonly used as indicators); of course, some removal of BOD occurs in maturation ponds and anaerobic and facultative ponds remove pathogens and plant nutrients to some extent.

Anaerobic ponds are most advantageous to treat strong wastewaters with a high concentration of suspended solids. They have no dissolved oxygen and contain no (or very few) algae.

Facultative and maturation ponds have large algal populations, which play an essential role in waste stabilization; they are thus sometimes called photosynthetic or natural ponds. There are some variations of these types: for example, facultative ponds may be divided into primary and secondary facultative ponds, which receive raw and settled sewage, respectively (the latter commonly being the effluent from anaerobic ponds). Maturation ponds are sometimes used to improve the bacteriological quality of the final effluent from conventional sewage treatment work, and are then often referred to as polishing ponds.

The three main types of WSP are usually arranged in a series (or several series in parallel) with either a primary facultative pond followed by one or more maturation ponds, or an anaerobic pond followed by one or more maturation ponds, or an anaerobic pond followed by a secondary facultative pond and one or more maturation ponds (see Figure 4-1). Such series of ponds are very advantageous, as they enable the different types of ponds to perform their different functions in wastewater treatment and so produce an effluent of the desired quality (Mara & Pearson, 1987).

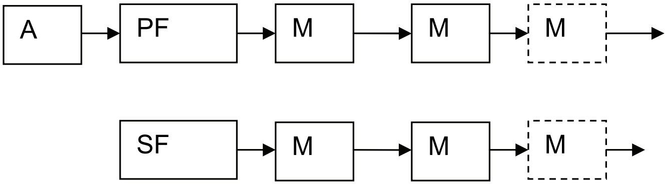
The main mechanisms occurring in WSP are (Arthur, 1983):

1. The reservoir effect, enabling ponds to absorb both organic and hydraulic sudden loadings;

2. Primary sedimentation, allowing SS (definer) to sink to the bottom of the pond; and.

3. Treatment of the organic waste by aerobic bacterial oxidation (in presence of oxygen) and anaerobic digestion (in the absence of oxygen).

FIGURE 4-1
STABILIZATION POND LAYOUTS (EXAMPLES)



A. Anaerobic pond; PF. Primary facultative pond; SF. Secondary facultative pond; M. Maturation pond.

Anaerobic digestion and aerobic oxidation work as follows:

- Anaerobic digestion is a two stage process:

The first stage is putrefaction where bacteria digest organic matter to produce new bacterial cells and an assortment of organic acids.

$$\text{Organic matter} \xrightarrow{\text{bacteria}} \text{new bacterial cells + mixed organic acids.}$$

The second stage is the breakdown of the products formed in the first stage by methanogenic bacteria to produce methane and other simple products.

$$\text{Mixed organic acids} \xrightarrow{\text{bacteria}} \text{new bacterial cells} + CH_4 + CO_2 + H_2O + NH_3\text{, etc.}$$

- Aerobic oxidation can be represented as a simple stage process:

$$\text{Organic matter} + O_2 \xrightarrow{\text{bacteria}} \text{new bacterial cells} + H_2O + CO_2 + PO_4^{3-} + NH_3\text{, etc.}$$

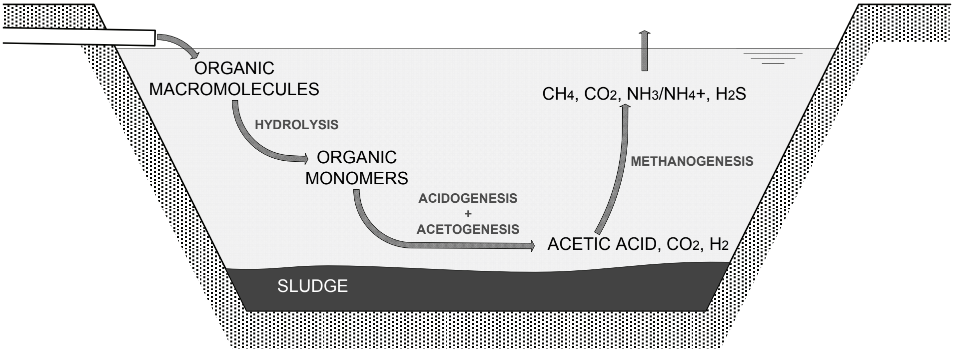
The oxygen is provided in large amounts by algal photosynthesis.

$$H_2O + CO_2 \xrightarrow{\text{algae + light}} \text{new algal cells} + H_2O + O_2$$

Anaerobic ponds

Anaerobic ponds usually are 2-5 m deep. They receive raw wastewater with such a high organic loading (>100g BOD_5/m^3 per day) that they have no dissolved oxygen (Mara et al., 1992). They function much like open septic tanks and are used as the first step to treat strong wastewater. The settleable solids in the raw wastewater sink to the bottom of the pond to form a sludge layer, where they undergo anaerobic digestion performed by acidogenic, acetogenic, and methanogenic bacteria at temperatures above 15°C (see Figure 4-2). Anaerobic ponds work particularly well in warm countries. Total BOD removal is high, from around 40% at 10°C or below to over 60% at 20°C and above. A scum layer often forms on the surface; it does not need to be removed, although fly breeding may be a nuisance in the summer and may require remedial action, such as spraying with clean water or final effluent or, in some exceptional cases, with a suitable biodegradable insecticide (Mara and Pearson, 1986; 1987).

FIGURE 4-2
DEGRADATION OF ORGANIC COMPOUNDS IN ANAEROBIC PONDS



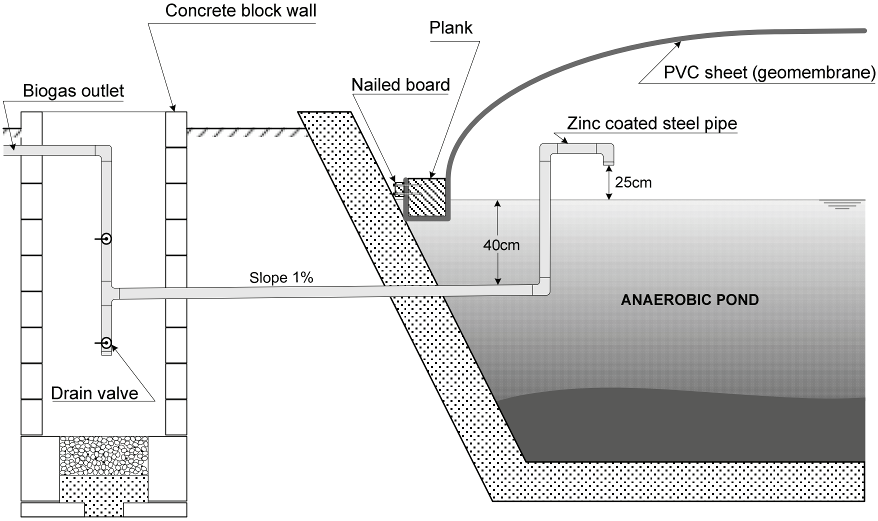
Source: adapted from Ruihong, 2001.

Odour release (mainly hydrogen sulphide) is a major disadvantage of anaerobic ponds and has scared, in the past, many designers to use anaerobic ponds (Mara et al., 1992). In anaerobic ponds, sulphate reducing bacteria such as *Desulfovibrio* reduce sulphate into hydrogen sulphide, which has a low odour threshold and smells like rotten eggs. Once dissolved in water, hydrogen sulphide (H_2S) is involved in a series of chemical reactions. The chemical reactions are the dissociation of the molecular H_2S to form the bisulphide ion (HS^-) and the dissociation of the bisulphide ion to the sulphide ion (S^{2-}). The distribution of H_2S, HS^- and S^{2-} depends on the pH. At pH 7.5, a normal value for anaerobic ponds, 75% of the sulphide is represented by the odourless bisulphide form. Thus, for a given sulphide concentration, the higher the pH in the anaerobic pond, the lower the odour release will be.

Odour nuisance is not a problem if design values of permissible BOD loading are respected and if the concentration of SO_4^{2-} in raw wastewater does not exceed 500 mg/L (Mara et al., 1992). Anaerobic ponds sometimes appear dark red or purple. This is due to the presence of species of anaerobic sulphide-oxidizing photosynthetic bacteria whose growth is beneficial and prevents hydrogen sulphide release (Mara & Pearson, 1987).

Anaerobic ponds may be equipped with a gas holder (PVC sheet covering the surface of the pond) in order to recover the biogas produced from the anaerobic digestion of the organic matter contained in wastewater (see Figure 4-3). Biogas primarily consists of CH_4 and CO_2 but contains also small amounts of H_2O, N_2, O_2, H_2S and other compounds.

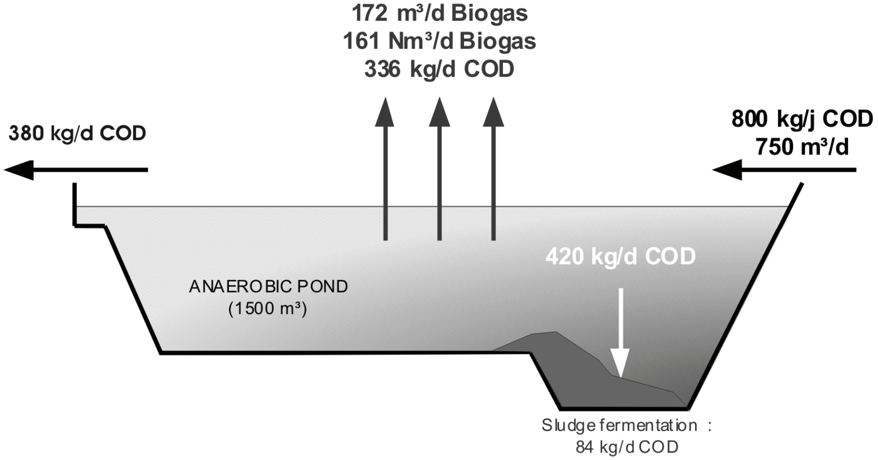
FIGURE 4-3
BIOGAS RECOVERY: CROSS SECTION



Source: adapted from Driouache et al. (1997)

In Ben Sergao (Maroc), a 1,500 m³ anaerobic pond has been covered with PVC sheets. Raw wastewater contains 2,5 L of sludge per m³ (measured by a sedimentation analysis). The wastewater treatment plant treats 750 m³ of wastewater per day (10,000 inh. eq.), therefore the anaerobic pond receives more or less 1,875 m³ of sludge per day. The 750 m³ contains 800 kg of COD, 380 kg/d leave the anaerobic pond and 420 kg/d undergo sedimentation. After 15 months, the COD of the sludge has been reduced by 80%. So, 336 kg of COD produce 172 m³ of biogas per day, which corresponds to 6.3 m³ biogas per capita per year (see Figure 4-4). The biogas is then carried into a generator set to produce electricity, which can be used for various applications (Driouache et al., 1997).

FIGURE 4-4
BIOGAS RECOVERY: COD BALANCE AND BIOGAS PRODUCTION



Source: adapted from Driouache et al. (1997)

More information on the anaerobic treatment is available in Chapter 4.5.

Facultative ponds

There are two types of facultative ponds: primary facultative ponds that receive raw wastewater and secondary facultative ponds that receive particle-free wastewater (usually from anaerobic ponds, septic tanks, primary facultative ponds, and shallow sewerage systems). Facultative ponds usually are 1.5 m deep, although depths between 1 m and 2 m are used. Depths less than 0.9 m are not recommended, as rooted plants may grow in the pond and provide a shaded habitat suitable for mosquito breeding. They operate under lighter organic loading than anaerobic ponds.

In primary facultative ponds (receiving raw wastewater), two main mechanisms remove BOD (Mara and Pearson, 1987):

- Sedimentation and subsequent anaerobic digestion of settleable solids; up to 30% of the influent BOD may leave the pond as methane gas.

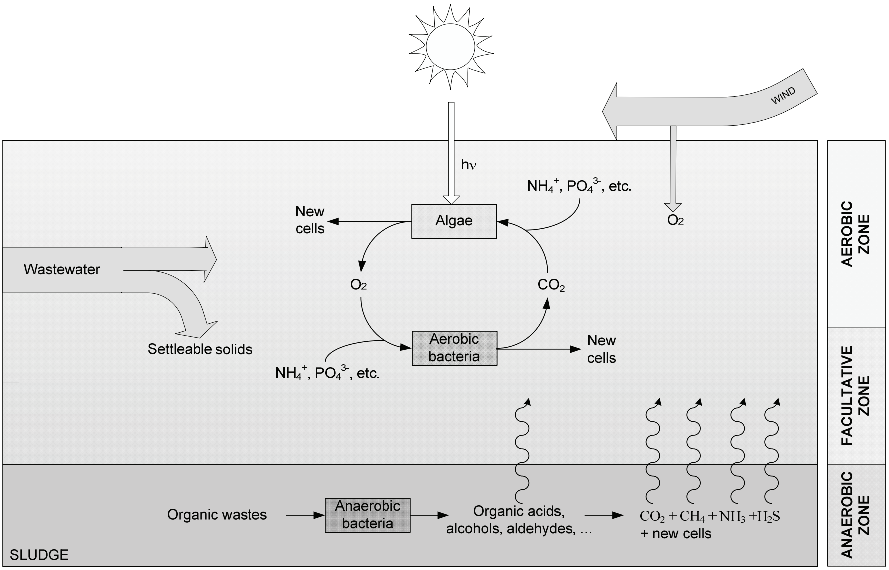
- Aerobic bacterial oxidation of the non-settleable organic compounds, together with the solubilised products of anaerobic digestion. The oxygen needed for this comes partly from the air through surface re-aeration, but mainly from the photosynthetic activities of the microalgae, which grow profusely in the pond and colour it dark green; the algae in return receive most of their carbon dioxide from the end product of bacterial metabolism (see Figure 4-5).

In secondary facultative ponds (receiving anaerobic pond effluent, which is particle-free), the first mechanism for BOD removal does not occur significantly. The remaining non-settleable BOD is oxidised by heterotrophic bacteria (*Pseudomonas, Flavobacterium, Archromobacter and Alcaligenes* spp). The oxygen required to oxidise BOD is obtained from the photosynthetic activity of the micro-algae that grow naturally and profusely in facultative ponds.

The wind has also an important effect on the behaviour of facultative ponds because it induces vertical mixing of the pond liquid. Mixing ensures a more uniform distribution of BOD, dissolved oxygen, bacteria, and algae, and provides a better degree of waste stabilization.

Facultative ponds are designed to remove BOD on the basis of a relatively low surface loading (100 – 400 kg BOD/ha.day) to allow the development of a healthy algal population, since the oxygen for BOD removal by the pond bacteria is generated primarily via algal photosynthesis. The facultative pond relies on naturally-growing algae. The facultative ponds are usually dark-green in colour because of the algae they contain. Motile algae (*Chlamydomonas* and *Euglena*) tend to predominate in the turbid water of facultative ponds, compared to none-motile algae (*Chlorella*).

FIGURE 4-5
PATHWAYS OF BOD REMOVAL IN A FACULTATIVE WASTE STABILIZATION POND



Source: adapted fromRuihong, 2001

As a result of the photosynthetic activities of the pond algae, there is a diurnal variation in the concentration of dissolved oxygen. After sunrise, the dissolved oxygen level progressively rises to a maximum in the afternoon and then falls down to a minimum at night when photosynthesis ceases and respiratory activities consume oxygen. At peak algal activity, carbonate and bicarbonate ions react to provide more carbon dioxide to the algae, leaving an excess of hydroxyl ions: as a result, the pH of the water can rise to above 9.4 (Mara, 2005). It has been shown by exposing faecal bacteria in the dark to elevated pH that pH alone is not really toxic but at extreme high values which are rarely encountered in WSPs (Curtis et al., 1992). It is the interaction of pH and sunlight that is toxic (Mara, 2005). Good water mixing, usually facilitated by the wind within the upper water layer, ensures a uniform distribution of BOD, dissolved oxygen, bacteria and algae, thus leading to a better degree of waste stabilization (Mara and Pearson, 1987).

Maturation ponds

Maturation ponds, usually 1-1.5 m deep, receive the effluent from the facultative ponds. Their primary function is to remove excreted pathogens. Although maturation ponds achieve only a small degree of BOD removal, their contribution to nutrient removal can be significant. Maturation ponds usually show less vertical biological and physicochemical stratification and are well-oxygenated throughout the day. The algal population in maturation ponds is much more diverse than in the facultative ponds, with non-motile genera tending to be more common. The algal diversity generally increases from pond to pond along the series; in other words, species diversity decreases as the organic loading increases (Mara and Pearson, 1986). Although faecal bacteria are partially removed in the facultative ponds, the size and number of the maturation ponds determine the number of faecal bacteria in the final effluent. There is some removal of solids-associated bacteria in anaerobic ponds, mainly by sedimentation. The main mechanisms for faecal bacterial removal in facultative and maturation ponds are:

- Time and temperature;
- High pH (> 9) combined with sunlight; and
- High light intensity, combined with high dissolved oxygen concentration.

High pH values (above 9) occur in ponds, due to rapid photosynthesis by pond algae, which consumes CO_2 faster than it can be replaced by bacterial respiration. As a result, carbonate and bicarbonate ions dissociate, as follows:

$$2\,HCO_3^- \rightarrow CO_3^{2-} + H_2O + CO_2 \qquad \textbf{(E. 12)}$$

$$CO_3^{2-} + H_2O \rightarrow 2\,OH^- + CO_2 \qquad \textbf{(E. 13)}$$

The algae fix the resulting CO_2 and the hydroxyl ions accumulate, often raising the pH to values above 9. In WSPs, faecal bacteria (with the notable exception of *Vibrio cholerae*) die very quickly at pH values higher than 9 (Pearson *et al.,* 1987).

Pathogen removal

The main parameters affecting the removal of faecal bacteria in ponds are light intensity, temperature, pH, and retention time. Faecal bacteria removal increases with high temperatures, high pH (most faecal bacteria are quickly killed at pH>9), long retention times, and high light intensities (Mara et al., 1992).

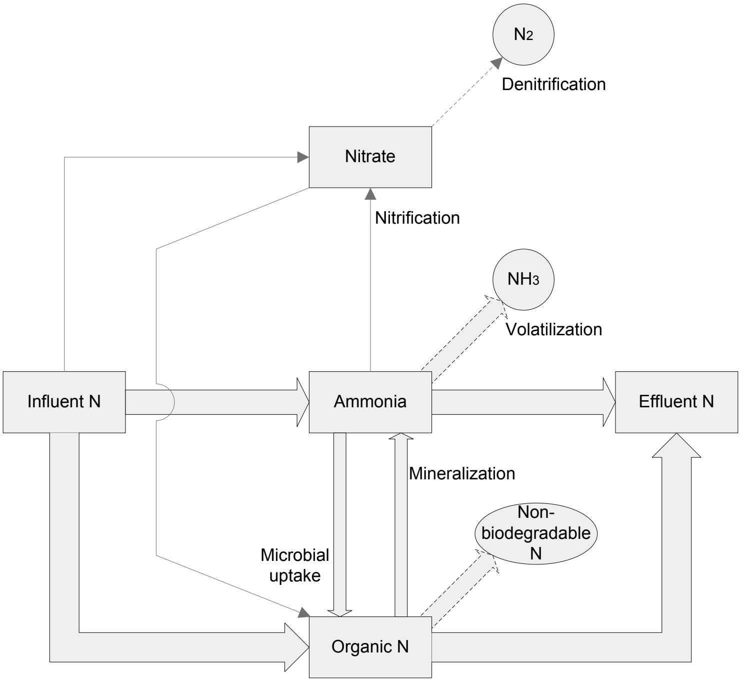
The sun plays an important role in removing faecal bacteria. It warms up the pond and provides enough energy to enhance algal photosynthesis, which raises the pH and produces high concentration of oxygen necessary to promote photo-oxidative damage. Sedimentation removes excreted protozoan cysts and helminth eggs and a series of ponds with an overall retention time of 11 days or more will produce an effluent free of cysts and eggs.

Nutrient removal

Organic nitrogen is first mineralized into ammonia in anaerobic ponds or in the sediments of facultative ponds. Due to ammonification (mineralization) of the nitrogenous organic compounds, the ammonia concentration is most of the time higher in anaerobic ponds than in the raw wastewater. Ammonia removal occurs mainly in maturation ponds. Ammonia removal is related to pH and surface temperature and is better in the summer than in the winter.

The three mechanisms of ammonia removal in ponds are loss by volatilization, bacterial nitrification (nitrosomonas and nitrobacter) followed by denitrification, and fixation into algal biomass. The main mechanism of ammonia removal is volatilization. It is important to have a good anaerobic treatment to mineralise the organic nitrogen into ammonium. Subsequently, in facultative ponds for instance, ammonium will volatilise due to high pH. Removal by nitrification is thought to be low. However, nitrogen removal in waste stabilization ponds may reach 80% (Mara et al. 1992). Figure 4-6 summarises the various nitrogen transformation and losses that occur in WSP.

FIGURE 4-6
NITROGEN TRANSFORMATION AND LOSSES



The thickness of the arrow indicates the relative quantitative importance of the pathway; the broken arrows show mechanisms of net nitrogen removal.
Source: Mara and Pearson, 1986

Phosphorus removal in WSP is associated with its uptake by algal biomass, precipitation and sedimentation (Mara and Pearson, 1986). Houng and Glovna (1984) suggested that the best way to remove much of the phosphorus in the wastewater by WSP is to increase the number of maturation ponds as progressively more phosphorus become immobilized in the oxidized surface layers of the sediments of these ponds. However, both nitrogen and phosphorus must be removed to prevent eutrophication in receiving water bodies. The common practice in the design of the WSP is not based on nutrient removal, but on BOD and faecal coliform removal.

Aerated Ponds

When land is limited and strict odour control is desired, oxygen may be supplied mechanically by diffusers or aerators. The rate of oxygen input then becomes at least one order of magnitude higher than algal systems can provide. Depending on the size, type, and disposition of the aerators, an aerated lagoon may be a fully mixed aerobic lagoon or there may be some areas where solids settle in the bottom and decompose anaerobically.

The mixing action of aeration increases turbidity, which excludes light penetration to an extent such that algal activity is virtually eliminated. Due to the shorter detention time, the biological community of aerated ponds is not as diverse as in facultative ponds. Bacteria compose the dominant microbial species.

4.1.2 Hydraulic considerations and physical design

The physical design of WSP must be carefully done since it is, at least, as important as the process design and can significantly affect the treatment efficiency.

Context

Pond location

Ponds should be located at least 200 m (preferably 500 m) downwind from the community they serve and away from any likely area of future expansion. This is mainly to discourage people from visiting the ponds, for obvious security reasons mainly regarding children and unaware people.

Odour release, even from anaerobic ponds, is most unlikely to be a problem in a well designed and properly maintained system, but the public may need assurance about this at the planning stage, and a minimum distance of 200 m normally allays any fears. The ponds must be located at a fairly accessible place and, in order to minimize earthworks, the site should be flat or gently sloping. Ponds should not be located within 2 km from airports since birds attracted by the ponds may constitute a risk to air navigation.

Geotechnical considerations

Geotechnical aspects are very important. The main objectives of a geotechnical investigation are to ensure correct embankment design and to determine whether the soil is sufficiently permeable to require the pond to be lined. The maximum height of the ground water table should be determined and the following properties of the soil at the proposed pond location should be measured:

- Particle size distribution;
- Maximum dry density and optimum moisture content (modified Proctor test);
- Atterberg limits;
- Organic content; and
- Coefficient of permeability.

At least four soil samples should be taken per hectare and they should be as undisturbed as possible. The samples should be representative of the soil profile to a depth 1m greater than the envisaged pond depth.

Organic (e.g., peaty) and plastic soils and medium-to-coarse sands are not suitable for embankment construction. If there is no suitable local soil with which, at least, a stable and impermeable embankment core can be formed, some suitable soil should be imported to the site and the local soil used for embankment slopes. Black cotton soils (Dark-colored usually calcareous tropical soils that swell when wet and that crack intensely when drying) are impermeable and very suitable for ponds, but red coffee soils are too permeable and the ponds will require lining. Embankment should be protected from storm water erosion by providing adequate drainage.

Hydraulic balance

To maintain the liquid level in the ponds, the inflow must be, at least, greater than real evaporation and seepage at all times. Thus:

$$Q_i \geq 0.001A(E+S) \qquad \textbf{(E. 14)}$$

Where:

- Q_i = inflow at first pond [m³/d]
- A = total area of ponds [m²]
- E = net evaporation [mm/d]
- S = seepage [mm/d]

Seepage losses must be smaller than the inflow minus net evaporation in order to maintain the water level in the pond. The maximum permissible permeability of the soil layer making up the pond base can be determined from Darcy's law:

$$k = \frac{Q_s}{86{,}400A}\frac{\Delta l}{\Delta h} \qquad \textbf{(E. 15)}$$

Where:

- k = maximum permissible permeability [m/s]
- Q_s = maximum permissible seepage flow (=Q_{in}-0.001AE) [m³/d]
- A = base area of the pond [m²]
- Δl = depth of soil layer below pond base to aquifer or more permeable stratum [m]
- Δh = hydraulic head (= pond depth + Δl) [m]

If the impermeability of the soil is more than the maximum permissible, the pond must be lined. There is a variety of lining materials and local costs dictate which should be used. Satisfactory lining has been achieved with ordinary Portland cement (CMIIB – 32.5 – 8 kg/m²), plastic membranes and 150 mm layers of low permeability soil. As a general guide, the following interpretations may be placed on values obtained for the in situ coefficient of permeability (Mara and Pearson, 1987):

$K > 10^{-6}$ m/s: the soil is too permeable and the pond must be lined;
$10^{-7} < k < 10^{-6}$ m/s: some seepage may occur but not sufficiently to prevent the pond from filling;
$10^{-9} < k < 10^{-8}$ m/s: the ponds will seal naturally;
$K < 10^{-9}$ m/s: there is no risk of ground water contamination (if $k > 10^{-9}$ m/s and ground water is used for potable supplies, further detailed hydrogeological studies may be required.

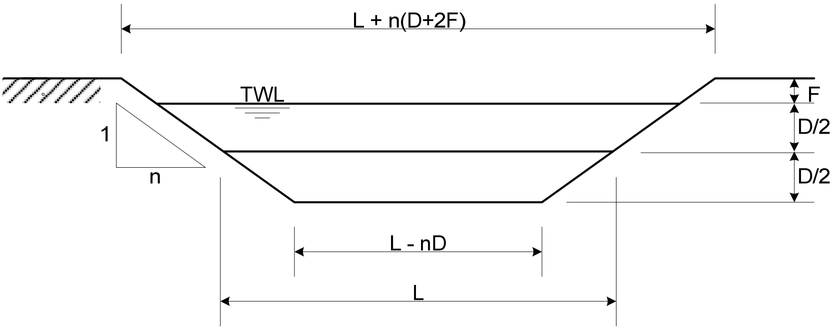
Ponds geometry

Ponds geometry is essential; the shape of the pond and the relative position of its inlet and outlet should be designed to minimize short circuiting. In general, anaerobic and primary facultative ponds should be rectangular, with length-to-width ratios less than 3 to 1, to avoid sludge settlement and accumulation near the inlet pipe. Secondary facultative and maturation ponds should, wherever possible, have higher length-to-width ratios (up to 10 or 20 to 1) so that they better approximate plug flow conditions.

Irregular shapes have to be rejected because agitation is weaker and floating algae accumulate in the corners and generate odour problems. Ponds do not need to be strictly rectangular but may be gently curved if necessary or if desired for aesthetic reasons.

To facilitate wind induced mixing of the pond surface layers, the pond should be positioned to have its longest dimension (diagonal) pointing in the same direction as the prevailing wind. The inlet should also be placed wind facing so that the wastewater flow of the pond is against the wind. Given that the areas calculated by the process design procedures are mid-depth areas, the dimensions calculated from these areas are mid-depth dimensions, which need to be corrected for the slope of the embankment, as shown in Figure 4-7.

FIGURE 4-7
CALCULATION OF TOP AND BOTTOM POND DIMENSIONS



Source: adapted from Mara and Pearson (1987)

A more precise method can be used for anaerobic ponds (because they are relatively small):

$$V_a = [(LW) + (L - 2sD)(W - 2sD) + 4(L - sD)(W - sD)].\frac{D}{6} \quad \textbf{(E. 16)}$$

Where:

- V_a = anaerobic pond volume [m³]
- L = pond length at TWL [m]
- W = pond width at TWL [m]
- s = horizontal slope factor
- D = pond liquid depth [m]

With the substitution of L as nW, based on a length to breadth ratio of n to 1, Equation E.16 becomes a simple quadratic in W.

The dimensions and levels that the contractor needs to know are those of the base and the top of the embankment; the latter includes the effect of the freeboard. The minimum freeboard is to prevent waves, induced by the wind, from overtopping the embankment. For small ponds (under 1 ha in area), a 0.5 m freeboard should be provided; for ponds between 1 ha and 3 ha, the freeboard should be 0.5-1 m, depending on site considerations. For larger ponds, the freeboard may be calculated as follows (Oswald, 1975):

$$F = \sqrt{\log_{10} A} - 1 \quad \textbf{(E. 17)}$$

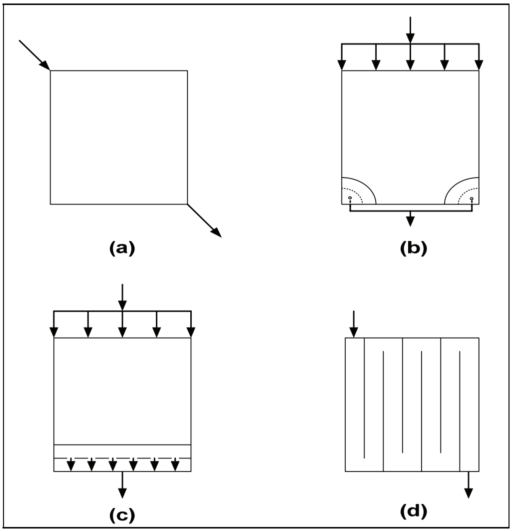
Where

- F = freeboard [m]
- A = pond area at TWL [m²]

Inlets, outlets, and short circuiting

A single inlet and outlet are usually sufficient, their precise design is relatively unimportant. A poor arrangement of inlet and outlet piping often leads to hydraulic short circuiting, which reduces the effective treatment area and thus also the mean retention time. To avoid short-circuiting, inlet and outlet should be located in diagonally opposite corners of the pond (see Figure 4-8). Baffles can also be placed into the pond to insure a full use of wetted pond area and to control short-circuiting.

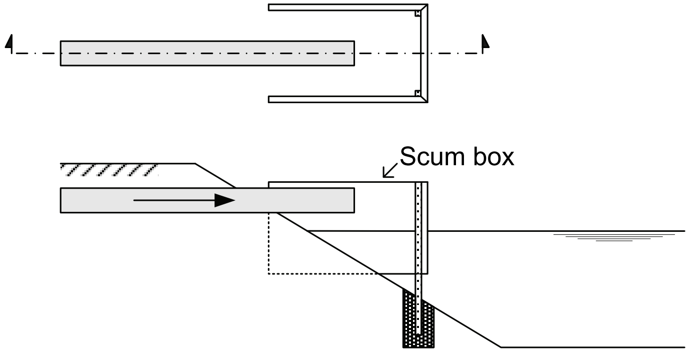
FIGURE 4-8
INLETS, OUTLETS, AND BAFFLE ARRANGEMENT



(a) diagonally opposed inlet and outlet ; (b) multiple inlets and two outlets with siphoniform partition ; (c) multiple inlets and outlets (notched weir) ; (d) system with multiple baffles.
Source: adapted from EPA 1977b

Inlets should discharge wastewater below the liquid surface to prevent short circuiting and to minimize the amount of scum (greenish water vegetation and impurities that accumulates and floats on the surface of a pond). If the inlet discharges above an anaerobic or primary facultative pond, a simple scum box should be used (see Figure 4-9).

FIGURE 4-9
INLET STRUCTURE FOR ANAEROBIC AND PRIMARY FACULTATIVE PONDS



Outlets should be flanked with scum guard to keep away from scum discharge. The depth of the scum guard controls the take-off level for the effluent and has a significant influence on the effluent BOD. The take-off level should be near the surface (well above the sludge layer) in anaerobic ponds and below the algal band in facultative ponds. A variable height scum guard is appropriate since it can be adjusted while the WSP system is functioning (Mara et al., 1992). Recommended effluent take-off levels are (Mara et al., 1992):

- anaerobic ponds : 30cm;
- facultative ponds : 60cm;
- maturation ponds : 5cm.

A weir associated with a scum board is a common outlet structure. Weirs are advantageous because they offer a simple method to measure the outgoing flow (see paragraph 3.7 – Flow measuring devices). Since the depth of water flowing over the weir is correlated to the water flow, it is easy to determine the weir's required height. In a weir of a given size and shape, there is theoretically only one water height for a particular outgoing flow.

The outlet from the final pond in a series should discharge into a simple flow-measuring device such as a triangular or rectangular notch. Since the flow into the first pond is also measured, this allows to calculate the rate of evaporation and seepage or, if evaporation is measured separately, the rate of seepage.

Preliminary treatment

All but very small systems (for <1,000 people) should have adequate screening and grit removal facilities. Even for small systems, a screening device of 50 mm bar is recommended to keep away large solids from entering the system and contaminate waterways.

Security

Well-maintained WSP may look like inviting swimming pools or places to fish. Keep in mind that a WSP system is a wastewater treatment plant and not a recreational place:

- Hygienic hazards cannot be avoided; and
- Accidents (like falling into a pond) can always happen.

Some measures should be taken to secure the system:

- Fences should be installed around the perimeter and the entry should be locked.
- Only authorized persons should be able to enter the site.
- Informative panels should be placed in front of the entrance.

Applying theses simple rules will help to reduce or moderate potential risks.

4.1.3 Process design procedures (Mara et al., 1992)

Anaerobic ponds

Anaerobic ponds should be designed on the basis of volumetric BOD loadings (λ_v, g/m³d), given by:

$$\lambda_v = \frac{L_i Q}{V_s} \qquad \textbf{(E. 18)}$$

Where:

- L_i = influent BOD [mg/L or g/m³]
- Q = flow [m³/d]
- V_s = anaerobic pond volume [m³]

Table 4-1 lists suitable design values for λ_v (BOD loadings) at various temperature ranges. The permissive design value of λ_v as the removal of BOD_5 increases with pond temperature, but currently there are insufficient field data to establish the mathematical relationship between λ_v or BOD_5 removal and the temperature.

Given that the mean hydraulic retention time in the pond (θ_s, d) is:

$$\theta_s = \frac{V_s}{Q} \qquad \textbf{(E. 19)}$$

Then,

$$\lambda_v = \frac{L_i}{Q_s} \qquad \textbf{(E. 20)}$$

The values of λ_v in Table 4-1 are restricted to the range of 100-300 g/m³d since smaller values do not maintain anaerobic conditions and higher values (>400 g/m³d) lead to unacceptable levels of odour release (although odour release occurs at values ≤400 g/m³d if the sulphate concentration is higher than 500 mg/L).

TABLE 4-1
DESIGN VALUES OF VOLUMETRIC LOADINGS AND BOD_5 REMOVALS IN ANAEROBIC PONDS

Mean monthly temperatures (T, in °C)	Volumetric BOD_5 loadings (λ_v, in g/m³d)	BOD_5 removal (%)
<10	100	40
10-20	20T-100	2T+20
>20	300	60

Theoretically, there is no limit on how deep anaerobic ponds should be. In general, a depth of 3 meters is suitable.

Facultative ponds

There are different methods to design facultative ponds; it is recommended to use the permissible design value of surface BOD loading (λ_s, Kg/ha d), given by:

$$\lambda_s = 10 L_i Q / A_f \qquad \textbf{(E. 21)}$$

Where:
- A_f = facultative pond area [m²]

The permissible design value of λ_s increases with temperature. To determine λ_s, Mara et al. (1992) suggested the following global design equation:

$$\lambda_s = 350(1.107 - 0.002T)^{T-25} \qquad \textbf{(E. 22)}$$

Where:
- T = temperature [°C]

Due to the absence of the sludge layer in secondary facultative ponds (which is responsible for up to 30% BOD removal in primary facultative ponds), the design loading should be reduced by 30% compared to a primary facultative pond.

Once λ_s and A_f have been calculated, retention time (θ_f, d) can be determined from:

$$\theta_f = \frac{A_f D}{Q_m} \qquad \textbf{(E. 23)}$$

Where:
- D = depth [m]
- Q_m = mean flow [m³/day]

The mean flow is the mean of the influent and effluent flow (Q_i and Q_e).

$$\theta_f = \frac{A_f D}{\left[\frac{(Q_i + Q_e)}{2}\right]} \qquad \textbf{(E. 24)}$$

Since $Q_e = Q_i - 0.001A_f e$ (if seepage is negligible and where e is the evaporation rate [mm/d]), the retention time can be expressed as:

$$\theta_f = \frac{A_f D}{\left(2Q_i - 0.001A_f e\right)} \qquad \textbf{(E. 25)}$$

The BOD removal in primary facultative ponds is usually around 70 to 80 percent based on unfiltered samples and above 90 percent based on filtered samples. In secondary facultative ponds, the removal is smaller, but the combined performance of anaerobic and secondary facultative ponds does generally equal (or is even better than) the performance of primary facultative ponds.

Maturation ponds

BOD loading and removal

The permissible loading design value on a maturation pond (λ_{sm}) must be smaller than 75% of the loading on the facultative pond. Assuming that the treatment in the previous ponds removed 70% of the total BOD, the loading on the first maturation pond is calculated as follows:

$$\lambda_{sm1} = \frac{10(0.3L_i)Q}{A_m} = \frac{10(0.3L_i)D}{\theta_m} \qquad \textbf{(E. 26)}$$

And the maturation pond area is calculated from:

$$A_m = \frac{2Q_i\theta_m}{2D + 0.001e\theta_m} \qquad \textbf{(E. 27)}$$

BOD removal commonly reaches 25% in each maturation pond.

Pathogen removal

Maturation ponds are primarily designed to remove pathogens. Given that faecal bacteria are used as indicators of excreted pathogens, maturation ponds are generally designed to reduce faecal coliforms to a given concentration. The size and the number of maturation ponds govern the quality of the final effluent of the pond series. The design procedure assumes that faecal coliform removal is a first order kinetic reaction:

$$B_e = \frac{B_i}{\left(1 + K_T\theta_m\right)} \qquad \textbf{(E. 28)}$$

Where:

- B_e = Coliform bacteria concentration per 100ml effluent [FC/100ml]
- B_i = Coliform bacteria concentration per 100ml influent [FC/100ml]
- K_T = First order constant for coliform removal at T°C [d^{-1}]
- θ_m = maturation pond retention time [d]

For a series of anaerobic, facultative and n maturation ponds, the equation becomes:

$$B_e = \frac{B_i}{(1+K_T\theta_a)(1+K_T\theta_f)(1+K_T\theta_{m1})(1+K_T\theta_{m2}).....(1+K_T\theta_{mn})} \quad \textbf{(E. 29)}$$

The values of K_T at different temperatures is:

$$K_T = 2.6(1.19)^{T-20} \quad \textbf{(E. 30)}$$

B_e is often stipulated as a required effluent standard. B_i can be measured from the wastewater if it exists or approximated to $1x10^8$ per 100mL.

To design a WSP system, the number of maturation ponds and their retention time should be determined by trial and error. The recommended minimum value of θ_m is three days to avoid short circuiting. It is also recommended to have a θ_m smaller than θ_f. The greater the number of maturation ponds, the shorter the maturation pond retention time and therefore the land area requirements will be minimized (Mara et al., 1992).

Helminth egg removal

Helminth eggs are normally removed by sedimentation in the anaerobic or primary facultative ponds. If the final effluent is used for restricted irrigation, it is necessary to ensure that it contains no more than one egg per litre. Analysis of egg removal in the pond has yielded the following relation reported by Ayres et al. (1992):

$$R = 100[1 - 0.14\exp(-0.38\theta)] \quad \textbf{(E. 31)}$$

Where R is the percent egg removal and θ is a retention time (day). The equation corresponding to the lower 95% confidence limit is:

$$R = 100[1 - 0.41\exp(-0.49\theta + 0.0085\theta^2)] \quad \textbf{(E. 32)}$$

Nitrogen removal

In WSP, nitrogen removal may reach 80% or more and appear to be related to the pH, the temperature and the mean hydraulic retention time. Design equations for nitrogen removal have been developed in North America and could possibly provide inaccurate results in another region.

The overall nitrogen removal in a series of ponds (presented by Reed, 1985) is:

$$N_e = N_i \exp\{-[k(1.039)^{T-20}]\}.[\theta + 60.6(pH - 6.6)] \qquad \textbf{(E. 33)}$$

Where:

- N_e = total nitrogen concentration in the final effluent [mg/L]
- N_i = total nitrogen concentration in pond influent [mg/L]
- k = first-order rate constant for total nitrogen removal [= 0.0064 d^{-1}]
- θ = mean hydraulic retention time for the ponds series [d]
- T = temperature [°C]

The overall ammonia nitrogen removal in a series of pond (presented by Pano & Middlebrooks, 1982) is given by the following equations:

For Temperature < 20°C:

$$C_e = \frac{C_i}{1 + [(\frac{A}{Q}).(0.0038 + 0.000134T) \times \exp((1.041 + 0.044T).(pH - 6.6))]} \qquad \textbf{(E. 34)}$$

For Temperature > 20°C:

$$C_e = \frac{C_i}{1 + [5.035.10^{-3}(A/Q).\exp((1.540.(pH - 6.6))]} \qquad \textbf{(E. 35)}$$

Where:

- C_e = ammonia nitrogen concentration in the final effluent [mg/L]
- C_i = ammonia nitrogen concentration in pond influent [mg/L]
- A = pond series area [m²]
- Q = influent flow rate [m³/d]
- T = temperature [°C]

The pH value can be estimated from the following equation:

$$pH = 7.3\exp(0.0005Alk) \qquad \textbf{(E. 36)}$$

Where:

- Alk = influent alkalinity, mg $CaCO_3$/L

4.1.4 Operation and maintenance

Filling the ponds

Start up procedure, in other words filling the ponds with water, has to be executed as fast as possible. It the filling is too slow, vegetation could quickly grow in the basins and destabilize the embankments, and compacted soil embankments could desiccate and loose their impermeability.

The quantity of influent wastewater is not sufficient to fill a pond fast enough. In addition, the filling of facultative and maturation ponds with freshwater generally favours gradual set up of the symbiosis existing between algal and bacterial populations (BCEOM, 1990). Anaerobic and primary facultative ponds may be half filled with freshwater, then gradually loaded up with raw wastewater (they may also be seeded with sludge from another treatment plant). However, filling up the ponds with freshwater is most of the time too expensive and is generally avoided.

Routine maintenance

- Maintain preliminary treatment device: it is undoubtedly the most frequent operation. Screenings debris and grit from preliminary work should be removed daily. A simple rake is in general enough for preliminary treatment maintenance requirements. Debris are collected and sent into a public disposal or buried on the spot.

- Clean embankments: a careful control of the embankment vegetation is fundamental. A pond has no tall weed growing on the embankments (U.S. EPA, 1977a). Grass has to be mowed and removed right away so that it does not fall into the pond. The aquatic part of the vegetation is an excellent shelter for mosquito larvae. The aerial part represents a “take-off track” for adult mosquitoes (BCEOM, 1990). This operation will be done manually or mechanically, but herbicides should be avoided (because they would at the same time harm and/or kill the algae populations and compromise all biological treatment mechanisms occurring in ponds).

- Clean inlets and outlets: inlets and outlets must be kept free of scum, floating debris, or other junk.

- Remove floating scum and floating macrophytes: floating scum and floating macrophytes (or anything that provides shade in the pond and that could perturb the algae photosynthesis) should be removed from the surface of facultative and maturation ponds. Floating scum and crust should not be removed from anaerobic ponds because they keep the pond anaerobic and minimize foul odours (U.S. EPA, august 1977a).

- Repair any damage to embankments, fences, gates, …

Staffing level

For routine O&M tasks, WSP must be adequately staffed. The level of staffing depends on the type of inlet works (for example, mechanically raked screens and proprietary grit removal units require an electromechanical technician, but manually raked screens and manually cleaned grit channels do not), whether there are on-site laboratory facilities, and how the grass is cut (manually or by mechanical mowers). Table 4-2 shows recommended staffing levels for WSP serving populations up to 250,000; for larger systems, the number of staff could be increased *pro rata.*

TABLE 4-2
RECOMMENDED STAFFING LEVELS FOR WSP SYSTEMS

Population Served	10,000	25,000	50,000	100,000	250,000
Foreman/ Supervisor	-	-	1	1	1
Mechanical engineer[a]	-	-	-	1	1
Laboratory technician[b]	-	1	1	1	2
Assistant foreman	-	1	2	2	2
Labourers	1	2	4	6	10
Driver[c]	-	1	1	1	2
Watchman[d]	1	1	3	5	5
Total	2	6	10	15	23

[a] Depends upon amount of mechanical equipment used.

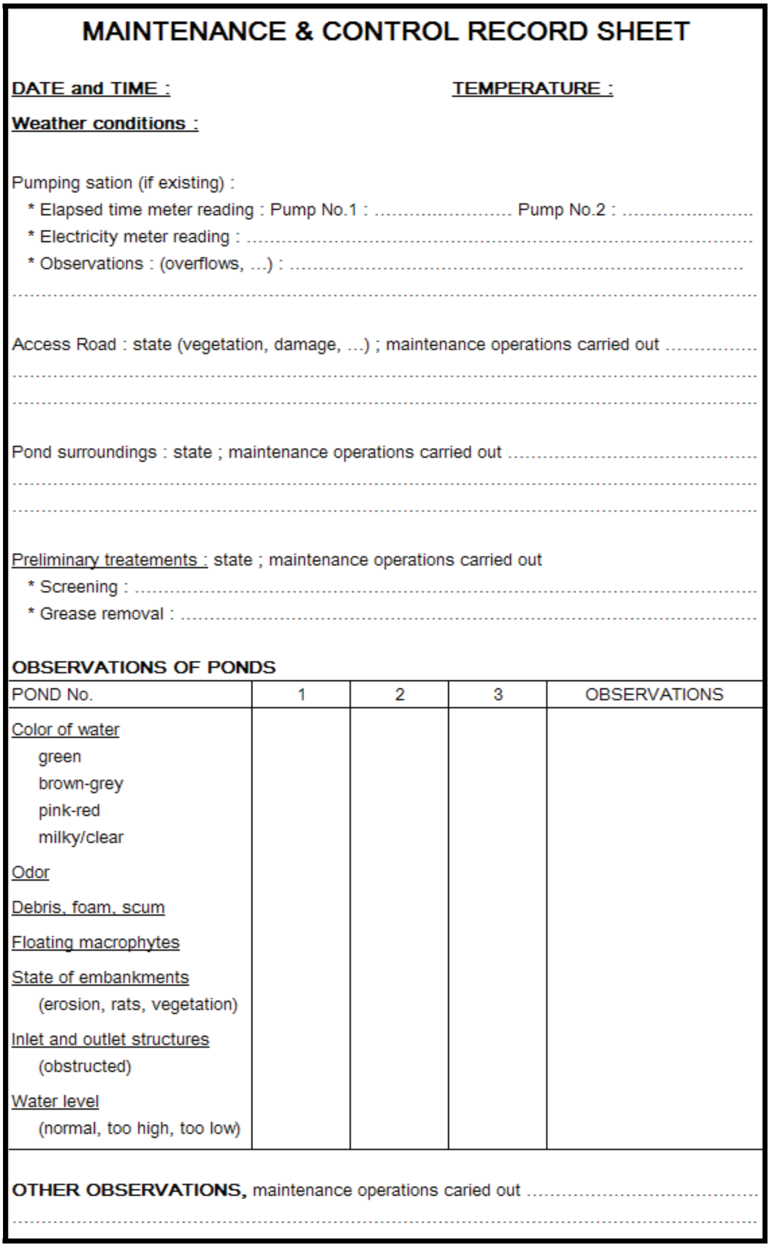
[b] Depends upon existence of laboratory facilities.

[c] Depends upon use of vehicle-towed lawn mowers, etc.

[d] Depends upon location and amount of equipment used.

Source: Arthur, 1983

FIGURE 4-10
SAMPLE MAINTENANCE AND CONTROL RECORD SHEET



MAINTENANCE & CONTROL RECORD SHEET

DATE and TIME : **TEMPERATURE :**

Weather conditions :

Pumping sation (if existing) :
* Elapsed time meter reading : Pump No.1 : .... Pump No.2 : ....
* Electricity meter reading : ....
* Observations : (overflows, ...) : ....
....

Access Road : state (vegetation, damage, ...) ; maintenance operations carried out ....
....
....

Pond surroundings : state ; maintenance operations carried out ....
....
....

Preliminary treatements : state ; maintenance operations carried out
* Screening : ....
* Grease removal : ....

OBSERVATIONS OF PONDS

POND No.	1	2	3	OBSERVATIONS
Color of water green brown-grey pink-red milky/clear				
Odor				
Debris, foam, scum				
Floating macrophytes				
State of embankments (erosion, rats, vegetation)				
Inlet and outlet structures (obstructed)				
Water level (normal, too high, too low)				

OTHER OBSERVATIONS, maintenance operations caried out ....
....

Source: CEMAGREF, 1985

Desludging

Every one to three years, sludge is removed from anaerobic ponds to maintain the proper design volume. Anaerobic ponds need desludging when they are one third full of sludge, Mara et al., 1992 give a desludging frequency (desludging occurs every n years) :

$$n = \frac{V}{3Ps} \qquad \textbf{(E. 37)}$$

Where:

- V = volume of anaerobic pond [m^3]
- P = number of persons served by the treatment
- s = sludge accumulation rate [commonly $0.04 m^3$/person year]

Anaerobic ponds should never be completely cleaned; a small amount of sludge should be left in the pond as it contains bacteria needed for the anaerobic digestion. The depth of sludge in anaerobic and facultative ponds can be determined using the “white towel” test[1]. A white towel is wrapped along a long pole, which is lowered vertically into the pond until it reaches the bottom and then slowly withdrawn. The depth of the sludge layer is clearly visible since some sludge particles will have been captured on the towel.

Desludging can be performed frequently from the edge of the pond by a pump. If desludging is not performed frequently, the sludge accumulates and becomes compressed on the bottom. Desludging old compressed sludge with a pump is rendered impossible and needs to be performed by a shovel truck while taking care not to damage the impermeability of the pond. If the sludge is not removed, the design volume and the treatment efficiency decrease and this can lead to some serious problems.

Monitoring and performance evaluation

As soon as a WSP system has been constructed, a monitoring scheme and an adequate control of the process (influent, pond and effluent) have to be implemented. It is necessary to control monthly (if possible weekly) the process to evaluate its performance and to know if the quality of the effluent meets the regional requirements.

Wastewater samples must be representative of the water. Pond effluent quality changes during the time of the day, so, it is sometimes useful to take samples at different times during the day. Therefore, a sampling procedure has to be established. The WSP system should at least be analysed for the parameters that the local authorities require. Whenever possible, flow-weighted samples should be used because they better represent the actual wastewater strength. Common key quality and performance indicators are temperature, flow, pH, dissolved oxygen, BOD_5, suspended solids, faecal coliform, nitrogen, and pond colour.

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[1] http://www.leeds.ac.uk/civil/ceri/water/tphe/publicat/pdm/indiafiles/IPDMc7.pdf

WSP Design example

Assume a population (P) of 100,000, a BOD$_5$ contribution of 40 g/PE.d, and a wastewater flow of 100 l/PE.d. Design temperature: 26^{0}C. Design concentration of faecal coliforms in the final effluent: 1,000 per 100 ml. The sewage is to be treated by anaerobic, facultative, and maturation ponds operating in series.

Anaerobic pond

Flow Q = 100. 10^{-3}.100,000 = 10,000 m^3/day
Influent BOD$_5$, L_i = 40.10^3/100 = 400 mg/l
From Table 4-1, design BOD loading λ_v= 350 g/m^3.day.
Volume V:

$$V = \frac{L_i Q}{\lambda_v} = \frac{400 \cdot 10000}{350} = 11{,}430 m^3 \qquad \textbf{(E. 38)}$$

If the depth is 3 m, the working area is 0.38 ha. The hydraulic retention time, *V/Q,* is 1.14 days, and the BOD$_5$ removal is about 60 percent. Desludging would be required every n years, where n is given by:

$$n = \frac{\frac{V}{3}}{P \cdot 0.04} = \frac{\frac{11430}{3}}{100{,}000 \cdot 0.04} = 0.95 \approx 1 year \qquad \textbf{(E. 39)}$$

This assumes a sludge accumulation rate of 0.04 m^3 per person yearly and desludging of the pond when it is one third full of sludge.

Facultative ponds

The design loading is given by equation (E. 22):

λ_s=350(1.107-0.002T)$^{T-25}$ = 350[1.107-(0.002.26)]$^{26-25}$=369 (kg/ha.day)

The area is given by equation (E. 21):

A_f=10$L_i Q/\lambda_s$ = 10.(400.0.4).10,000/369= 43,360(m^2)

The retention time is given by equation (E.25):

$$\theta_f = \frac{A_f D}{\left(2Q_i - 0.001 A_f e\right)}$$

Where *e* is net evaporation rate (e= 6 mm/day). Taking a depth of 2.0 m, this becomes:

$$\theta_f = \frac{2 \cdot 43{,}360 x 2}{2x 10{,}000 - 0.001 \cdot 43{,}360 \cdot 6} = 8.78(days)$$

The effluent flow is:

Q_e=Q_i-0.001$A_f e$= 10,000-(0.001.43,360.6) =9739.8 (m^3/day)

Maturation ponds

For 26°C the value of k_T is given by (E. 30):

K_T= 2.6(1.19)$^{26-20}$ = 7.38 (day^{-1})

Equation E. 28 or 29 can be rearranged as follows:

$$\theta_m = \frac{\left[\dfrac{10^8}{10^3(1+(7.38x1.14)).(1+(7.38x8.78))}\right]^{\frac{1}{n}}}{7.38}$$

= 21.7 days for n=1
= 1.58 days for n=2

For n=2, θ_m equal to 2 days is chosen.

Check the loading on the maturation pond from equation (E. 26):

$\lambda_{sml} = \dfrac{10(0.3L_i)D}{\theta_{ml}}$) = 10 . 0.3 . 400 . 1.5 / 2 = 900 kg/ha.day

This value is higher than 75 percent of the load on the facultative pond (=0.75.369 = 276.75 kg/ha.day). Thus $\lambda_{s(ml)}$ is taken as 277 kg/ha.day and θ_{ml} calculated from:

$\theta_{ml} = \dfrac{10L_iD}{\lambda_{ml}}$ θ_{ml}= 10 . 0.3 . 400 . 1.5 / 277= 6.5 days

The retention times in the subsequent maturation ponds are calculated from:

$$\theta_m = \frac{\left[\dfrac{10^8}{10^3(1+(7.38x1.14)).(1+(7.38x8.78)).(1+(7.38x6.5))}\right]^{\frac{1}{n}}}{7.38}$$

=0.31 days for n=1
=0.11 days for n=2

For a depth of 1.5 m, the area of the first maturation pond is given by equation (E. 27):

$$A_{m1} = \frac{2Q_i\theta_m}{2D+0.001e\theta_m} = \frac{2x9739.8x6.5}{(2x1.5)+(0.001x6x6.5)} = 41{,}664m^2$$

The effluent flow is:

Q_e= Q_i-0.001$A_{m1}e$=9739.8-(0.001x41,664x6)= 9489.8 m^3/day

And for the second maturation pond:

$$A_{m2} = \frac{2x9489.8x0.31}{(2x1.5)+(0.001x6x0.31)} = 1{,}960m^2$$

and

Q_e= Q_i-0.001$A_{m1}e$=9489.8-(0.001x1,960x6)= 9,478 m^3/day

BOD removal

Assuming a cumulative removal of filtered BOD of 90 percent in the anaerobic and facultative ponds and 25 percent in each of the two maturation ponds, the final effluent will have a filtered (non-algal) BOD of 400 x 0.1 x 0.75 x 0.75 = 22.5 mg/l, which is satisfactory.

Summary

Anaerobic pond		
	volume	11,430 m^3
	retention time	1.14 days
Facultative pond(s)		
	activated area	43,360 m^2
	TWL area with L:W= 10:1	54,200 m^2
	retention time	8.78 days
First maturation pond(s)		
	activated area	41,664 m^2
	TWL area with L:W= 10:1	52,080 m^2
	retention time	6.5 days
Second maturation pond(s)		
	activated area	1,960 m^2
	TWL area with L:W= 10:1	2,450 m^2
	retention time	0.31 days

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4.2 Wetlands

4.2.1 Introduction

Wetlands are ecosystems that have shallow standing water or a water table at or near the surface and that have a prevalence of vegetation adapted for life in saturated soil conditions. The vegetation uses solar energy to assimilate carbon from the atmosphere and to produce organic matter, which in turn provides energy for heterotrophs (animals, bacteria, and fungi).

The productivity of wetlands is among the highest in the world because of the ample supply of water and nutrients in these ecosystems. Wetlands also have a high capacity to decompose and transform organic matter and other substances. Constructed wetlands (CWs) use this capacity to enhance water quality (treatment of municipal, industrial, agricultural, and urban runoff wastewater). Wetlands are the “kidneys of the landscape” because of their functions in the hydrologic and chemical cycles, as the downstream receivers of waste from both natural and human sources (Mitsch and Gosselink, 1993).

While water treatment is the primary goal of these systems, some of them provide side benefits for public use and wildlife habitat. Wetlands accommodate an unusually large percentage of our wildlife. Wetlands are “biological supermarkets” because of the rich biodiversity they support. Many species of wildlife (birds, reptiles, amphibians, fish, etc.) require wetland habitats at some stage in their life cycle, and an even greater number of species use wetlands periodically (Hammer, 1992). Wetlands also have a high aesthetic value.

4.2.2 Wetland definitions and terminology

Wetlands have shallow standing water or a water table at or near the soil surface and are vegetated by plants that are adapted to growing in water-saturated soils.

Constructed wetlands (CWs) are intentionally created for the sole purpose of wastewater or storm water treatment, whereas *created wetlands* are intentionally created to produce or replace natural habitat (Hammer, 1992). Until the late eighties, the literature used *artificial wetlands* instead of constructed wetlands *or treatment wetlands*; today, most wetland scientists prefer the last term. *Restored wetlands* usually refer to the rehabilitation of wetlands that may be degraded or hydrologically altered. *Mitigation wetlands* refer to wetlands that are built to replace the wetland "function" lost by development projects, such as highway construction and commercial development.

4.2.3 Wetland hydrology and hydraulics

The hydrologic conditions of wetlands affect the soils, flora and fauna, since the flow and storage characteristic determine the time that nutrient rich water will stay in the system and the availability and possibility of interaction of substances with the ecosystem. The physical design of the system, the flow rates, the soil characteristics, and the vegetation determine the hydraulic conditions. Water can enter a wetland through inflow, precipitation, runoff, and even from ground water.

On the other hand, water can leave a wetland through outflow, evapotranspiration and ground infiltration. The balance of water between the inputs and the outputs in the wetland and the physical characteristics of the basins will determine the hydraulics of the system.

The wetland water budget describes the basic hydraulic features of the wetland. In constructed wetlands (CWs), the dominant flow tends to be the inlet. Local discharge restrictions might limit the infiltration due to the nature of the water. Other components of the budget depend on climatic factors. The water budget is as follows:

$$Q_i - Q_o + Q_c - Q_b + Q_{sm} + (P - ET - I)A = \frac{dV}{dt} \qquad \textbf{(E. 40)}$$

Where

- Q_i = inlet flow rate [m^3/d]
- Q_o = output rate [m^3/d]
- Q_c = catchment runoff rate [m^3/d]
- Q_b = bank loss [m^3/d]
- Q_{sm} = snow and ice melt [m^3/d]
- P = Precipitation rate [m^3/d]
- ET = Evapotranspiration [m^3/d]
- I = Infiltration rate [m^3/d]
- A = area [m^2]
- t = time [1/d]
- V = volume

Even though the theoretical water budget in the wetland suggests that all the water inside the system is in motion, the shape of the beds, the water distribution and collection systems, the lack of proper compartmentation, and other factors can create stagnant zones within the wetland. These “dead zones” do not participate in the pollution removal processes and therefore reduce the effective area of the system and should be avoided by optimising the design.

4.2.4 Types of constructed wetlands

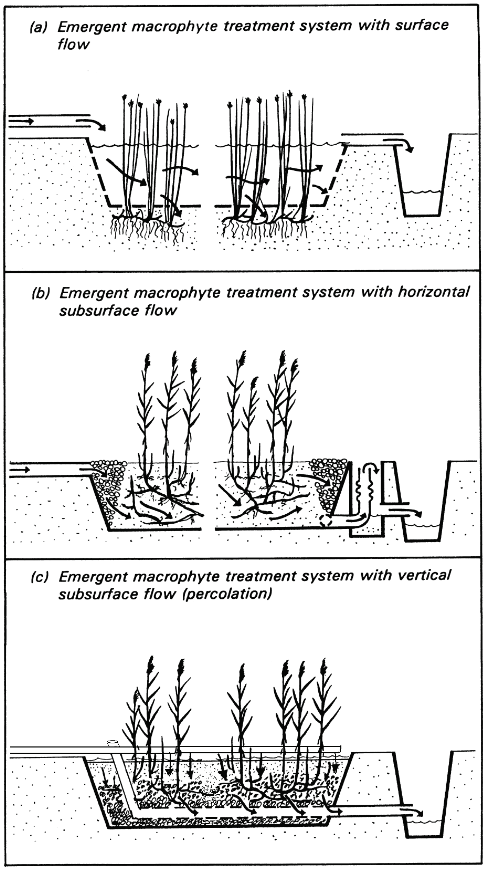
Constructed wetlands may be classified according to the life form of the dominating macrophyte into *free-floating* macrophyte-based systems, *rooted emergent* macrophyte-based systems, and *submerged* macrophyte-based systems (Brix and Schierup, 1989). Most systems in operation are planted with rooted emergent macrophytes, but their designs vary in terms of media used and flow regime (see Figure 4-11).

Surface flow systems

Surface-flow systems are flooded and expose the water surface to the atmosphere; in *subsurface flow* systems, the water level is below the surface of the media in the beds. In systems with subsurface horizontal flow, the medium is maintained water-saturated; in vertical flow systems, the medium is not saturated, because water is usually applied at timed intervals and allowed to percolate through the unsaturated medium (similar to intermittent sand filters).

All types of systems contain at least one species of rooted emergent aquatic macrophyte planted in some type of media (usually soil, gravel or sand). A combination of physical, chemical, and biological processes remove the pollutants through sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue, and microbial transformations (Brix, 1993; Vymazal *et al*, 1998).

FIGURE 4-11
EMERGENT-MACROPHYTE-BASED WASTEWATER TREATMENT SYSTEMS



a) system with surface flow, the species shown is *Scirpus lacustris*; b) system with horizontal subsurface water flow, the species shown is *Phragmites australis*; and c) system with vertical subsurface water flow, the species shown is *Phragmites australis* (modified from Brix, 1993).

Natural wetlands vary in size from less than 1 ha to >1000 ha; about 50 percent are between 10 and 100 ha. Constructed surface flow wetlands are generally smaller: about 60 percent are less than 10 ha. In general, the hydraulic loading rate is less for natural wetlands than for constructed surface flow wetlands, although there is no design consensus (Kadlec and Knight, 1996). Systems designed to treat effluents with very low levels of nitrogen and phosphorus (or for complete retention) generally have very low surface area specific loading rates, whereas systems designed to remove biochemical oxygen demand (BOD) and suspended solids generally have somewhat higher loading rates. The depth of water in the systems ranges from 5 to 90 cm, although 30 to 40 cm is common. The most common pre-treatments are facultative and aerated lagoons reflecting the fact that many of the systems are polishing steps in an existing lagoon system.

Subsurface flow systems

In Europe, several hundred soil and gravel based subsurface flow systems have been constructed. Most systems are planted with the Common Reed (*Phragmites australis*), but some systems include other species of wetland plants. The media can be soil or gravel, which secures subsurface flow. Nearly all of the soil-based systems are plagued with problems of surface runoff, while gravel is often clogged. Subsurface flow systems generally have smaller surface areas (<0.5 ha) and higher hydraulic loading rates than surface flow systems

In Europe, the systems tend to provide secondary treatment for village-sized communities of up to about 4,400 persons equivalent; in North America, they tend to provide tertiary treatment for larger populations.

4.2.5 Removal mechanisms in constructed wetlands

The major removal mechanism for nitrogen in constructed wetlands is nitrification-denitrification (Gersberg and Goldman, 1983; Reddy et al., 1989). Nitrifying bacteria in aerobic zones oxidize ammonia to nitrate, and denitrifying bacteria in anoxic zones convert nitrates to di-nitrogen gas (N_2). The oxygen required for nitrification comes from the atmosphere and from plant roots. In vertical flow beds with intermittent loading, the oxygenation is much more efficient - and hence the nitrification capacity higher than in beds that are constantly water saturated. The plants take up nitrogen and incorporate it into the biomass. Plant uptake of nitrogen is, however, generally of less importance than denitrification.

Other mechanisms can also contribute to the degradation of pollutants. Anaerobic zones are of common occurrence in constructed wetlands and can also participate in the removal of pollutants. Anaerobic heterotrophic bacteria can degrade organic compounds, and are essential for denitrification of nitrates. Denitrification can only occur in the absence of free oxygen and with sufficient organic carbon to support the denitrifying bacteria.

Phosphorus removal in constructed wetlands occurs mainly as a consequence of adsorption and precipitation reactions with aluminium (Al), iron (Fe), calcium (Ca), and clay minerals in the sediment (Richardson, 1985). Alternate wet and dry periods enhance the fixation of phosphorus in the sediments (Bayley et al., 1985; Sah and Mikkelsen, 1986). Plant uptake may be significant in systems with a low area specific loading rate (Reddy and De Busk, 1985; Breen, 1990).

Wetlands remove pathogens through sedimentation and filtration, and as a consequence of natural die-off in an unfavourable environment (Lance et al., 1976; Gersberg et al., 1987; Watson et al., 1989). Furthermore, root excretions from the macrophytes have an antibiotic effect on bacteria (Seidel et al., 1978). Ultraviolet radiation has a significant effect in systems with open water sections.

Trace metals have a high affinity for adsorption and complexation with organic material and will accumulate in the wetland sediment. Plant uptake and microbial transformations may also be of importance (Watson et al., 1989).

Table 4-3 summarises these removal mechanisms.

TABLE 4-3
REMOVAL MECHANISMS IN CONSTRUCTED WETLANDS

Constituent	Removal mechanism
Suspended Solids	▪ Sedimentation/filtration and degradation
BOD	▪ Microbial degradation (aerobic and anaerobic) ▪ Sedimentation (accumulation of organic matter/sludge on the sediment surface)
Nitrogen	▪ Ammonification followed by microbial nitrification and denitrification. ▪ Plant uptake ▪ Ammonia volatilization
Phosphorus	▪ Soil sorption (adsorption-precipitation reactions with aluminium, iron, calcium, and clay minerals in the soil) ▪ Plant uptake
Pathogens	▪ Sedimentation/filtration ▪ Natural die-off ▪ UV radiation ▪ Excretion of antibiotics from roots of macrophytes

4.2.6 Treatment performance

All types of constructed wetlands remove suspended solids efficiently, with outlet concentrations generally less than 20 mg/l and often less than 10 mg/l despite high inlet concentrations. Outlet concentrations may be higher if the system contains open water areas close to the discharge point because of production of planktonic algae in these areas. Wetlands should be constructed with a shallow water zone vegetated with emergent plants at the downstream end of the wetland to take out the algae before discharge to the receiver. The emergent plants will limit growth of algae in the water because of the light attenuation in the vegetation cover.

Constructed wetlands remove BOD efficiently, with typical outlet concentrations less than 20 mg/l and even lower. All wetlands, however, natural and constructed, have an internal carbon cycle producing low levels of BOD (1-3 mg/l), which sets the lower limit of BOD in the effluent (Kadlec and Knight, 1996). Even in temperate areas with freezing temperatures in the winter, BOD effluent concentrations seem to be consistently low (Brix, 1998).

Removal of nitrogen and phosphorus in constructed wetlands is more variable and depends on design and loading characteristics. The accretion of biomass residuals and minerals is the only sustainable removal mechanism for phosphorus in wetlands. Given that this is a slow process, surface flow wetlands constructed with the main goal of removing phosphorus are generally large and receive very dilute or pre-treated wastewater. Wetlands remove nitrogen more easily than phosphorus. Micro-organisms transform and release nitrogen as gas to the atmosphere. Given that oxygenation is often the limiting step for nitrogen removal, the design of the wetland and the type and composition of the wastewater affect nitrogen removal. Subsurface flow systems generally remove about 30-40% of nitrogen; free water surface flow systems have lower loading rates and often remove more than 50% of nitrogen.

Wetlands seem to be effective at retaining significant loads of several heavy metals. However, their storage capacity is likely to be eventually exceeded and concentrations may reach toxic levels for biota. Therefore, wetlands should not treat wastewaters with significant amount of these elements.

Constructed wetlands remove pathogens through natural die-off, low temperatures, ultraviolet radiation, unfavourable water chemistry, predation, and sedimentation. In general, the residence time in wetlands is long and therefore the removal processes appear to be effective, especially in vegetated systems.

Wetlands plants are very productive and therefore require considerable amounts of nutrients for their growth and reproduction. Plant uptake can remove nutrients from wastewater that can be bound to the biomass and eliminated from the system by plant harvesting. However, since the systems are mainly built to treat wastewater the amount of nutrients that can be removed by harvesting is insignificant considering that nutrient loading rates from wastewater might be high and consistent (see more details in role of the plants).

4.2.7 Ancillary benefits of constructed wetlands

All wetlands – natural or constructed – provide support to plant and animal populations, and have aesthetic value to society.

Food chain support

The type of plant produced and thus the type of food chain that can be supported depend on the physical habitat in the wetland. Natural wetlands are among the most productive ecosystems on earth because of the ample provision of water and nutrients from adjacent uplands (Mitsch and Gosselink, 1993). For example, in wetland systems with shallow water, emergent plants dominate and limit growth of algae in the water because of the light attenuation in the vegetation cover. If production of algae is desired to enhance an aquatic food chain (such as fish and shellfish), then the wetlands should include deep, open water areas. However, if the wetland is to reduce suspended solids, including algae, then the wetland should have a shallow water zone vegetated with emergent plants downstream to take out the algae before discharge. In some cases, secondary benefits of wetlands constructed to improve water quality include the production of 'domesticated' species, e.g. baitfish or freshwater mussels. However, great operational control is required if the wetlands are to produce crayfish or other types of aquaculture, and special consideration must be given regarding pathogen infection.

Wildlife habitat

One of the most obvious ancillary benefits of constructed wetlands is the potential for enhancing wildlife. No matter how small the wetland is and how it is designed and constructed, it will provide habitat for some animals. Creating some physical heterogeneity in the wetland can increase faunal diversity. For example, waterfowl populations are enhanced if open water areas are interspersed with vegetated shallow water areas and even with islands that are never flooded. Wading birds, however, require shallow, sparely vegetated, littoral areas and open mudflats, and transitional ecotones between open deep water and dry land provide breeding habitat for fish, which in turn provide food for diving and wading birds. Larger wetlands may even provide food and habitat for raptors such as hawks and kites. If living or dead trees are in the wetland, they can serve as perching and possibly nesting sites for birds. Small mammals such as mice, muskrat, and nutria may also colonise the constructed wetland, and larger mammals may forage in the wetland. Hence, the ancillary benefit potentially achieved when treatment wetlands attract wildlife may require relatively little capital and operating cost and promote public and social acceptance.

Human uses

Humans can use constructed wetlands for hunting, plant harvesting, aquaculture, and public recreation. Some large constructed wetlands are open for hunting to public or private groups, and edible crops, such as water chestnut, can be cultivated in treatment wetlands. There are no reported cases, however, where the products produced in wetlands are harvested on a significant basis.

The primary human use function is for recreation activities such as hiking, jogging, biking, and wildlife study. Some large constructed wetlands designed with public use in mind have been incorporated into park settings that encourage public use. Trails, boardwalks, and observation towers allow the public to observe the diversity of the wetland habitat and the resulting wildlife population. These human uses, including the satisfaction of having a wetland and wildlife at the edge of town, may be the most important factors behind public support for protecting and restoring existing wetlands.

4.2.8 Design of constructed wetlands

Constructed wetlands (CWs) for wastewater treatment can be classified by the spatial direction of the hydraulic flow. The characteristics of the hydraulic flow in the beds have important performance implication that influence the system’s design, operation, and maintenance and as such for this purpose, horizontal flow and vertical flow must be differentiated.

Horizontal flow constructed wetlands

Constructed wetland design involves several activities, such as calculating the hydraulic performance of the system, designing for the desired pollutant removal and structures, and isolating elements.

System sizing and layout

The system's size, layout, and physical characteristics depend on the topography, geology, and the soils found on the site. Sizing a constructed wetland and its components must address the hydraulic design and simultaneously guarantee the removal of pollutants. The hydraulic design of constructed wetlands is not a simple task and must take into account several factors. Constructed wetlands are not static systems; as time goes by, the system's physical characteristics evolve and the conditions that develop may modify its hydraulic performance. Traditionally, the hydraulic design for subsurface flow constructed wetlands has used Darcy's type flow while the hydraulic design for free water surface flow constructed wetlands has used open channel flow formulas. Nowadays, thanks to the computer, there are more complex numerical models.

Darcy's law is as follows:

$$Q = k_s A_c S_w \qquad \textbf{(E. 41)}$$

Where:

- Q = average flow through the wetland [m^3/d
- k_s = hydraulic conductivity [m/d]
- A_c = cross sectional area of the bed [m^2]
- S_w = slope of the hydraulic gradient [m/m]

Some of the factors to consider for the hydraulic design include the cell slopes, water slope, friction created by components of the units such as plants, biofilm growth and media, effective depth of the water column, flooding and dry out cycles, and possible clogging. Additional factors include local precipitation, especially for maximum and minimum flows. The bottom slope of the beds should not be used to control flow. The beds must be fitted with drainage devices and water level control systems.

Treatment pollutant removal performance is usually calculated with first order removal models that provide either the area required for a definite quality target or the water volume that can be treated. There are also more complex models, but they require computing resources, a very good understanding of the occurring processes, and more data than are generally available for new designs. The most accepted area-based model for design considers a background pollutant concentration (k-C*), thus taking into account the pollutant concentration present and/or generated by the wetland itself (Kadlec and Knight, 1996).

$$q\frac{dC}{dy} = -k(C_{out} - C^*) \quad \textbf{(E. 42)}$$

$$\ln\left(\frac{C_{out} - C^*}{C_{in} - C^*}\right) = \frac{-k}{q} \quad \textbf{(E. 43)}$$

Where:

- q= hydraulic loading rate [m/d]
- k= 1st order rate constant [m/d]
- C_{in}= inlet pollutant concentration [mg/L]
- C_{out} = pollutant concentration of the effluent [mg/L]
- $C*$ = background pollutant concentration [mg/L]

This model provides an equation to estimate the area required for pollutant removal:

$$Area = \frac{Q}{k}\ln\left(\frac{C_{in} - C^*}{C_{out} - C^*}\right) \quad \textbf{(E. 44)}$$

Where:

- Q = hydraulic loading rate [m^3/d]
- k = 1st order rate constant [m/d]
- C_{in} =inlet pollutant concentration [mg/L]
- C_{out} =outlet target concentration [mg/L] (different from previous)
- $C*$ = background pollutant concentration [mg/L]

The C* value varies depending on system type, type of vegetation, type and strength of wastewater treated and during the season (Kadlec and Knight, 1996). The background concentrations (C*) are typically: TSS 2-5 mg/L, BOD 1-5 mg/L, total-N < 1.5 mg/L, total-P < 0.02 mg/L, and faecal coliforms <300 mg/L. For design purposes data from similar systems treating similar kinds of wastewater must be found.

The 1st order rate constant depends on the pollutant and type of constructed wetland. For some pollutants, this constant also depends on temperature.

$$k_t = k_{20}\theta^{(T-20)} \quad \textbf{(E. 45)}$$

where:

- k_T = 1st order rate constant at temperature T [m/y]
- k_{20} = 1st order rate constant at 20°C [m/y]
- θ = temperature coefficient
- T = temperature [°C]

Table 4-4 shows values commonly used for the design of horizontal flow constructed wetlands.

TABLE 4-4
COMMONLY USED VALUES FOR DESIGN OF CONSTRUCTED WETLAND

Pollutant	**Surface flow constructed wetland**		**Sub-Surface flow constructed wetland**	
	k_{20} m/y	θ	k_{20} m/y	θ
BOD_5	34	1.00	180	1.00
TSS	1000^a	1.00	3000^a	1.00

Total-N	22	1.05	27	1.05
Total-P	12	1.00	12	1.00
Faecal Coliforms	75	1.00	95	1.00

a = unsubstantiated rough estimate

Source: Kadlec & Knight, 1996

Compartmentation

Regardless of their size, constructed wetlands should have at least two cells operating in parallel. They can have more cells, but such decisions depend on economic and geographic limitations, and on the effluent water quality requirements. Increasing the cell number will affect the costs of the systems. Cell redundancy will increase the total area needed due to the higher number of berms around the cells and the higher number of distribution and collection manifolds.

Besides redundancies on the number of cells, it is also important to define the cell shape and the berms separating them. Establishing deep zones in the cells will favour removal processes. Establishing deep zones in the cells will favour removal processes and promote better water distribution and hydraulic control, which in turn minimise the potential for hydraulic short circuits and provide internal flow control and better water quality effluent.

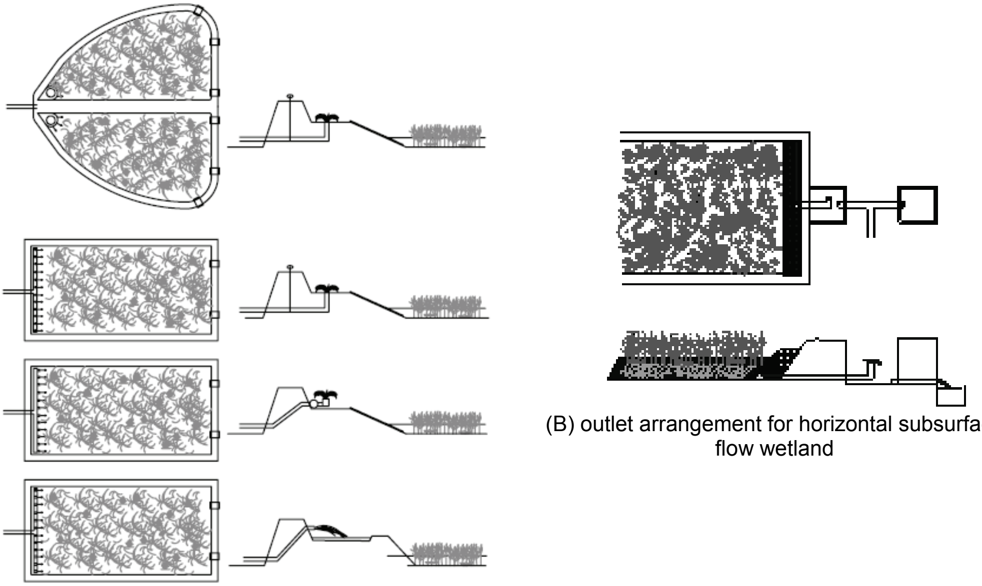
Aspect ratio of the beds (length to width ratio) is determined by the hydraulics of the system. This means that the decisions on aspect ratio should be made during the design phase and will depend on the hydraulic needs, but some other factors must be considered including the topography of the site, the construction area available, and the environmental impact of the system. A generally accepted rule of the thumb is that the aspect ratio should be greater or at least equal to 4.

Inlet and outlet structures

Inlet and outlet structures are the main components of the system and can determine its success or failure. Inlet and distribution manifolds in constructed wetlands should be effective, trouble free, and relatively simple to operate. Additionally, the distribution systems should be accessible for flow adjustments and maintenance. The most common distribution mechanisms include drilled pipes, gated pipes, trenches, and distribution channels. In regions with cold winter conditions, the distribution systems should be underground below the freezing line and have thermal insulation and/or heating units.

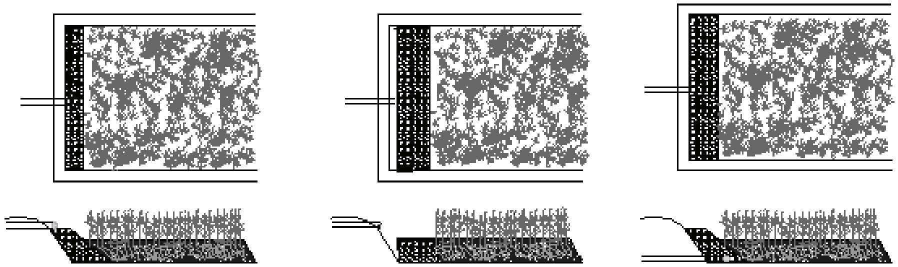
Outlet structures can effectively collect and evacuate water, but also regulate the water levels in the water-filled beds. Figure 4-12 shows options for inlet and outlet structures.

FIGURE 4-12
ALTERNATIVE INLET AND OUTLET ARRANGEMENTS
for (A) surface flow wetlands, (B) outlet arrangement for horizontal subsurface flow wetland, and (C) inlet arrangement for subsurface flow constructed wetland



(B) outlet arrangement for horizontal subsurface flow wetland

(A) surface flow wetlands



(C) inlet arrangement for subsurface flow constructed wetland

Media selection

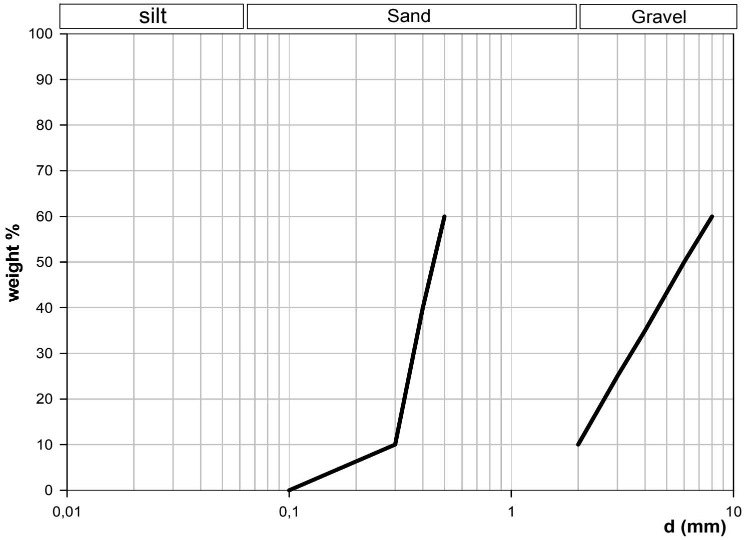
Media selection depends on the type of constructed wetland. Free water surface flow CWs require media at the bottom of the cells to support the plants' rooting systems. Subsurface flows CWs require media of different characteristics to support plants and biofilm while maintaining hydraulic conductivity and to avoid clogging.

To minimise costs, the source for free surface flow CWs media should be the same topsoil found in the site. Once the cells are excavated, the soil should be separated and piled until construction is finished, when the soil can be distributed on top of the cell. The typical root depth growth for macrophytes is ca 40 cm; a constructed wetland should have at least that media depth. If there is no soil, new adequate soil should be imported. The physico-chemical characteristics of the soil are important; factors such as pH, metal content, soil texture, porosity, granulometry, and nutrient availability determine the survivability of the plant material.

One of the subsurface flow CW characteristics is the flow of water through the media for both horizontal and vertical flow systems. There should be a balance between high hydraulic conductivity and appropriate conditions for plant development and enough surface of the media grains for biomass growth. For subsurface horizontal flow constructed wetlands, typical sand and gravel are between 0.3 and 12 mm.

There are several ways for choosing the media and as and example Vymazal (1998) recommends the use of gravel, with different degrees of grading according the quality of the incoming water (3-6, 5–10, 6–12 mm). On the other hand, Danish subsurface flow CW construction guidelines (Ministry of Environment and Energy, 1999) present a granulometry graph that limits the size of the sand, and the size parameters used for sand (d_{10}, d_{60} and uniformity coefficient UC) (see Figure 4-13). The grain size distribution curve should be located between the two accept lines in the granulometry graph.

FIGURE 4-13
GRANULOMETRIC GRAPH FOR THE SELECTION OF MATERIAL AS MEDIA FOR HORIZONTAL FLOW CONSTRUCTED WETLAND



The European Commission has issued a guide that tackles natural wastewater treatment processes (2001) and in one of its units deals with constructed wetlands. Concerning sizing the guidelines recommend areas according to the type of wastewater and the concentration of the influent. For the physical components and the layout of the system, the guideline specifies partitioning, slope, materials, and plants to be used. Additional paragraphs are dedicated to geographical location, operation performance and technical advantages and drawbacks.

Vertical flow constructed wetland

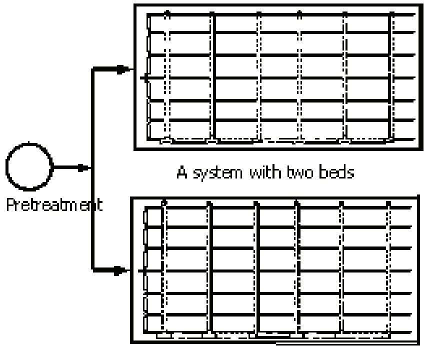
Due to the saturated beds and low oxygen availability in horizontal flow constructed wetland they have limited nitrifying capacity and additionally require large areas. To improve the oxygen transfer rates to the beds a design alternative where planted unsaturated beds filled with sand and/or gravel are fed intermittently. Since the beds are not water saturated vertical flow systems have higher oxygenation rates. Vertical flow constructed wetlands require less area and have greater possibility of nitrifying and therefore are becoming more common where stricter discharge regulations are enforced. Several European countries like Austria, Denmark, France, and Germany have produced official guidelines for the design and construction of vertical flow constructed wetlands.

The basic components of a typical vertical flow constructed wetland include pre-treatment, a pumping system, an impermeable bed filled with graded filtersand, a distribution system on the surface of the bed, and a collecting pipes system on the bottom of the bed to evacuate treated waters.

The sewage must be pre-treated prior to discharge onto the surface of vertical flow wetlands to minimize the risk of clogging of pipes and the vertical filter. There are, however, some experiences where the pre-treatment is limited to removing particles larger than 2 mm, but these systems demand larger areas and the functioning scheme differs from traditional systems.

The pretreated wastewater is loaded onto the surface of a planted filterbed (see Figure 4-14). The pollutants are removed or transformed by the microorganisms that are attached to the filtersand and the root system of the plants. It is important that the filter is not saturated or covered with water in order to secure a high oxygen level in the filter (Brix and Schierup, 1990).

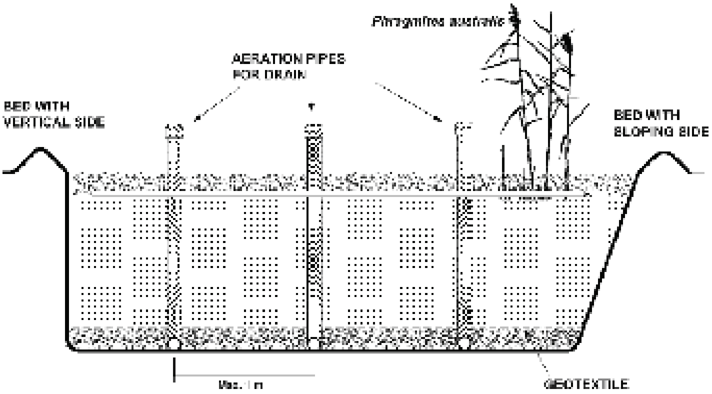
FIGURE 4-14
LAYOUT OF VERTICAL FLOW CONSTRUCTED WETLAND



Traditionally the bed is planted with common reed (*Phragmites australis*) but other plants that can withstand the harsh wastewater environment can be used. The main function of the plants is to counteract clogging of the filter. If the system is established in temperate geographical regions, the standing aboveground biomass also insulates the filter against freezing during winter (Brix, 1994; Brix, 1997). After trickling through the filter, the treated wastewater is collected in a system of passively aerated drainage pipes placed in the bottom of the filter. For better total nitrogen removal, the effluent from the bed can be recirculated to the primary treatment or even to the pumping well in order to enhance denitrification and to stabilise performance of the system.

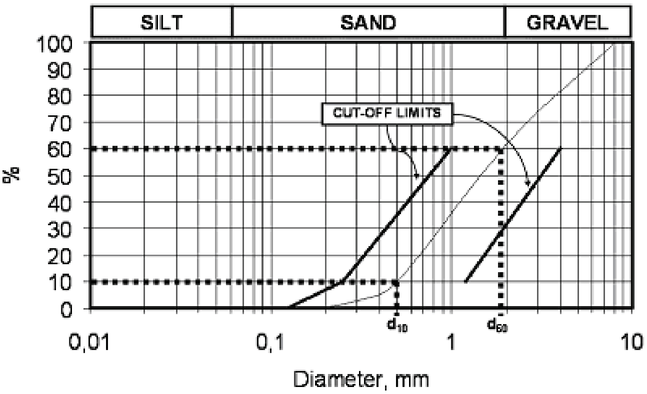
The normal depth of the filter is of at least 1.4 m and consists of a drainage layer of at least 0.2 m filled with coarse gravel, a geotextile, a 1.0 m layer of filtersand, and on top a surface insulation layer of 0.2 m. Additionally, a 0.2 m high embankment is established around the filterbed to prevent surface water from the surroundings entering the system. A watertight membrane (minimum 0.5 mm thickness) must enclose the filter bed. The membrane must be protected by a geotextile on both sides. The drainage layer is built up of coarse gravel (Ø 8-16 mm) in which a number of conventional drainage pipes are placed. The drainage pipes are connected on one side to a collecting pipe that discharges the effluent from the bed to the effluent well. Vertical pipes extending 0.3 m over the filterbed surface (see Figure 4-15) passively aerate the drainage system and consequently the unsaturated bed.

FIGURE 4-15
SIDE VIEW OF A VERTICAL FLOW CONSTRUCTED WETLAND BED



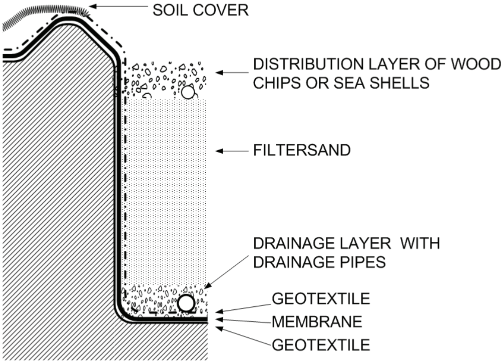
The filter medium should be sand with a d_{10} between 0.25 and 1.2 mm, a d_{60} between 1 and 4 mm, and the uniformity coefficient ($U=d_{60}/d_{10}$) should be less than 3.5 (Figure 4-16). The contents of clay and silt (particles less than 0.125 mm) must be less than 0.5%. In practice, only washed sand materials can be used. The effective filter depth is of at least 1.0 m, and the surface of the filter should be level. The filtersand is separated from the drainage layer in the bottom of the bed either by the placement of an open geotextile between the two layers or by a layer of graded gravel that will prevent the filtersand from penetrating and blocking the drainage layer. It is important not to compact the filtersand during construction. Therefore, the use of heavy machinery should not be allowed within the bed during construction.

FIGURE 4-16
GRANULOMETRIC GRAPH FOR THE SELECTION OF MEDIA FOR VERTICAL FLOW CONSTRUCTED WETLANDS



The influent sewage is distributed evenly over the surface of the bed by a network of pressurised distribution pipes. The distribution pipes should have appropriate diameter to conduct the water and avoid clogging and should have holes placed in the bottom of the pipes for every 0.4-0.7 m. It is important that the whole distribution system function under pressure for a period that is long enough to secure an even distribution of water over the entire bed surface. In practice, the pump volume should be at least three times the volume capacity of the distribution pipe system in order to ensure that the water pulse covers the bed. This loading frequency at a normal loading rate will be 8 to 12 pulses per day, and when the effluent water is recirculated in the system, the number of pulses increase to 16-24 pulses per day. If necessary, the distribution pipes are insulated against frost by a 0.2 m layer of coarse wood chips or seashells placed on the surface of the filter (see Figure 4-17).

FIGURE 4-17
DETAIL OF THE LAYERS OF THE BED



Environmental impact

Table 4-5 summarises some of the considerations to minimise the impacts of wetlands.

TABLE 4-5
CONSIDERATIONS TO MINIMISE IMPACT OF CONSTRUCTED WETLANDS

Water quality considerations:	
• Pre-treat toxic metals and organics	⇒ Avoid toxic effects on biota
• Pre-treat high BOD	⇒ Avoid anaerobic conditions
• Maintain non-zero dissolved oxygen	⇒ Provide good life-conditions for biota
Wildlife habitat considerations:	
• Provide physical heterogeneity	⇒ Increase habitat diversity
• Incorporate deep-water zones	⇒ Improve mixing, increase residence time, and provide perennial habitat for fish
• Construct water level control options	⇒ Control plant growth
• Include islands in open water areas	⇒ Provide refuge for birds and reptiles
• Install nesting platforms	⇒ Increase number of nesting places
• Use a diversity of plant species	⇒ Provide greater resilience to pests and operational upsets
• Incorporate vertical structure (herbs, shrubs and trees)	⇒ Create habitat variety for feeding, roosting and nesting
• Incorporate horizontal diversity (dry land, shallow and deep water)	⇒ Promote plant and habitat diversity
• Use irregular shorelines	⇒ Provide visual cover and greater edge length
Public use considerations:	
• Provide parking and safe access to wetland	⇒ Attract the public
• Provide boardwalks and observation points	⇒ Give the public access to the wetland environment
• Incorporate interpretative displays	⇒ Let the public learn about the wetland environment and wetland functions
• Publicise wetlands	
• Enlist volunteer participation	⇒ Get public acceptance and support
	⇒ Raise sense of ownership to enlist support
• Establish accessible monitoring points	⇒ Document water quality function of the wetland
• Provide blinds for wildlife study	⇒ Observe wildlife without disturbing
• Maintain adequate monitoring records	⇒ Let public know about the performance of the system

Source: adapted from Knight, 1997

Heavy metals and organic compounds that may concentrate in biota through biomagnification and eventually reach toxic levels should not be discharged. Municipal systems should remove most suspended solids and biochemical oxygen demand before the wetland system to maintain adequate dissolved oxygen levels in the wetland. High loadings of oxygen demanding substances will create anaerobic conditions and hence hostile conditions for aquatic life.

Constructing islands within the cells will encourage bird diversity. Deep-water areas will increase the hydraulic residence time in the system and hence the water treatment, but will provide good habitat for fish. Open water areas should not be connected along the flow path, but should be interspersed with densely vegetated shallow water areas.

The diversity of plant species in the wetland system will affect the diversity of fauna and hence the wetland's wildlife potential. Expensive management to exclude specific species should be avoided. In some regions, it might be advantageous to stock the wetland with mosquito fish to control mosquitoes effectively.

Human access to the wetland and the preparation and distribution of information material is important to secure public awareness and use of the wetland.

Potential nuisance problems

The water quality and wetland habitat should support a population of predaceous organisms (fish and other insects) that can naturally control mosquito larvae. Access to the areas that may have dangerous reptiles such as poisonous snakes and alligators should be avoided. Drowning is a potential problem in wetlands with deep-water areas. Therefore, boardwalks over deep water should have handrails. Consumption of fish and wildlife from constructed wetlands should be avoided.

4.2.9 Plants in wetlands

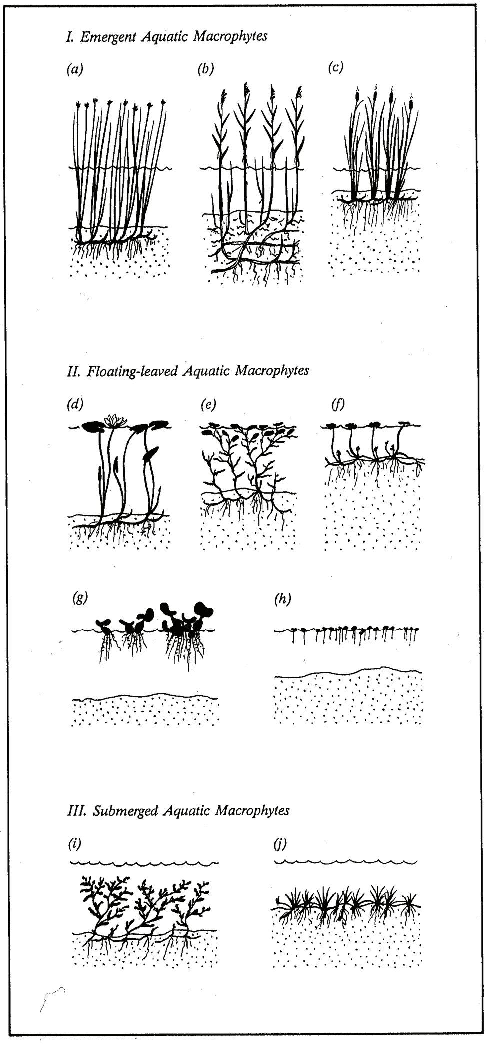
The larger aquatic plants growing in wetlands are macrophytes; they include aquatic vascular plants (angiosperms and ferns), aquatic mosses, and some larger algae that have easily visible tissues. Macrophytes use solar energy to assimilate inorganic carbon from the atmosphere and produce organic matter, which subsequently provides energy for heterotrophs (animals, bacteria and fungi). Associated with this high productivity is usually a high heterotrophic activity, i.e. a high capacity to decompose and transform organic matters and other substances. Although the most important removal processes in constructed wetlands are physical and microbial, the macrophytes have several functions related to water treatment. There are three major groups of macrophytes (see Figure 4-18) according to their life form (Brix and Schierup, 1989; Cronk and Fennessy, 2001; Wetzel, 2001):

1. *Emergent aquatic macrophytes*: are the dominating life form in wetlands and marshes, growing within a water table range from 50 cm below the soil surface to a water depth of 150 cm or more. In general, they produce aerial stems and leaves and an extensive root and rhizome system. The plants are morphologically adapted to growing in a water-logged or submersed substrate thanks to large internal air spaces that transport oxygen to roots and rhizomes.

2. *Floating-leaved aquatic macrophytes*: include species rooted in the substrate and species freely floating on the water surface.

3. *Submerged aquatic macrophytes*: have their photosynthetic tissue entirely submerged, but usually the flowers are exposed to the atmosphere.

FIGURE 4-18
DOMINANT LIFE FORMS OF AQUATIC MACROPHYTES



Species shown: (a) Scirpus lacustris, (b) Phragmites australis, (c) Typha latifolia, (d) Nymphaea alba, (e) Potamogeton gramineus, (f) Hydrocotyle vulgaris, (g) Eichhornia crassipes, (h) Lemna minor, (i) Potamogeton crispus, and (j) Littorella uniflora
Source: Brix and Schierup, 1989

4.2.10 Role of plants in constructed wetlands

The most important effects of the macrophytes in relation to wastewater treatment are the physical effects the plant tissues (e.g., erosion control, filtration, provision of surface area for attached micro-organisms). The metabolism of the macrophytes (plant uptake, oxygen release, etc.) affects treatment to various extents depending on design. The macrophytes have other site-specific valuable functions –e.g., provide a suitable habitat for wildlife, improve aesthetics. Table 4-6 summarises the major roles of macrophytes in constructed wetlands**.**

TABLE 4-6
MAJOR ROLES OF MACROPHYTES IN CONSTRUCTED WETLANDS

Macrophyte property	Role in treatment
Aerial plant tissue	• Light attenuation → reduced growth of phytoplankton • Influence on microclimate → insulation during winter • Reduced wind velocity → reduced risk of resuspension • Aesthetic pleasing appearance of system • Storage of nutrients
Plant tissue in water	• Filtering effect → filter out large debris • Reduce current velocity → increase rate of sedimentation, reduces risk of resuspension • Provide surface area for attached biofilms • Excretion of photosynthetic oxygen → increases aerobic degradation • Uptake of nutrients
Roots and rhizomes in the sediment	• Stabilising the sediment surface → less erosion • Prevents the medium from clogging in vertical flow systems • Release of oxygen increase degradation (and nitrification) • Uptake of nutrients • Release of antibiotics

Source: Brix, 1997

Physical effects

The presence of vegetation in wetlands distributes and reduces the current velocities of the water (Pettecrew and Kalff, 1992; Somes et al., 1996). This creates better conditions for sedimentation of suspended solids, reduces the risk of erosion and re-suspension, and increases the contact time between the water and the plant surface areas. In vertical flow systems, macrophytes, together with an intermittent loading regime, help prevent clogging the medium (Bahlo and Wach, 1990).

The vegetation cover in a wetland is like a thick biofilm between the atmosphere and the wetland soil or water surface in which there are significant gradients of various environmental parameters. Reduced wind velocities near the soil or water surface reduce re-suspension of settled material, thus improving the removal of suspended solids by sedimentation. A drawback of reduced wind velocities near the water surface is, however, the reduced aeration of the water column.

Light is attenuated, hindering the production of algae in the water below the vegetation cover. In the winter, especially in temperate areas, when snow covers the standing litter, the vegetation cover helps keep the soil free of frost.

Effects on soil hydraulic conductivity

Hydraulic dimensioning of constructed wetlands with subsurface flow should not assume that the hydraulic conductivity increases because of root and rhizome growth. In vertical flow constructed wetlands and sludge mineralization beds, the development and growth of plants can counteract clogging (see Figure 4-19). The root growth and physical presence of the stems that move with the wind keep the bed substrate permeable to water.

FIGURE 4-19
SLUDGE MINERALIZATION BEDS WITH VERTICAL FLOW

Surface area for attached microbial growth

The stems and leaves as well as the roots and the rhizomes of the macrophytes provide areas for the development of biofilms composed of photosynthetic algae and micro-organisms. These biofilms and the biofilms on all other immersed solid surfaces in the wetland system, including dead macrophyte tissues, are responsible for most of the microbial processing that occurs in wetlands.

Nutrient uptake

Wetland plants require nutrients for growth and reproduction, and the rooted macrophytes take up nutrients primarily through their root systems. Some uptake also occurs through immersed stems and leaves from the surrounding water. As wetland plants are very productive, there are considerable amounts of nutrients in the biomass. The uptake capacity of emergent macrophytes, and thus the amount that can be removed if the biomass is harvested, is about 30 to 150 kg P ha^{-1} $year^{-1}$ and 200 to 2500 kg N ha^{-1} $year^{-1}$ (Brix and Schierup, 1989; Gumbricht, 1993a; Gumbricht, 1993b; Brix, 1994). If the wetlands are not harvested, the vast majority of the nutrients into the plant tissue will decompose and return to the water.

Root release

Wetland plants leak oxygen from their roots (see Figure 4-20).

FIGURE 4-20
ROOT RELEASE OF OXYGEN BY PHRAGMITES AUSTRALIS

The blue colour around the roots comes from the radical oxygen release from the roots oxidising the reduced form of methyl blue.

Species with an internal convective throughflow ventilation system have higher internal oxygen concentrations in the rhizomes and roots than species relying exclusively on diffusive transfer of oxygen (Armstrong and Armstrong, 1990); the convective throughflow of gas significantly increases the root length that can be aerated, compared to the length by diffusion alone (Brix, 1994). Therefore, wetland plants with a convective throughflow mechanism have the potential to release more oxygen from their roots than species without convective throughflow. The oxygen leakage at the root-tips oxidises and detoxifies potentially harmful reducing substances in the rhizosphere. Root systems also release other substances besides oxygen (antibiotics, compounds that affect the growth of other species, organic compounds like organic carbon).

Other roles

In large systems, the wetland vegetation may support a diverse wildlife such as birds or reptiles. Macrophytes can also have an important environmental, economical value (fruits, bio-energy plants, fodder), and aesthetic (see Figure 4-21). Since constructed wetlands may require large areas aggregated to water quality improvement, in some areas the use of the system to host plants with some economical, energetical or fodder value might be feasible. The decision on which plants that can supply the extra benefits will depend on factors such as water quality, health risks, climatic conditions, and economical evaluation.

FIGURE 4-21
CONSTRUCTED WETLAND SYSTEM PLANTED WITH *CANNA LILIES*

4.2.11 Planting

This section addresses only *Phragmites australis* (the Common Reed), the most commonly used macrophyte in constructed wetlands in Europe. Similar techniques and precautions must be taken with other wetland species. The information given here is from experimental work in the UK (Cooper et al., 1996), from the literature (Haslam, 1971a; Haslam, 1971b; Rodewald-Rudescu, 1974; Véber, 1978; Weisner and Ekstam, 1993), and from builders in Denmark and other European countries. Four kinds of materials can establish the desired vegetation of *Phragmites* in a constructed wetland:

1. *Transplanted rhizomes:* small sections of vertical or horizontal rhizome, or larger clumps of material planted in the bed in a regular pattern or roughly distributed ('rhizome soil' technique).

2. *Stem cuttings:* used to produce rooted plantlets in glasshouses for transplanting, or cuttings planted directly in the beds. A variation of this method is the layering of growing stems to produce rooted plants where stem nodes contact the ground.

3. *Seedlings:* cultivated in glasshouses from seeds and later transplanted.

4. *Seeds:* sown directly on the soil.

Seed production in natural reed stands

The seed production in reed stands varies considerably by site. Seeds for seedling propagation can be collected from late October until March or even later. However, the seeds gradually shed during the winter, so the best time is probably late November. Seeds can be easily stored in a dry and cold place for several years with little loss of viability.

Germination of seeds from Phragmites

The percentage of seed germination varies from 2 to 96% among panicles from a small plot of reeds (Haslam, 1973). Fresh seeds may need to be chilled and stored at 5°C for several months to enhance germination. Seeds germinate successfully on damp soil or moist filter paper under controlled laboratory conditions, with a day night temperature regime of 30°C/20°C (Haslam, 1973; Cooper et al., 1996).

Establishment from rhizome

Horizontal and vertical rhizomes with at least one shoot or bud can be planted directly in the reed bed. The success of this technique depends on the developmental stage of the shoots and on their degree of damage during sampling and planting (Véber, 1978).

Establishment from cuttings

Stem cuttings can be successfully planted directly into a water-saturated bed under field conditions in mid-May at a survival rate of approximately 35%. This avoids the expense of glasshouse propagation and minimises the disturbance due to transplanting growing plants. Stem cuttings need to be at least two nodes long, but should not include the immature nodes at the base of the stem. Trimming the upper leafy part of the stem will increase the percentage of success.

Establishment from seedlings

Seedlings are much easier to handle and plant than rhizomes --no seedling mortality, all seedlings produce some rhizomes during the first growing season, and seedlings spread more quickly. Presently, potted seedling is the most commonly used technique in northern Europe. A density of 4 plants m^{-2} is generally used (see Figure 4-22).

FIGURE 4-22
PLANTING OF POTTED SEEDLINGS IN A SLUDGE MINERALIZATION BED

Direct seeding as a method of establishment

In theory, *Phragmites* beds could be established directly from seeds; for very large areas, this may be the only practical method. Establishment from seeds should be almost as rapid as from seedlings or rhizomes. The seeds may be left in the panicles because they germinate just as well there. Seeds can germinate under field conditions in mid May and by autumn, each seedling may have produced up to 140 cm of rhizome. In practice, however, establishment from seeds is likely to be difficult unless the preparation of the site and its subsequent management are well controlled. The soil bed must be moist, and if possible covered with a clear plastic sheet to enhance germination and early seedling growth rate. A good supply of water and nutrients must be available throughout establishment because seedlings are sensitive to drought and lack of nutrients. They are also vulnerable to flooding, frost, high salt concentrations, shade, and inadequate soil aeration (Haslam, 1971b; Haslam, 1973; Weisner et al., 1993; Weisner and Ekstam, 1993; Cooper et al., 1996).

Subsequent management

Fertilisation: plants may need to be fertilised just after planting in gravel beds if not watered by effluent.

Fencing: particularly in rural areas with grazing problems --in the spring, *Phragmites* young shoots are one of the favourite food of deer and rabbits, it is necessary to fence off the reed bed.

Weed removal: weeds must be removed in the first two years (see later).

Frost protection: frost may kill many shoots in natural *Phragmites* stands. To avoid losses of plant material due to frost, transplanting of rhizomes or seedlings should not begin until May or early June. In vertical flow constructed wetlands, it is advisable to insulate the distribution system against frost (Figure 4-23).

FIGURE 4-23
INSULATION WITH WOODCHIPS IN A VERTICAL FLOW CONSTRUCTED WETLAND

4.2.12 Operation and maintenance

System start-up

Like any other biological systems, constructed wetlands require the adaptation of all their components before producing satisfactory and consistent wastewater treatment. Once the system is constructed, the first start up activity is to test the water control components such as pumps (if installed), distribution systems, and valves. The next step is the initial and gradual flooding/filling of the system; the same procedure is recommended for pollutant loading to favour the adjustment of the living material to the harsh chemical conditions generated by wastewater, that can particularly affect plants and the growth of biofilm.

Weed control

During the early years of establishing *Phragmites* beds, weeds may grow excessively, particularly on soil-based beds. The most effective method of weed control is flooding. However, *Phragmites* do not tolerate excessive depths of water, particularly during early establishment (Weisner et al., 1993). Therefore, beds should be flat or nearly flat, so that 30 cm of water will flood the entire bed. When gravel is the medium, weeds are generally not a problem during the establishment of the bed. The seeds used at the banks of the beds may be washed onto the gravel, however, resulting in considerable grass growth.

Routine maintenance

Control of water level: as previously explained, young rhizomes or seedlings should not be too deeply flooded (Weisner et al., 1993). If the soil is allowed to dry, however, this will inhibit growth, increase weed competition, and may kill the plants. If the roots and rhizomes of the plants are aerated through standing aerial stems, shallow flooding can benefit bud development and, providing insulation, may allow shoot emergence earlier than in non-flooded beds.

4.2.13 Costs

Constructed wetlands are usually low cost systems because they are low technology, easy to build, and use local resources. The total construction and operation costs for constructed wetlands mainly depend on the local economy and the design. The main construction costs include:

- land;
- excavation;
- liners and impermeabilization;
- plants;
- media and soil;
- hydraulic control systems (distribution and recollection); and
- other expenses (fencing, access roads, signs, etc.)

Chapter 10 presents a detailed description of costs.

Capital costs

Capital costs include the expenses for designing, constructing, and buying all materials for the constructed wetland. The evaluation should use local prices.

Operation and maintenance costs

Like capital costs, operation and maintenance costs depend on local economic conditions. Operation costs include the costs of quality follow up and flow control. Maintenance includes pumps and hydraulic structures maintenance, weed control, plague control, aesthetic maintenance, signs, and fencing.

4.2.14 Applications

Constructed wetlands can treat a wide variety of wastewaters, including

- Domestic and municipal sewage;
- Agro-industry wastewater;
- Landfill leachate;
- Acid mine drainage;
- Industrial wastewater;
- Storm water; and
- Mine drainage.

The most common use is for domestic and municipal wastewater, and the experience for this type of wastewater is huge. For other types of wastewater the constructed wetland systems are usually designed specifically for the type of pollutant to be removed and the discharge standards. Therefore, system design is often site-specific.

4.2.15 Case studies

Domestic and municipal wastewater: Uggerhalne (Denmark)

Description: one of the first reed beds constructed in Denmark after the root-zone-method was introduced in the early eighties (Brix 1994). The design was mainly based on German ideas (Kickuth, 1981) --root system of the reeds to increase the hydraulic conductivity of the soil to accommodate the hydraulic loading for a period of three years; soil to contain at least 20% of clay to secure a good removal of phosphorus. Kickuth's representative in Denmark designed the system. The catchment area of the reed bed includes Uggerhalne, a small residential area North of Aalborg, Denmark. There are only small industries, like gas tanks, etc., connected to the combined sewerage system receiving rainwater and domestic sewage. The system is dimensioned for secondary treatment of the sewage from 400 PE.

Constructed: August-November 1985

Operational: November 1985 to 2001

Costs**:** about 1 million DKr (1985) = ca. US$150,000, ca. US$375/PE

Process Description: the sewage is pre-treated in a sedimentation tank, and then pumped into the middle of a 80-m long inlet trench with open water. After the reed bed, the effluent is collected in a gravel-filled effluent trench through a drainage pipe at the bottom of the effluent trench, and then discharged to the recipient.

Dimensions: the system consists of a single bed --33 m long, 80 m wide, surface area of 2,640 m^2 (corresponding to 6.6 m2/PE). Depth of the bed: 0.60-0.65 m; slope of the bed: 1.2%.

Media: as prescribed by the designer, the medium in the bed is imported soil with about 20% of clay and organic soil mixed in the proportion 2:1. However, the grain size analysis of the actual soil in the bed shows 25% of silt and 75% of sand (Schierup et al., 1990). The organic content of the soil is 5.9%, and the contents (on a dry weight basis) of nitrogen (total-N) 1.71 mg/g, phosphorus (total-P) 0.34 mg/g, iron (Fe) 8.6 mg/g, calcium (Ca) 2.9 mg/g, and aluminium (Al) 9.4 mg/g.

Plants: *Phragmites australis* imported from Germany, planted in November 1985

Liner: 2-mm HDPE

Inlet Distribution: open trench with gravel in the bottom.

Outlet Collection: gravel-filled trench with a 145-mm PVC drainage pipe.

Effluent standards: effluent standards for the system were less stringent during the first three years of operation, i.e. in 1986-1988, because of the time needed for the vegetation to develop (Table 4-7).

TABLE 4-7
EFFLUENT STANDARDS FOR THE UGGERHALNE SOIL-BASED CONSTRUCTED WETLAND

Parameter:	First three years	After three years
Amount of effluent:		
During dry weather:	< 150 m^3/day < 15.5 m^3/h	< 150 m^3/day < 15.5 m^3/h
During rain:	< 10 L/sec	< 10 L/sec
Temperature	< 30°C	< 30°C
pH	6.5 - 8.5	6.5 - 8.5
BOD_5 (modified)	40 mg/L	10 mg/L
Settleable sludge (2 hours)	0.5 mL/L	0.5 mL/L
TSS	30 mg/L	15 mg/L

Performance: the performance of the system is checked 6 to 12 times a year with 24-h samples proportional to the volume at the inlet and outlet of the reed bed. The inlet sampling is done after the settler, i.e. the performance data in Table 4-8 only include the actual reed bed. The standards in Table 4-7 have been met throughout the whole period of operation. However, the removal of N and P is poor (about 30%) and the systems do not produce a nitrified effluent.

TABLE 4-8
ANNUAL AVERAGE PERFORMANCE DATA FOR THE UGGERHALNE WETLAND

Year	n	q	TSS		COD		BOD_5	
		[mm day-1]	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
1986	13	35	110	38.4	207	78	89	33.8
1987	11	42	113	12.9	245	110	99	14.2
1988	10	53	89	13.1	244	100	99	16.2
1989	12	34	127	7.4	314	70	164	10.1
1990	10	46	103	8.8	215	46	120	5.9
1991	8	33	179	7.1	140	30	224	5.0
1992	9	50	219	6.0			159	3.3
1993	7	27	165	5.9	450	24	225	4.8
1994	7	90	232	5.1			193	7.0
1995	8	39	125	6.1	403	77	176	3.9
1996	6	52	148	6.8	408	93	150	9.5
1997	10	39	180	5.3	377	65	184	4.5
1998*	4	39	158	6.4	330	63	115	6.0
1999	7	66	77	7.7	186	47	82	3.1
2000	5	42	135	16.2	317	72	106	7.0
2001	5	66	151	23.4	292	75	111	5.2

Year	n	q	Total-N		NH_4-N		Total-P	
		[mm day-1]	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
1986	13	35	27.9	23.2			7.3	6.2
1987	11	42	28.3	20.3			9.1	6.5
1988	10	53	26.8	20.8			8.8	7.1
1989	12	34	37.2	20.3			12.1	7.8
1990	10	46	29.1	18.6	27.0	15.0	6.7	4.0
1991	8	33	24.0	14.0	12.0	18.2	3.7	2.1
1992	9	50			33.2	12.6		
1993	7	27	94.0	31.0	28.6	14.2	9.0	7.0
1994	7	90			13.5	13.6		
1995	8	39			20.9	11.6		
1996	6	52	35.6	23.0	24.9	15.6	8.3	7.1
1997	10	39	38.7	20.2	28.1	13.6	9.8	6.6
1998*	4	39	22.5	16.8	17.3	12.5	4.8	4.8
1999	7	66	16.1	11.5	9.7	8.5	3.3	3.2
2000	5	42	30.0	20.3	21.2	14.0	6.6	5.5
2001	5	66	25.0	18.4	16.7	12.5	4.9	4.3

n: number of samples; q: hydraulic loading rate; all concentrations mg/L
*January – July

Single household vertical flow constructed wetland system: Mosehuset (Denmark)

Description: The vertical flow constructed wetland system installed consists of a pre-treatment system (a 2 m^3 sedimentation tank), a ca. 1 meter deep bed filled with sand-gravel and planted with *Phragmites australis*. The system also includes wells for housing level controlled pumps, recycling and in the first couple of years, an external well that contains a P-removal filter filled with calcite. Later on and since the P removal capacity was not consistent enough, a chemical injection systems was installed. A recycling system has been installed in order enhance the removal of total nitrogen via denitrification as well as to mitigate the high concentrations of pollutants typically found in single household wastewater where no dilution effects of rain takes place. Furthermore, the usage of water saving devices is a common practice making the wastewater relatively concentrated. The surface area per PE of the bed required in these systems is relatively small, and several authors have documented it to be in the range of 1 to 2 m^2 (Cooper, 2001; Cooper, 2003; Brix, 2003; Arias, *et al*. 2003). This surface area has proven sufficient to reduce BOD to the required concentrations, and to nitrify and even reduce total nitrogen significantly (see Figure 4-24).

FIGURE 4-24
INSULATED PLANTED BED AFTER FIRST MONTH OF OPERATION
The lake where the treated water is finally disposed is in the background

Constructed: May 2002

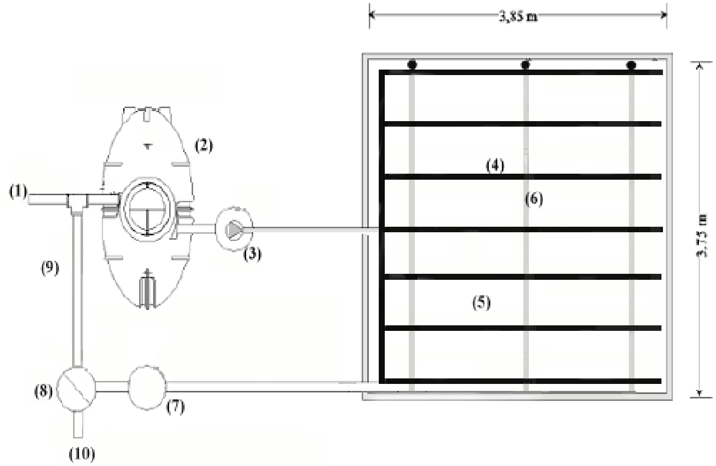
Operational: May 2002

Costs: About 30.000 Danish Kr ca. US$ 4.000 (2002), US$ 800/PE

Process Description**:** After pre-treatment, the water is pulse-feed onto the surface of a one-meter deep square bed. The bed is passively aerated through 50 mm pipes that connect the atmosphere with the drainage system at the bottom of the bed allowing convective air flow. The bed is thermally insulated with a 15 cm layer of wood chips engulfing the distribution pipes. The water percolates vertically through the unsaturated bed and organic matter is removed by aerobic processes and ammonium is nitrified during the passage. The effluent water is collected in drainage pipes in the bottom of the bed. Half of the treated effluent is recycled to the sedimentation tank to enhance denitrification. The effluent from the system is finally disposed in an artificial lake, constructed within the property at the time of establishment of the system (for details of the construction and design of the system see Johansen, *et al*. 2002). Figure 4-25 presents the system's layout and its general characteristics. Since P removal was not satisfactory in the second semester of 2004, a P precipitation chemical injection system in the sedimentation tank was installed.

FIGURE 4-25
TOP LAYOUT TECHNICAL DRAWING OF SYSTEM CONSTRUCTED AT MOSEHUSET

(1) Raw wastewater inlet coming form the house; (2) 2m^3 three chamber sedimentation tank; (3) pumping well; (4) distribution system; (5) planted bed; (6) drainage system (7) P-filter; (8) recycling well; (9) recycling pipe to the sedimentation tank; (10) outlet of treated wastewater to the artificial lake.



Dimensions: 15 m^2 bed. ca 3m^2/PE

Media: washed sand-gravel with granulometry of 0 to 4 mm diameter.

Plants: The bed was planted with one-year-old common reeds plants (*Phragmites australis*) at a density of ca. 4 plants m^{-2}.

Inlet: A pulse-loaded pressurised water distribution system placed on top of the bed ensures homogenous and complete water dispersal on the surface of the bed.

Effluent Collection: At the bottom of the bed, a gravity driven pipe drainage manifold is fitted at the bottom of the bed to evacuate the waters from the bed and simultaneously boost the potential of air diffusion into the bed from below through pipes that reach the surface of the bed. The system is fitted with recycling so different volumes of treated water can be diverted to the sedimentation tank for enhanced denitrification (see Figure 4-26).

Effluent standards: Danish discharge regulations for small wastewater producers in rural areas states four types of restriction for individual wastewater treatment, according to the characteristics of the recipient (Ministry of Environment and Energy, 1997). The class corresponds to the type of treatment required. SOP class requires the removal of organic material, nitrification, and the removal of total phosphorus. SO demands the removal of organic material and nitrification, OP class requires the removal of organic material and phosphorus, while the P class demands only the removal of organic material (see Table 4-9).

FIGURE 4-26
RECYCLING SYSTEM

1) outlet from the planted bed; (2) recycled water back to the sedimentation tank; (3) water to the P-removal filter; (4) outlet of treated water after passing through the P-filter; (5) outlet to the sedimentation tank (6) P-binding material

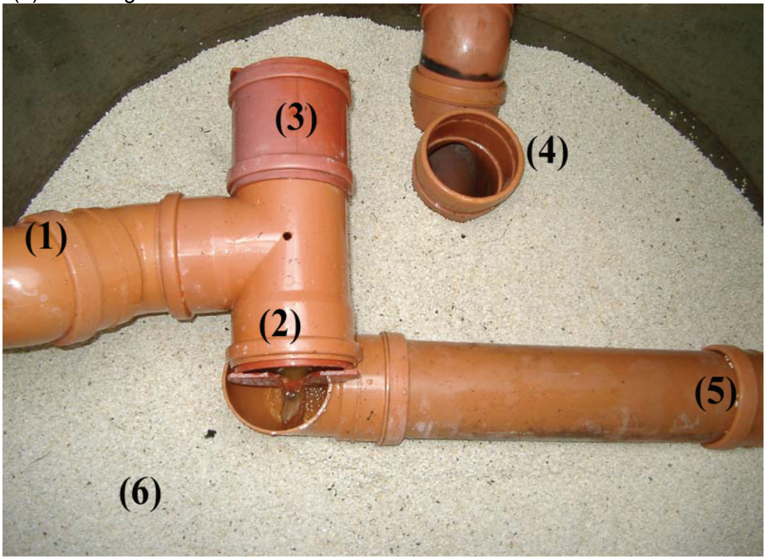


TABLE 4-9
DANISH DISCHARGE REGULATIONS FOR THE RURAL AREAS

Class	Organic pollution BOD$_5$ removal (%)	Nitrification NH$_4$-N removal (%)	TP removal removal (%)
SOP	95	90	90
SO	95	90	
OP	90		90
O	90		

Performance: The system has operated both with and without recirculation, but after 2005 has always operated with recycling. The removal performance of the system fulfilled the SOP requirements the first six months of operation, due to the good performance of the phosphorus removal media. After the first six months, the P removal filter showed signs of saturation and required change of media. Unfortunately, the media selected was no longer in the market and finding a suitable replacement proved to be unsuccessful. Therefore, a chemical injection system was installed in the sedimentation tank in 2004. Through the whole time, the system has been monitored; the removal performance for the other parameters has been satisfactory and meeting discharge standards (BOD$_5$ and NH$_4$-N), except for total phosphorus. After the installation of the injection system, the total P concentration in the effluent decreased reaching the limit required by the local authority (see Table 4-10).

TABLE 4-10
ANNUAL AVERAGE PERFORMANCE DATA FOR MOSEHUSET SINGLE HOUSEHOLD VERTICAL FLOW CONSTRUCTED WETLAND

Year	**n**	**q**		**TSS**	**Oxygen saturation (%)**			**BOD_5**
		[mm day^{-1}]	Inlet	Outlet (removal)	Inlet	Outlet	Inlet	Outlet (removal)
2002	17	25	83	6.2 (93%)	1	10	227	17.2 (92%)
2003	11	25	121	11.1 (91%)	>1	33	267	10.8 (96%)
2004	12	25	66	12.7 (81%)	12	48	243	7.6 (97%)
2005*	7	25	92	5.1 (94%)	7	50	230	9.5 (96%)
2006	5	25	86	7.7 (91%)	10	51	228	8.4 (96%)

Year	**n**	**q**		**Total-N**		**NH_4-N**		**Total-P**
		[mm day-1]	Inlet	Outlet (removal)	Inlet	Outlet (removal)	Inlet	Outlet (removal)
2002	17	25	109	35 (68%)	91	19.2 (79%)	14.4	1.5 (90%)
2003	11	25	118	63 (47%)	92	11.7 (87%)	26	22 (15%)
2004	12	25	107	56 (51%)	60	2.9 (95%)	18.7	15* (22%)
2005**	7	25	139	65 (53%)	59	3.8 (94%)	11.3	2.8 (75%)
2006	5	25	94	54 (43%)	57	3.3 (94%)	10.4	2.1 (80%)

n: number of samples; q: hydraulic loading rate; all concentrations mg/L

*The P injection system started to function in October 2004. During this period, the average P concentration was 2.95 mg/L

** From this date on the system operated always with recycling

4.2.16 References

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4.3 Intermittent Sand Filters (ISF)

4.3.1 Description

There are two main types of intermittent sand filters (ISF) depending on the filtration rate. Slow ISF were first developed in Great Britain in the early 19th century and have been widely used all over the world. A little later, rapid ISF were developed to treat turbid clay-bearing water of the major rivers in the United States (McGhee, 1991). Rapid ISF (5 to 15 $m^3/h.m^2$) operate up to 50 times faster than slow ISF (0.1 to 0.4 $m^3/h.m^2$); rapid filtration generally combines coagulation, flocculation, clarification, and disinfection (Thonart, 2006; McGhee, 1991). The filter medium in slow ISF (typical grain size 0.15-0.3 mm) is usually finer than in rapid ISF (typical grain size 0.6-2 mm). The cleaning method is also different; rapid ISF are frequently cleaned, usually every couple of days, by reversing the flow of water through the filter bed (i.e., backwashing), while slow ISF are cleaned less frequently (every two to three months) by removing a few centimetres off the top layer of sand (Thonart, 2006). This section focuses on slow ISF, which are appropriate for wastewater treatment.

The treatment mechanisms in slow ISF are based on aerobic biological treatment in a mass of sand, physical filtering of solids, and adsorption. A particular gelatinous coat, called Schmutzdecke, forms on the surface of the filter (McGhee, 1991). The ACTE (1981) defines the schmutzdecke as a layer of biological growth that forms on the surface of a slow sand or trickling filter. This biofilm is composed of bacteria, filamentous algae, diatoms, protozoa, rotifers, small worms and other small organisms. It works as a biological membrane; it traps and digests organic matter, bacteria, and dead algae contained in wastewater.

A viscous biological coat similar in composition to the schmutzdecke also forms on the surface of each particle of sand. That coat phagocytises the absorbed impurities and its constituents eat each other (Thonart, 2006).

As a result, with depth, available food for microorganisms decreases and competition among microorganisms increases. The effluent of a sand filter usually contains only simple inorganic salts that are inoffensive. The effluent may contain a poor amount of dissolved oxygen and a little carbon dioxide but its subsequent aeration (by a spillway for instance) counteracts these problems.

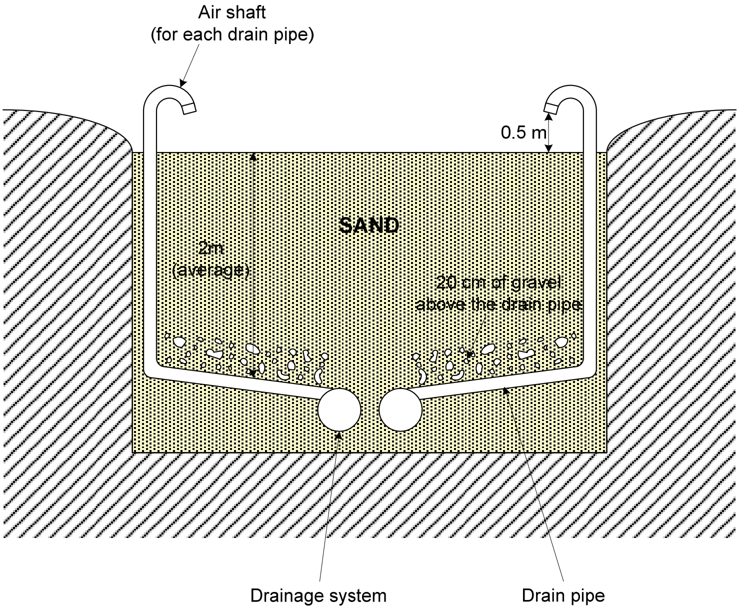
The accumulation of matter by the effluent decreases the initial infiltration capacity. The infiltration capacity may be recovered by allowing aeration intervals (without loading) between running periods.

If ground water recharge is desired, the bottom of sand filters can be made of permeable soil so that water percolates from the top of the filter to the aquifer; these filters are sometimes called bottomless sand filters. In most cases, however, the bottom of the filter is totally watertight (liner or concrete) and treated wastewater that has percolated through the sand is collected by drains at the outlet of the filter.

Typical system

Figure 4-27 shows a cross section in a typical slow sand filter.

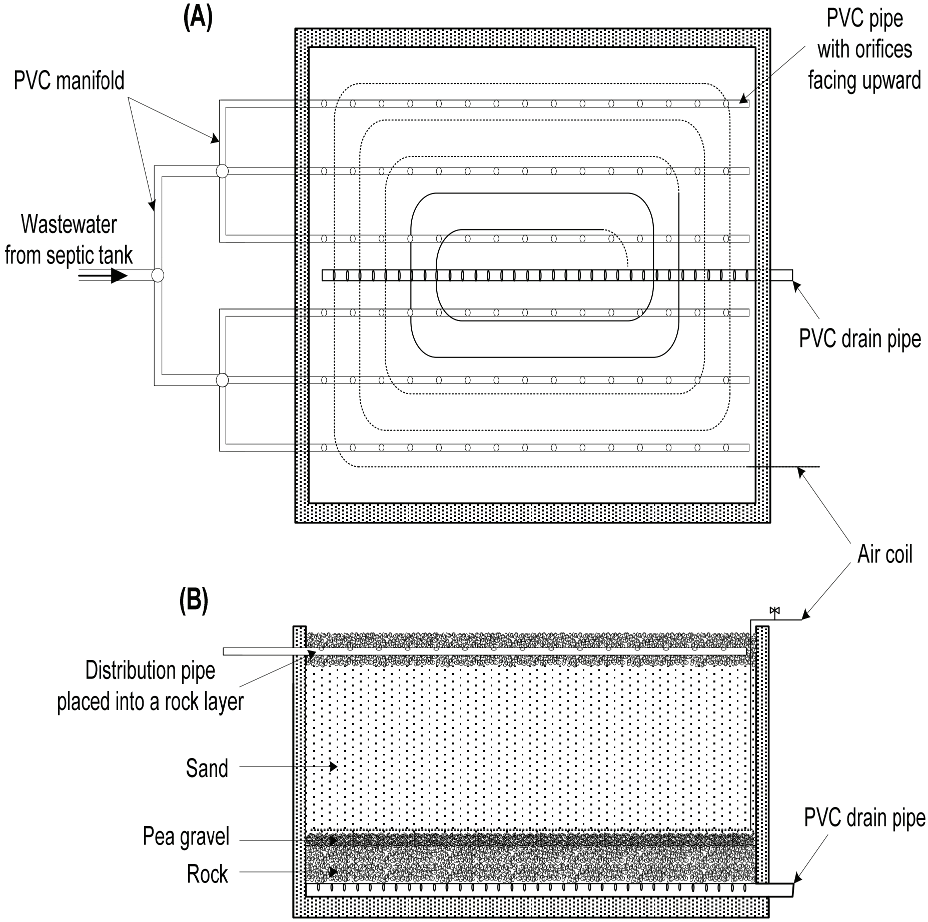
FIGURE 4-27
CROSS SECTION IN A TYPICAL SLOW SAND FILTER (BEN SERGAO, MOROCCO)



Source : adapted from Driouache et al. (1997)

In a modern ISF (see Figure 4-28), an optional air coil system blows air into the bottom of the filter to re-oxygenate an overloaded or poorly maintained sand filter.

FIGURE 4-28
(A) PLAN VIEW AND (B) TYPICAL CROSS SECTION OF MODERN ISF



4.3.2 Use and performance

Types of use

ISF are generally used for small communities of less than 10,000 people equivalent (Xanthoulis, 1998). However, ISF may be suitable for larger communities; in Agadir, Morocco, an ISF is planned for 400,000 people equivalent. Sand filters commonly pre-treat septic tank effluents before a wastewater treatment plant. Other ISF uses include polishing and nitrifying secondary effluents, and treating facultative pond effluent (Crities and Tchobanoglous, 1998). In Tunisia and Morocco, treated wastewater from sand filters is used in agriculture for non-restrictive irrigation or replenishes aquifers (Xanthoulis, 1998).

Treatment performance

To optimise performance, the following guidelines should be respected (Xanthoulis, 1998):

- As the name implies, an ISF must operate intermittently.
- The submersion periods should be as short as possible to have long drying periods that allow a re-oxygenation of the filter medium. In other words, dosing frequency should be as high as possible.
- The effluent should be spread on the top of the sand filter as fast as possible to rapidly cover the entire surface of the filter.
- Seasonal climate variations may force the operator to change his or her management approach depending on the season.

If properly designed, a sand filter produces a high quality effluent (see Table 4-11).

TABLE 4-11
EFFLUENT CHARACTERISTICS OF ISF IN BOONE COUNTY

Parameter	Septic tank	Sand filter	% Change
BOD (mg/L)	297	3	99.0
TSS (mg/L)	44	3	93.2
NH_4-N (mg/L)	37	0.48	98.7
NO_3-N (mm/L)	0.07	27	384.71
Faecal coliform (N°/100 mL)	4.56×10^5	7.28×10^1	99.9

Source: ISF in Boone County (Missouri, USA) constructed in 1995 and monitored during 15 months (EPA, 1999)

Table 4-12 shows the performance of an experimental sand filter constructed in Ben Sergao, Morocco, in 1986 to treat 750 m³/d (10,000 people equivalent) (Driouache & al., 1997).

TABLE 4-12
PERFORMANCE OF THE SAND FILTER OF BEN SERGAO

Parameter	Wastewater	Settled WW	Treated WW	Removal
MES [mg/L]	431	139	2,8	99%
COD [mg/L]	1189	505	52	96%
BOD_5 [mg/L]	374	190	10	97%
NTK [mg N/L]	116	99	17	85%
Nitrates [mg N/L]	0	--	56,7	--
Total N [mg N/L]	116	--	73,7	36%
Total P [mg/L]	26	24,5	15,8	39%
K [mg/L]	37	--	37	--
Ca [mg/L]	143	--	238	--
Faecal Coliforms [FC/100ml]	$6.156\ 10^6$	$4.96\ 10^6$	327	100%
Helminth eggs [eggs/L]	214	47	0	100%

Source: Driouache & al., 1997

4.3.3 Design criteria and materials

Sand

As the filter medium, sand is the most important material of the system. Its particle size distribution and characteristics are the filter's main parameters. The thickness of filter medium (vertical depth of sand) varies from one filter to another and is typically between 0.5 and 2 m (Crites and Tchobanoglous, 1998; McGhee, 1991; Xanthoulis, 1998), although sand depths of 1 m are more common (McGhee, 1991). Some deeper sand beds have been used in the past because the top 2 to 5 cm was removed periodically. The minimum satisfactory depth is reported to be about 0.5 m; shallow beds of less than 0.5 m have shown a good removal of BOD and suspended solids, but a significantly reduced degree of nitrification (Crites and Tchobanoglous, 1998; McGhee, 1991).

The particle size distribution of the filter medium must avoid a deep migration of suspended solids in wastewater, should help set up the biological surface coat, and must allow a migration speed of the effluent through the filter bed that is suitable for a good re-oxygenation and an efficient filtration. Particle size distribution should be as homogeneous as possible and should meet the following recommendations (although other particle size distribution could also fit):

- d90% = 2 mm
- d50% = 800 µm
- d10% = 330 µm
- UC = d60/d10 ≤ 3

The uniformity coefficient (UC) equal to the 60% size divided by the 10% size describes the homogeneity of particle size. A non-uniform particle size distribution often negatively affects the process of filtration. It is also important to use a long-lasting and clean sand, free of dust, silt, clay, organic, and calcareous particles that could clog the filter.

Filtration surface area and number of filters

Sand filters need areas ranging from 0.4 m² to 4 m² per population equivalent depending on the type of wastewater, daily water consumption, sand particle size distribution, height of filter medium, climate, maintenance operations realised between running cycles, etc (Xanthoulis, 1998).

The filtration surface area (A) equals (Thonart, 2006):

$$A = \frac{Q}{v_h} \qquad \textbf{(E. 46)}$$

Where:

- A = filtration surface area [m²]
- Q = volume of wastewater to treat per day based on peak flow [m³/d]
- v_h = superficial filtration velocity [m/d]

The superficial filtration velocity (v_h) can be approached by Hazen's formula (E. 47) for the velocity of flow of water through a porous medium under saturated flow conditions (McGhee, 1991).

$$v_h = C(d_{10})^2 \frac{h}{L}\left(\frac{T+10°}{60}\right) \qquad \textbf{(E. 47)}$$

Where:

- v_h = superficial (approach) filtration velocity [m/d]
- C = coefficient of compactness (varies from 700 to 1000 for new sand, and from 500 to 700 for sand that has been used for a number of years)
- d_{10} = effective size of medium [mm]
- h = head loss [m]
- L = depth of filter bed or layer [m]
- T = temperature, [°F]

The filtration surface area has to be distributed over several filters (at least two) because some time must be allowed to the maintenance (one or two days) and for the development of the schmutzdecke (from 6 hours to 30 days) (Thonart, 2006; McGhee, 1991).

The area of an ISF should be between 100 m² and 5,000 m². The number of filters (n) roughly equals (Thonart, 2006):

$$n = \frac{1}{4}\sqrt{Q} \qquad \textbf{(E. 48)}$$

Where:

- n = number of filters ($n \geq 2$)
- Q = flow rate to treat [m³/h]

Hydraulic loading and application rate

It is strongly recommended to use peak flow for designing because the long-term performance of an ISF depends on restricting the amount of organic matter added per dose. Typical hydraulic loading rates (L_w) vary from 40 to 80 mm/d; higher loading rates may clog the filter when using fine sand. Another parameter, the hydraulic application rate or HAR, is often used to assess the performance of an ISF system (Crites and Tchobanoglous, 1998):

$$HAR = \frac{L_w}{DF} \qquad \textbf{(E. 49)}$$

Where:

- HAR = hydraulic application rate [mm/dose]
- L_w = hydraulic loading rate [mm/d]
- DF = dosing frequency [doses/d]

HAR may also be expressed as a surface loading rate, which corresponds to the loading rate (m^3/h or m^3/d) divided by the surface area (m^2). The surface loading rate is thus expressed in m/h or in m/d.

Organic loading rate

The organic loading rate of a sand filter represents the daily organic loading --in BOD or COD-- applied to the surface area of the filter. Generally, the organic loading rate is expressed in kg of BOD/m^2.d and common values are between 0.0025 and 0.01 kg BOD/m^2.d (Crites and Tchobanoglous, 1998). In general, the higher the organic loading, the lower the effluent quality for a given medium; in other words, an increase of the organic loading reduces effluent quality (EPA, 1999).

Dosing frequency

Instead of discharging all the wastewater volume at once on the surface of the filter, it is recommended to discharge small doses frequently. Crites and Tchobanoglous (1998) recommend a minimum of 18 doses per day for normal septic tank effluent and 24 doses per day for strong BOD effluent. It is important to distinguish doses from running periods. Two running periods are separated by a re-oxygenation or dry period; running periods usually range around 2-3 days. Between two doses, there is no drying period.

Drainage system

To re-oxygenate the filter medium (to maintain aerobic conditions), it is necessary to evacuate the treated effluent out of the filter medium as fast as possible. A drainage system must be installed at the bottom of the ISF and each drain pipe must be connected to an aeration pipe. Drain pipes should be installed on a non-calcareous gravel bed of 10-25 cm and covered with another layer of non-calcareous gravel of 25 cm. A drain header, collecting treated effluent from the different drain pipes, should be located at the centre of the ISF (Xanthoulis, 1998).

Distribution and dosing system

A distribution system is required to evenly apply the wastewater over the surface of the filter medium. The most common method for dosing ISF is a distribution manifold with evenly spaced openings that generally face upward.

4.3.4 Operation and maintenance

Typical operation and maintenance tasks include monitoring the effluent (BOD, COD, suspended solids, NH_4-N, NO_3-N and FC/100ml), checking the dosing equipment (inlet and outlets, distribution manifold, pumps, etc.), and maintaining the filter surface (EPA, 1999). Maintaining the filter surface consists in drying the filter surface then removing the top dry coat (2-5 cm with a shovel --Thonart, 2006; Xanthoulis, 1998) at least every four months. The cleaning material is fairly simple: only light wide rakes, shovels, forks, and wheelbarrows. The operator also needs protection boots and gloves.

4.3.5 Unit cost assessment

Sand filters require low construction skills. A fine and suitable sand can generally be found nearby at a reasonable price. Thus, ISF are generally low-costs. Of course, localisation, material and labour costs will affect the total cost. The price of a sand filter for a single-family residence in the United States is $10,000 (EPA, 1999). In Europe, the cost of a sand filter for more than 100 people equivalent is €1,000 per person equivalent.

4.3.6 Human resources

The construction of a sand filter does not require a high level of construction skills; its operation and maintenance require two hours per year and can be performed by unskilled workers (EPA, 1999).

4.3.7 Environmental impact

Advantages:

- ISF produce an effluent for various uses, such as aquifer replenishment or agricultural irrigation. If the effluent complies with the standards, it can be discharged into the environment.
- ISF construction respects the environment.
- No chemicals are used.

Disadvantages:

- Odours may be an environmental problem for surrounding citizens.
- The filter can be clogged.
- Some problems may occur in the winter with ice forming at the surface of the filter.

4.3.8 References

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4.4 Evapotranspirative Systems

Evapotranspirative systems (ET systems) were developed in the Scandinavian countries as a spin-off from agricultural willow plantations established for producing woody biomass for energy production. These plantations are planted with fast growing woody species. The growth of the trees is often limited by water availability during summer, and hence the idea that the plantations could be irrigated with wastewater arose. Since urban wastewater contains high concentrations of nitrogen and phosphorus in the right proportion for plant growth, the irrigation by wastewater supplies both water and nutrients to support the growth of plants. It was observed that the water loss by evapotranspiration from the systems was very high, and hence the idea that zero-discharge evapotranspirative wastewater treatment systems could be designed based on willows.

Currently evapotranspirative systems using willows can be found in all the Scandinavian countries, the Baltic countries, Poland, Ireland, England and there is some preliminary work done in France and Greece. Evapotranspirative wastewater treatment systems can be used where there is a deficit of water supply for plants with high evaporative capacity. Evapotranspirative systems can be designed so that the water loss from the systems is more than twice the potential evapotranspiration rate as calculated by meteorological parameters.

4.4.1 Definitions

Evapotranspiration (ET) is a method of onsite wastewater treatment and disposal that is an alternative to conventional soil absorption systems, particularly for sites where protecting surface water and ground water is essential or where soil infiltration is not possible. ET combines two separate processes removing water from the soil surface by evaporation and from plants by transpiration. An ET system is unique in its ability to evaporate wastewater into the atmosphere without discharging it to the surface water or ground water reservoir. In some cases, however, the ET concept can also combine seepage with evaporation as an alternative.

Evaporation

Evaporation converts liquid water to water vapour (vaporization) and remove it from the evaporating surface (vapour removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils, and wet vegetation. Energy is required to change the state of the molecules of water from liquid to vapour. Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide this energy. The driving force to remove water vapour from the evaporating surface is the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity and wind speed are climatological parameters to consider when assessing the evaporation process.

Transpiration

Transpiration vaporises liquid water in plant tissues and removes the vapour to the atmosphere. Plants predominately lose their water through stomata, which are small openings on the plant leaf through which gases and water vapour pass. The roots take up the water together with some nutrients and transport it through the plant. The vaporisation occurs within the leaf, namely in the intercellular spaces, and the stomatal aperture controls the vapour exchange. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant.

Evapotranspiration (ET)

Evaporation and transpiration occur simultaneously and there is no easy way to distinguish between the two processes. Apart from the water availability in the topsoil, the evaporation from a planted soil is mainly determined by the fraction of solar radiation reaching the soil surface. This fraction decreases over the growing period as the plants develop and the plant canopy shades more and more of the ground area. When the plants are small, water is predominately lost by soil evaporation; once the plants are well developed and completely cover the soil, transpiration becomes the main process. The ET rate is the amount of water lost by plants and soil from a planted surface in units of water depth and is normally expressed in millimetres (mm) per time unit --hour, day, decade, month or even entire growing period or year.

4.4.2 Climatic and site parameters

The meteorological factors determining ET are weather parameters which provide energy for vaporisation and remove water vapour from the evaporating surface. The main weather parameters to consider are presented below.

Solar radiation

The amount of energy available to vaporise water determines the ET process. Solar radiation is the largest energy source and can change large quantities of liquid water into water vapour. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons. The actual solar radiation reaching the evaporating surface depends on the turbidity of the atmosphere and the presence of clouds which reflect and absorb major parts of the radiation. Not all available energy is used to vaporise water; part of the solar energy is used to heat up the atmosphere and the soil profile.

Air temperature

The solar radiation absorbed by the atmosphere and the heat emitted by the earth increase the air temperature. The sensible heat of the surrounding air transfers energy to the plants and exerts a controlling influence on the rate of ET. In sunny, warm weather, the loss of water by ET is greater than in cloudy and cool weather.

Air humidity

While the energy supply from the sun and surrounding air is the main driving force for vaporising water, the difference between the water vapour pressure at the evapotranspiring surface and the surrounding air is the determining factor for the vapour removal. Well-watered plants in hot dry arid regions consume large amounts of water due to the abundance of energy and the desiccating power of the atmosphere. In humid tropical regions, notwithstanding the high energy input, the high humidity of the air will reduce the ET demand. In such an environment, the air is already close to saturation, so that less additional water can be stored and hence the ET rate is lower than in arid regions.

Wind speed

The process of vapour removal depends to a large extent on wind and air turbulence which transfers large quantities of air over the evaporating surface. When vaporising water, the air above the evaporating surface becomes gradually saturated with water vapour. If this air is not continuously replaced with drier air, the driving force for water vapour removal and the ET rate decrease.

4.4.3 Plant related factors

The plant type, variety, and development stage should be considered when assessing the ET from plant-covered fields. Differences in resistance to transpiration, plant height, canopy roughness, reflection, ground cover, and plant rooting characteristics result in different ET levels in different types of plants under identical environmental conditions. Crop evapotranspiration under standard conditions (ETc) refers to the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions, and achieve full production under the given climatic conditions.

Management and environmental conditions

Factors such as soil salinity, soil fertility, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests, and poor management may limit the plant development and reduce the ET. Other factors to be considered when assessing ET are ground cover, plant density, and soil water content. The effect of soil water content on ET is conditioned primarily by the magnitude of the water deficit and the type of soil. Too much water will result in waterlogging which might damage the root and limit root water uptake by inhibiting respiration. In ET systems, plants that tolerate permanent waterlogging like wetland helophytes or wetland trees are usually used.

Location

Altitude above sea level (m) and latitude (degrees north or south) of the location influence ET because the atmospheric pressure (a function of the site elevation above mean sea level), the extraterrestrial radiation and, in some cases, the daylight hours are influenced by altitude and latitude.

4.4.4 How to estimate evapotranspiration?

The potential evapotranspiration can be measured in the field, but accurate estimates demand sophisticated devices and multiple measurements. The methods are often demanding, expensive and require well-trained personnel, which make them inappropriate for practical reasons. Therefore these methods are mostly used to calibrate the accuracy of indirect methods. The methodology used to measure evapotranspiration is based on the measurement of evaporation with adjustments to account for the effect of plants and soil. Potential evapotranspiration is usually measured indirectly, from climatic factors, but also depends on the soil type for bare soil, the water status of the soil and the vegetation. Often a value for the potential evapotranspiration is calculated at a nearby climate station on a reference surface, conventionally short grass. This value is called the reference evapotranspiration, and can be converted to a potential evapotranspiration by multiplying with a surface coefficient. In agriculture, this is called a crop coefficient. The difference between potential evapotranspiration and precipitation is used in irrigation scheduling.

The United Nations through the agency FAO has developed a software called CROPWAT as a tool to calculate reference evapotranspiration, crop water requirements, and crop irrigation requirements. The calculations are performed based on a program that correlates local climatic information (a data base containing data from more than 140 countries) with different crop water requirement. The software is available for free from the internet and can be found and downloaded at the address http://www.fao.org/ag/AGL/aglw/cropwat.stm.

4.4.5 Types of ET systems and characteristics

There are different kinds of ET systems in the world. Willow plantations have successfully received municipal wastewater, sewage sludge, and landfill leachate (Rosenqvist et al., 1997; Hasselgren, 1998; Hasselgren, 1999; Venturi et al., 1999). These techniques use water and nutrients for biomass production; excess nutrients and water are discharged to receiving water bodies. Denmark has developed a willow-based ET system to treat sewage and recycle nutrients from single households at sites where effluent standards are stringent and soil infiltration is not possible (Gregersen and Brix, 2000; Gregersen and Brix, 2001; Brix and Gregersen, 2002). Willow ET systems have zero discharge of water (because of ET) and part of the nutrients can be recycled via the willow biomass. Furthermore, the harvested biomass can serve as a source of bio-energy.

Closed willow ET systems

In closed willow systems with no effluent, the basin receiving the wastewater has a watertight membrane so no infiltration to ground water can occur (Ministry of Environment and Energy, 2003a). All wastewater discharged into the system and precipitation falling onto the system have to be evapotranspired to the atmosphere on an annual basis.

Willow ET systems with infiltration

Willow systems that are not contained in a membrane-enclosed bed allow some soil infiltration (Ministry of Environment and Energy, 2003b). The system with infiltration is intended to be used on clayish soils, where infiltration is low.

FIGURE 4-29
TYPICAL WILLOW ET SYSTEM IN DENMARK FOR A SINGLE HOUSEHOLD

4.4.6 Dimensioning and design

Plant selection and transpiration potential

The plants to be used in ET systems should have the following characteristics:

- A high transpiration rate; usually plants growing on wet soils or in wetlands have high transpiration rates because they tend to keep stomata open at all times;
- Growth in waterlogged soils; wetland plants can grow in waterlogged soils by virtue of an internal system of air-filled lacunae in roots and shoots transporting oxygen to the roots;
- The growth form should maximise transpiration, e.g. by the ‘clothesline’ effect, where the vegetation height is greater than that of the surroundings;
- Toleration of high levels of nutrients and accumulation of nutrients and heavy metals in the aboveground harvestable biomass; and
- Toleration of salinity that might accumulate in the system with time.

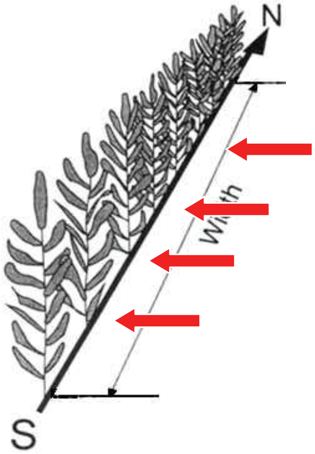
The following factors are important for maximising evaporative loss of water from the soil and plant surfaces:

- High energy input (solar radiation);
- High air-temperatures;
- Low relative humidity in the air;
- Exchange of air (wind);
- Canopy resistance;
- Stomata resistance;
- Leaf area index; and
- Factors like the ‘oasis’ effect, where warmer and dry air in equilibrium with dry areas flows across a vegetation of plants with a high water availability (Rosenberg, 1969).

The vegetation experiences enhanced evaporation using sensible heat from the air and radiant energy, and air is cooled by this process. The ‘clothesline’ effect, where the vegetation height is greater than that of the surroundings (different roughness conditions), may also increase evaporative water loss (Allen et al., 1998). This occurs where turbulent transport of sensible heat into the canopy and transport of vapour away from the canopy is increased by the 'broadsiding' of wind horizontally into the taller vegetation. In addition, the internal boundary layer above the vegetation may not be in equilibrium with the new surface. Therefore, ET from the isolated expanses, on a per unit area basis, may be significantly greater than the calculated potential ET.

Examples of the clothesline or oasis effects would be ET from a single row of trees surrounded by short vegetation or a dry non-cropped field, or ET from a narrow strip of cattails (a hydrophytic vegetation) along a stream channel. For example, a row of trees planted perpendicular to the prevailing wind direction will increase evaporative water loss because plants use sensible heat from the air to evaporate water and furthermore, the wind transport water vapour away from the plants (see Figure 4-30).

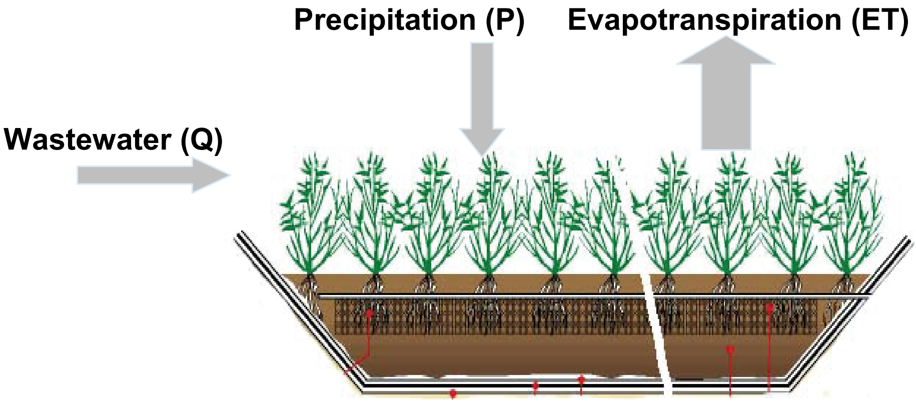
FIGURE 4-30
CLOTHESLINE EFFECT



Water balance and hydrology

One of the most important aspects of the willow ET systems is their ability to evapotranspire all of the sewage discharged into the systems and the rain falling onto the systems. On an annual basis the ET should equal the amount of wastewater (Q) discharged into the system plus the amount of precipitation (P) falling onto the system (see Figure 4-31). In most locations, the ET and precipitation vary over the year, whereas the wastewater production may be more stable. Hence, the seasonal variation in precipitation and ET must also be considered as the system should have enough volume (depth) to be able to store the sewage and rain during winter.

FIGURE 4-31
WATER BALANCE OF ET SYSTEM



Dimensioning structures

The willow wastewater cleaning facilities generally consist of a 1.5 m deep high-density polyethylene-lined basin filled with soil and planted with clones of willow (*Salix viminalis* L.). The surface area of the systems depends on the amount and quality of the sewage to be treated and the local annual rainfall. A single household in Denmark typically requires between 120 and 300 m^2. The annual precipitation at the site of construction is an important dimensioning parameter. Settled sewage is dispersed underground into the bed under pressure. The stems of the willows are harvested on a regular basis to stimulate the growth of the willows and to remove some nutrients and heavy metals.

The main characteristics of the willow systems are:

- For a single household (5 PE) system, the sewage has to be pre-treated in a 2- or 3-chamber sedimentation tank with a minimum volume of 2 m^3 before discharge into the willow system;
- Closed willow systems are generally constructed with a width of 8 m, a depth of minimum 1.5 m, and with 45 degree slopes on the sides;
- The bed is enclosed with a watertight membrane and wastewater is distributed underground within the system by a level controlled pump;
- A drainage pipe in the bottom of the bed can be used to empty water from the bed if salt accumulates after some years;
- One half or third of the willows are harvested every year to keep the willows in a young and healthy state, with high transpiration rates.

Willow systems with soil infiltration are dimensioned like closed willow systems. The willows will evaporate all wastewater during the growing season; during winter, some wastewater will infiltrate into the soil.

4.4.7 Location and establishment

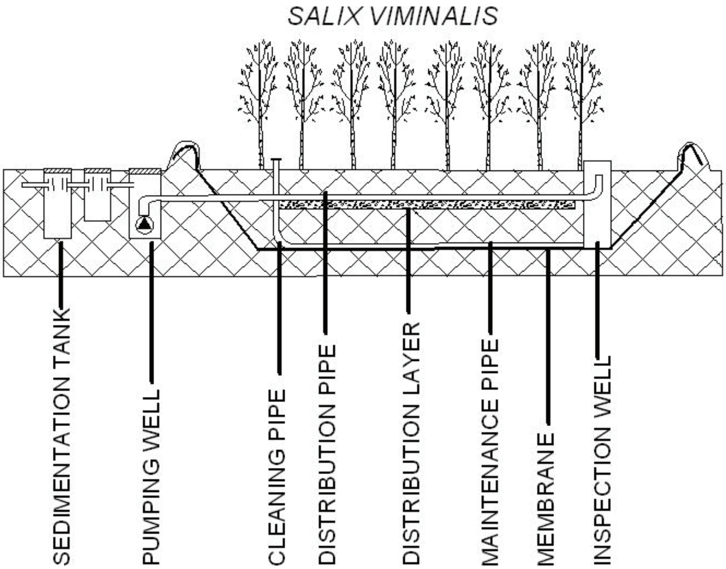
Placement of ET willow systems

To maximise ET, the ET willow systems should be placed in the open landscape, at some distance from buildings and trees. The systems must not be shaded by trees or high buildings and the planted bed should be perpendicular to the prevailing wind direction. Appropriate access must be available for all machinery involved in establishing and harvesting the willows.

Design and construction

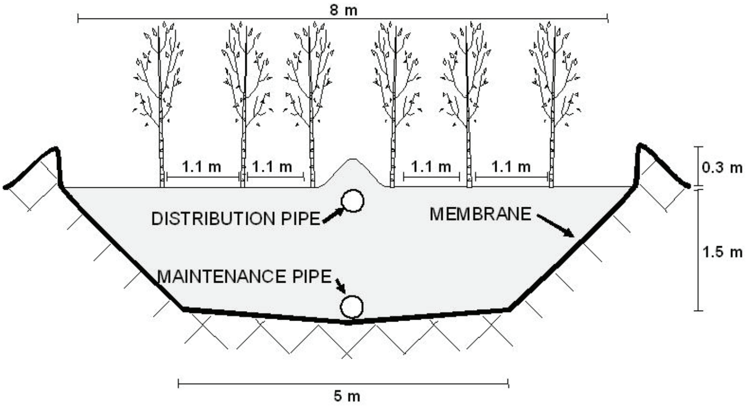
Wastewater must be properly pre-treated --e.g., in a sedimentation tank before discharge to the system. The wastewater is distributed in the bed by a pump and a pressurised distribution pipe placed in the middle of the system. The distribution pipe is placed in a layer of 16-32 mm gravel or some other material with a high porosity. The distant end of the distribution pipe is placed in an inspection and cleaning well (see Figure 4-32). The water level in the soil can be monitored in the well, which can be used to pump high salinity water out of the system, if necessary.

FIGURE 4-32
WILLOW SYSTEM WITH NO OUTFLOW (EVAPORATIVE SYSTEM)



A drainage pipe is placed in a layer of gravel in the bottom of the bed. The drain is used if it is necessary to pump water out of the system. The beds are built up in the original soil from the site. A 0.3 m high dike is built up around the bed to avoid water from the surroundings to enter the willow bed, and to allow water to accumulate on the surface during the winter (see Figure 4-33). Because of the availability of membranes, a standard system will have a width of 8 m, a depth of 1.5 m, and its length will depend on the needed area. It is an advantage to establish deeper beds, with more vertical slopes on the sides.

FIGURE 4-33
CROSS-SECTION OF TYPICAL ET WILLOW SYSTEM



Source: Gregersen et al., 2003a

Figure 4-34 shows how the distribution system is buried at a 0.6 m depth to avoid freezing problems during the winter. Figure 4-35 shows a cross section of a closed willow system showing the position of the distribution pipe and the drainage pipe in the bottom to empty the bed.

FIGURE 4-34
BURIED DISTRIBUTION SYSTEM TO AVOID FREEZING PROBLEMS DURING WINTER

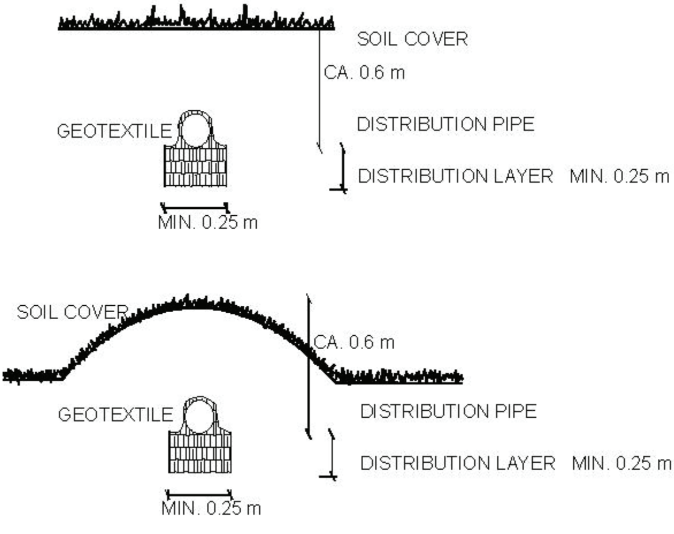
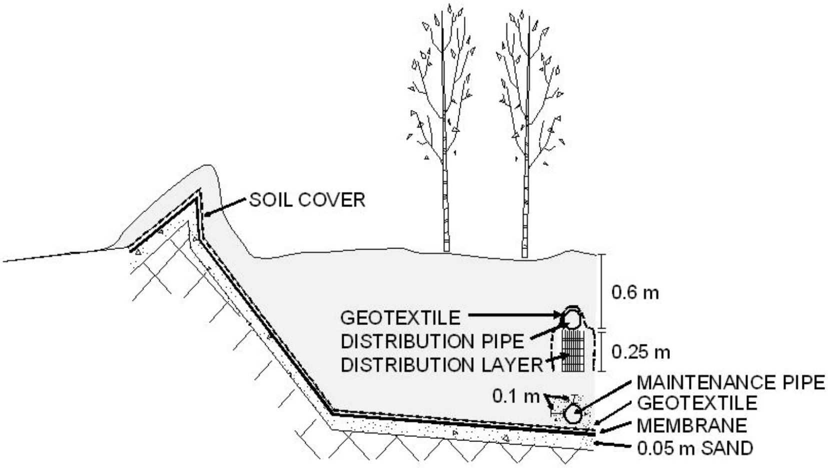


FIGURE 4-35
CROSS SECTION OF A CLOSED WILLOW SYSTEM



Plant establishment and propagation

Willow ET systems must be built in the spring with planting material produced by specialist breeders. The clones used must be of the fast-growing type which is developed to maximise biomass production. Willows collected from the nature are not suitable. The willow will grow rapidly in the first year reaching up to 4 m in height. During the winter after planting, the stems are cut back to the ground to encourage the growth of multiple stems i.e. coppiced. Generally, three years after cutback and again during the winter, the crop is harvested. The willow will produce good growth if there is enough soil moisture available within 1 metre of the soil surface. It can withstand seasonal flooding but not permanent waterlogging.

Weed control is a critical part of the willow establishment. Complete eradication of all invasive perennial weeds is essential prior to planting and also during the first two growing seasons. Fencing may be necessary to keep rabbits and other herbivores, if present, out of the willow bed at least during the first two years.

High-productive willow varieties, bred specifically for use as short rotation coppice energy crops, should be used (see Figure 4-36). These varieties have been developed to high yields, erect growth habit and resistance to, or tolerance of, disease. Ideally, a mix of willow varieties with diverse rust tolerance characteristics should be used. Willows are planted as 20-30 cm long cuttings taken from one-year-old material that is harvested between December and March when the plants are dormant. They must be either planted immediately or stored at -2 to -4°C, where cuttings will remain viable for several weeks. They should only be taken from cold storage and delivered to the planting site on the morning of planting. If cuttings are left in temperatures above 0°C, a break in their dormancy will occur, adventitious roots will develop, and the buds may burst. This will reduce their water and nutrient content, and consequently their viability.

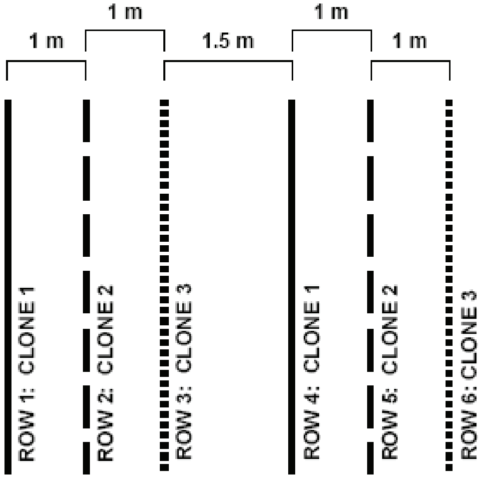
Planting should ideally take place after the last frosts but as early as February if soil conditions allow. Planting can be successful as late as June, but it is better to avoid late planting as the longer the first growing season the better to take the plants successfully into winter.

FIGURE 4-36
WILLOW CUTTINGS COLOUR-CODED BY VARIETY

Source: DEFRA, 2002

Willows should be planted in rows about 1 m apart and with approximately 1.5 m between each set of three rows. The spacing along the rows should be 0.4-0.5 m. From each cutting, 1 – 3 shoots will arise and reach up to 4 m in height by the end of the first growing season. To minimise the risk of pest damage, three different varieties of willows are planted in alternate rows (see Figure 4-37).

FIGURE 4-37
THREE DIFFERENT VARIETIES OF WILLOWS PLANTED IN ALTERNATE ROWS



The willows should be monitored carefully for pests, weed growth, and general health during the establishment year. Weeds should be removed mechanically. During the winter following planting, the willow is usually cut back to within 20cm of ground level to encourage the development of the multi-stemmed coppice. The work should be carried out as late as possible in the winter but before bud-break, generally late February. A contact herbicide can be applied after cutback to control those weeds that have grown during the establishment year. The herbicide should be applied before coppice bud-break otherwise the crop will be damaged. Five to 20 shoots will emerge from each cutback stool depending on the variety. Within three months of cutback, canopy closure will have occurred providing natural weed control due to reduced light at ground level.

Harvesting generally takes place on a 2 or 3-year cycle. Depending on the cycle chosen, half or a third of the bed is cut back every year. The work is carried out during the winter, after leaf fall and before bud-break, usually mid-October to early March.

4.4.8 System layout and sizing

The surface area of ET systems depends on the amount and quality of the sewage to be treated and the local annual rainfall. The annual precipitation at the site of construction and potential ET are important dimensioning parameters. The total annual water loss (ET) from the ET willow systems in Denmark is assumed to be 2.5 times the potential ET at the location, as determined by climatic parameters. In other parts of the world, this factor needs to be verified. The potential ET can be estimated from meteorological data. Calculating ET from meteorological data requires various climatic and physical parameters. Weather data measure some of the data; other parameters relate to commonly measured data and can be derived with the help of a direct or empirical relationship. These data allow to calculate how much water (in mm per year) can be lost from the system by ET. The necessary surface area of the systems is then determined by the amount of wastewater discharged, the ‘normal’ precipitation, and the potential ET at the location of the system. The seasonal variations in potential evaporation and precipitation are also important.

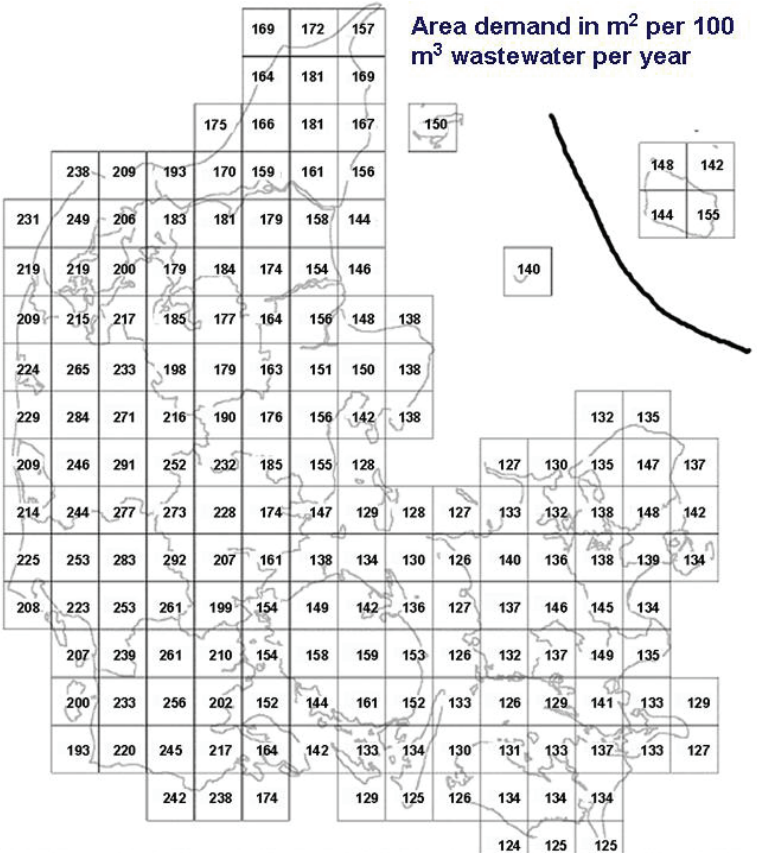
The ‘normal’ annual variability in precipitation and potential ET (monthly values can be used) can be used to model the seasonal variation in the water balance of the system and calculate the need for water storage volume during winter. In Denmark, experience shows that it is often the need for water storage capacity during winter rather than the ET rate that determines the surface area of the systems.

Sizing of ET willow systems in Denmark

Denmark’s guidelines present detailed instructions on how to design and construct ET willow systems, and to size the systems (Gregersen et al., 2003a; Gregersen et al., 2003b). As precipitation (and to a lesser extent ET) varies regionally, the sizing of the system varies by more than a factor of two in Denmark. In the region with the lowest precipitation, a surface area of 124 m^2 of willow bed is needed to evapotranspire 100 m^3 of wastewater per year whereas an area of 293 m^2 is needed in the region with the highest precipitation (see Figure 4-38). Hence, it is important to carefully evaluate the local climate before designing an ET system.

Willow systems with soil infiltration are dimensioned like closed willow systems. The willows will evaporate all wastewater during the growing season, but during winter some wastewater will infiltrate into the soil. In general, ET systems with soil infiltration offer more flexibility in sizing as water that is not evapotranspired is just infiltrated into the soil.

FIGURE 4-38
GRID MAP OF DENMARK WITH SURFACE AREA OF WILLOW SYSTEM NEEDED TO TREAT 100 M^3 OF WASTEWATER PER YEAR



4.4.9 Operation and maintenance

System startup

During startup of ET systems, the main concern is to secure a fast and dense establishment of the plants that should transpire the water. Therefore, the initial year should be managed to maximise plant establishment. This includes the time of startup, which in most cases is optimal in early spring. Once planting has occurred, the wastewater load should be managed according to the requirements of the plants (at least not to impede the growth of the plants). Weeds need to be removed during the first growing season as they will impede the growth of the planted plants. The water level in the systems should be monitored regularly during the initial year. As

ET rates are lower the first year when plants are small, the water level may reach the soil surface in late fall; if so, it will be necessary to pump water out of the system until next spring when ET rates increase.

Routine maintenance and pruning

After the first year, routine maintenance is limited to emptying the sedimentation tank yearly, inspecting the pump operation, and harvesting half or a third of the trees yearly, in case of willow systems. The cutting is carried out during the winter, after leaf fall and before bud-break, usually mid-October to early March. Pruning is needed to keep a healthy and highly transpiring vegetation. It is also most practical to cut the willows before they become too large.

FIGURE 4-39
STOOL OF WILLOWS AFTER CUTTING

4.4.10 Costs

Capital

The capital costs of ET systems will vary significantly depending on the actual site conditions and construction needs. The costs of the primary treatment, usually a sedimentation tank, and the pumping system delivering the wastewater to the system can be estimated with some certainty, but the costs of the actual ET system depend on the need for a membrane, the amount of soil to move, etc. According to a survey of 34 Danish single house ET willow systems (closed systems with membrane), capital costs vary between €2,000 and €12,000 (Gregersen et al., 2003c). The average capital cost of a closed willow system, including pre-treatment and pump, in Denmark is about €8,000. It is necessary to estimate capital costs for each individual project as costs depend significantly on the need for soil excavation and membrane.

Operation

Operation costs of ET systems are usually very low and restricted to the costs of emptying the sedimentation tank and pumping the wastewater to the system.

Pruning plants --needed once a year-- requires in general very little work. For a single household willow system, pruning can be done –usually by the house owner– in just a few hours. The first year after establishment, weeds need to be removed, which also requires in general very limited work. Operation costs for single households willow systems in Denmark, including the costs of emptying the sedimentation tank once a year, are about €300 per year.

An important issue when comparing costs is the fact that ET systems reduce the amount of effluent discharged from the system. In fact, in the case of closed systems, there are no effluent at all from the system. In Denmark the wastewater producer has to pay a discharge fee of about €5 per cubic metre discharged. Thus for a household discharging 100 cubic metres per year the discharge fee will be €500 per year. In closed ET systems there is no discharge, and therefore the wastewater producer does not have to pay any discharge fee. Hence, the savings of €500 per year is higher than the operating costs of about €300 per year.

4.4.11 Applications

ET systems are largely used as a method of onsite wastewater treatment and disposal particularly for sites where protecting surface and ground water is essential or where soil infiltration is not possible. In Denmark, willow ET systems are used in rural areas where effluent standards are strict and where soil infiltration is not possible, either because of ground water interests or because of clayish soils or high ground water tables. Systems are constructed at single households, but also serve small groups of houses. Willow ET systems with infiltration are mainly for single households, but some systems treat effluent from a zoo and some experimental systems treat leachate.

Experiences with zero-discharge willow systems in Denmark

At present, more than 100 zero-discharge willow systems operate in Denmark, mainly serving single households in rural areas. This section summarises six systems that were constructed in 1997 (Gregersen and Brix, 2000; Gregersen and Brix, 2001). The six facilities receive sewage from single households and have surface areas between 150 and 500 m^2, depending on the number of persons connected, their water consumption, and the local precipitation. Three different clones of *Salix viminalis* (‘Björn’, ‘Tora’ and ‘Jorr’) were planted as 20-cm cuttings with 5 cm above the soil surface. Wastewater discharges into the systems and precipitation were monitored as well as the water levels within the willow beds.

Water balance

One of the most important aspects of the willow wastewater cleaning facilities is their ability to evapotranspire all the sewage discharged into the systems and the rain falling onto the systems.

Table 4-13 presents data on the estimated evaporation from the six systems during the first two years of operation (Gregersen and Brix, 2001).

TABLE 4-13
ET RATES (mm PER YEAR) FOR SIX WILLOW FACILITIES IN DENMARK

Facility	Year 1 (April 1997-March 1998)	Year 2 (April 1998-March 1999)
1	980	1,470
2	1,270	2,090
3	1,140	1,650
4	1,130	1,690
5	980	1,660
6	1,020	1,880

Source: Gregersen and Brix, 2001

The wastewater loading into the systems was 450 to 600 mm per year. During the second year, the precipitation was approximately 400 mm higher than the 'normal' 30-year average (1,150 mm). Facilities 1 and 5 had relatively poor growth of willow because of vigorous growth of weeds in the beds. Facility 6 had some surface water flowing into the system because of construction problems. The high rate of precipitation in the second year resulted in completely saturated conditions (water on the bed surface) in some of the systems, and hence the systems were hydraulically overloaded.

Removal of water from the systems occurs by evaporation from the soil and plant surface and transpiration.

Biomass production and harvest

Data on biomass production and the contents of nutrients and heavy metals in the stem and leaves of one-year and two-year old shoots was collected in Facility 4. Here the plantation consists of three rows of the clone 'Jorr', two rows of the clone 'Bjørn', and two rows of the clone 'Tora'. Unfortunately, there is no accurate measurement of the nutrient and heavy metal discharged into the system. With 'normal' contents in 'normal' household wastewater, i.e. 30 mg/L total-N, 10 mg/L total-P (Henze, 1982), and 30 mg/L K, the amount of N, P and K in the harvestable biomass almost exactly balances the amount discharged into the system with the sewage. Only for P, the amount discharged into the system was about 30% higher than the amount in the harvestable biomass. The balance for P will however depend on the use of phosphate-containing detergents in the specific household.

For heavy metals, it is not possible, based on the available data, to evaluate the mass balance. But usually sewage from single households contains low levels of heavy metals. 'Normal' levels of heavy metals in domestic sewage have been reported to be Cd: 2 µg/L; Pb: 40 µg/L; Zn: 130 µg/L; Cu: 40 µg/L; Ni and Cr: 15 µg/L; and Hg: 1 µg/L (Henze, 1982). If these levels are used for the mass balance, it can be calculated that some accumulation of heavy metals may occur in the system over time. However, the uptake of heavy metals by willows depends on the levels in the soil as well as on the clone (Landberg and Greger, 1994; Landberg and Greger, 1996; Greger and Landberg, 1997; Greger, 2000) and therefore removal by harvesting may be higher than indicated by the present data. A worst case scenario, based on the present removal data and the concentration levels cited above, shows that after 25 years of operation the heavy metal levels in the soil will not exceed the present legislative standards for use of soil for agriculture (Cd: 0.5 mg/kg dry matter; Pb: 40 mg/kg dry matter; Zn: 100 mg/kg dry matter; Cu: 40 mg/kg dry matter; Ni: 15 mg/kg dry matter; and Cr: 30 mg/kg dry matter).

Salinity accumulation

The contents of salts in the system are likely to increase over time, but the rate of increase is unknown and depends on the amount of salts in the sewage and hence the habits of the sewage producers. If the contents of salt in the system increase to unacceptable levels, it is possible at some later stage to discharge the salt-containing water from the system.

Experiences

The initial experiences from the Danish systems show that it is important to keep a new-established bed free from weeds the first year after planting. Vigorous growth of weeds will significantly reduce the production of willow stems the first year. Usually, the willow stems are cut the first year to increase the number of stems per plant, but if the willows have had a low number of stems the first year they will also have a low number in the second and following years. Hence biomass production will be lower and ET and nutrient uptake will be affected. It is therefore urgent to keep the facilities free of weeds the first year. The second year the willows will outcompete the weeds if kept clean the first year.

The parameters of importance when designing a willow wastewater cleaning facility include:

- Exact amount of wastewater during the first year of operation;
- Amount of rainfall at the site of construction; and
- Ability of the selected willow clones to evapotranspire water and accumulate nutrients and heavy metals in the aboveground harvestable biomass.

For example: in an area where the annual mean precipitation is 700 mm per year, it is assumed that the willow can evapotranspire 1,200 mm per year. The difference between precipitation (700 mm) and ET (1200 mm), i.e. 500 mm or 500 L/m^2, is equal to the amount of sewage that can be loaded into the system on an annual basis. Assuming a water discharge rate of 100 L per person per day or 36,500 L per person per year, the surface area needed to evapotranspire the sewage equals 36,500 L/year divided by 500 L/m^2.year = 73 m^2 per person. The seasonal variation in precipitation and ET must also be considered as the system should have enough volume (depth) to be able to store the sewage and rain during winter. In addition, the amount of nutrients discharged into the system should balance the amount that can be removed by harvesting aboveground biomass.

Our data show that when willow growth is optimal during the first year of operation, the ET in the system may increase by at least 300 mm under Danish conditions the following year, i.e. from 1,200 mm to 1,500 mm per year. Therefore, willow wastewater cleaning facilities designed for 2-3 persons may be able to receive higher amounts of sewage than designed for the following years. However, there is still some uncertainty about the long-term performance of the systems, particularly the potential accumulation of salts and the sustained health of the willows.

4.4.12 References

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4.5 Anaerobic processes

4.5.1 Description

Anaerobic processes can treat wastewater with high concentrations of organics. In the absence of oxygen, anaerobic bacteria degrade organic compounds into carbon dioxide and methane (‘biogas’). In the past, such treatment was used on sludge, organic waste substances, and wastewater with high concentrations of organics; municipal sewage treatment plants had ordinary digesters. The shortage of energy in the 70s raised the interest for energy-producing anaerobic treatment. Later, more experiments and practices have developed and have considerably reduced the retention time of the sludge in the anaerobic reactor. Today, anaerobic biological treatment is used on wastewater with medium or low concentrations of organics, such as municipal wastewater.

4.5.2 History and Background

Before the end of the 19th century, methane was already known to be produced by a microbial-chemical process. In 1896, the first anaerobic digester appeared in Great Britain to produce methane to light the streets. After the end of World War II, the anaerobic treatment technology developed fast; in the mid-1950s, the anaerobic contact reactor appeared. This important development in anaerobic treatment enabled the sludge retention time (SRT) to be longer than the hydraulic retention time (HRT) in the reactor. At the end of the 1960s, Yong and McMarty invented the anaerobic filter (AF). In the late 1970s, Lettinga and his colleagues at Holland Agricultural University developed the up flow anaerobic sludge bed (UASB), which has now become the most widespread anaerobic wastewater treatment technology. The AF and UASB have promoted the development of high-rate anaerobic reactors built on the microbe mobilisation theory and aimed at improving the sludge and wastewater mixing efficiency. The anaerobic fluidized bed and expanded granular sludge bed (EGSB) are the best examples.

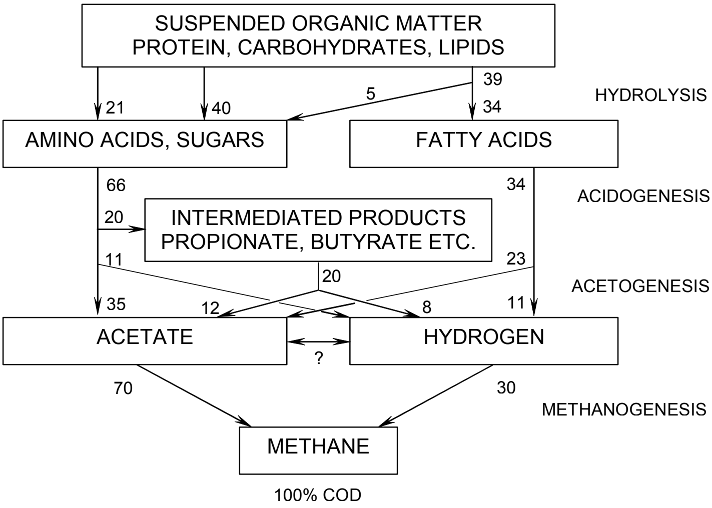
4.5.3 Mechanism of Anaerobic Fermentation

The transformation of complex macromolecules into biogas requires the mediation of several groups of micro-organisms. Different steps are necessary for the anaerobic digestion of proteins, carbohydrates, and lipids. The overall conversion process consists of four different phases (see Figure 4-40).

Hydrolysis

This process converts complex particulate matter into dissolved compounds with a lower molecular weight; it requires the mediation of exo-enzymes excreted by fermentative bacteria. Proteins are degraded via (poly) peptides to amino acids, carbohydrates are transformed into soluble sugars (mono- and disaccharides), and lipids are converted to long chain fatty acids and glycerine. In practice, the hydrolysis rate can be limiting the overall rate of anaerobic digestion. In particular, the conversion rate of lipids becomes very low below 20°C.

FIGURE 4-40
METHANE PRODUCTION FROM COMPLEX MACROMOLECULES



The numbers refer to percentages, expressed as COD; CO_2 production is not considered here.
Source: Gujer and Zehnder (1983)

Acidogenesis

Acidogenesis takes up dissolved compounds generated by hydrolysis in the cells of fermentative bacteria and excretes them as simple organic (volatile fatty acids, alcohols, lactic acid) and mineral (carbon dioxide, hydrogen, ammonia and hydrogen sulphide gas) compounds. Acidogenic fermentation is done by a diverse group of bacteria, most of which are obligate anaerobes. However, some are facultative and can also metabolise organic matter via the oxidative pathway. This is important in anaerobic sewage treatment, as dissolved oxygen might become toxic to obligate anaerobic organisms such as the methanogens.

Acetogenesis

The products of acidogenesis are converted into the final products for methane production: acetate, hydrogen, and carbon dioxide. As shown in Figure 4-40, about 70 percent of the COD originally present in the influent is converted into acetic acid and the remainder of the electron donor capacity is concentrated in the formed hydrogen. Depending on the oxidation state of the original organic matter, the formation of acetic acid may be accompanied by the formation of carbon dioxide or hydrogen.

Methanogenesis

Methanogenesis is often the rate-limiting step in the overall digestion process, although at lower temperatures this may be hydrolysis. Methane is produced from acetate or from the reduction of carbon dioxide by hydrogen using acetotrophic and hydrogenotrophic bacteria, respectively:

Acetotrophic methanogenesis

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \textbf{(E. 50)}$$

Hydrogenotrophic methanogenesis

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad \textbf{(E. 51)}$$

The bacteria producing methane from hydrogen and carbon dioxide grow faster than those using acetate (Henzen and Harremoes 1983), so that the acetotrophic methanogens are usually rate limiting during the transformation of complex macromolecules in sewage to biogas.

The different groups of bacteria involved in converting influent organic matter all exert anabolic and catabolic activity. Hence, parallel to the release of the different fermentation products, new biomass is formed associated with the four conversion processes described above. For convenience, the first three processes are sometimes lumped together and called acid fermentation, whereas the fourth one is called methanogenic fermentation.

Acid fermentation tends to decrease the pH because the production of volatile fatty acids and other intermediates dissociate and produce protons. As the methanogenesis only develops well at neutral pH, the reaction may become unstable if, for some reason, the rate of acid removal by methane production falls behind the acid production rate: the net production of acid tends to decrease the pH, and thus may reduce the methanogenic activity further. In practice, this so-called “souring” of the anaerobic reactor is the most common cause of operational failure of anaerobic treatment systems. To avoid souring, a proper balance between acidic and methanogenic fermentation should be maintained, i.e., both the methanogenic digestion capacity and the buffer capacity of the system should be sufficiently high.

4.5.4 Stoechiometry of Anaerobic Fermentation and Oxidation

A limited number of substrates are used by the methanogenic organisms and reactions defined as CO_2 and methyl group type reactions are shown as follows (Madigan et al., 1997), involving the oxidation of hydrogen, formic acid, carbon monoxide, methanol, methylamine, and acetate, respectively:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad \textbf{(E. 52)}$$

$$4HCOO^- + 4H^+ \rightarrow CH_4 + 3CO_2 + 2H_2O \qquad \textbf{(E. 53)}$$

$$4CO + 2H_2O \rightarrow CH_4 + 3CO_2 \qquad \textbf{(E. 54)}$$

$$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O \qquad \textbf{(E. 55)}$$

$$4(CH_3)_3N + H_2O \rightarrow 9CH_4 + 3CO_2 + 6H_2O + 4NH_3 \qquad \textbf{(E. 56)}$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \textbf{(E. 57)}$$

In the reaction for the aceticlastic methanogens (E. 57), the acetate is split into methane and carbon dioxide.
The COD loss in the anaerobic reactor is accounted for by the methane production. The COD of methane is the amount of oxygen needed to oxidise to carbon dioxide and water:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \textbf{(E. 58)}$$

From (E. 58), the COD per mole of methane is 2 . 2 . 16 = 64 g O_2/mole CH_4. The volume of methane per mole at standard conditions (0°C and 1 atm) is 22.414 L, so the CH_4 equivalent of COD converted under anaerobic conditions is 22.414/64 =0.35 L CH_4 /g COD.

4.5.5 Kinetics of anaerobic digestion

Biological growth kinetics are based on two fundamental relationships: growth rate and substrate utilization rate. The effect of growth-limiting substrate (i.e. the essential nutrient) concentration on the rate of microbial growth has been described by various mathematical models (Monod, 1949; Moser, 1958; Contois, 1959; Grau et al., 1975). Endogenous respiration, commonly defined as the self-destruction of biomass, cell maintenance, predation, and cell death and lysis are processes leading to a decrease in cell mass. These processes are important in waste treatment systems, especially anaerobic systems, since they usually operate at low specific growth rate. To account for the effect of these processes on the net growth rate, a microorganism decay rate is used to modify the growth rate.

The kinetics of micro-organism metabolism can be summarised by two basic expressions proposed by Monod:

(1) The growth rate of the micro-organisms, which was found to be proportional to the rate of substrate (sugars) utilisation:

$$\left(\frac{dX}{dt}\right)_g = Y\left(\frac{dS}{dt}\right)_u = X\mu = \frac{X\mu_m S}{(S+K_s)} \quad \textbf{(E. 59)}$$

(2) The decay rate of the micro-organisms, which can be expressed by a first-order equation:

$$\left(\frac{dX}{dt}\right)_d = -Xb \qquad \text{(E. 60)}$$

Where:

- X = micro-organism concentration [mg VSS/L];
- S = substrate concentration [mg COD/L];
- μ = specific growth rate of micro-organisms [d^{-1}] = relative increase of mass per time unit;
- μ_m = maximum specific growth rate [d^{-1}];
- b = death rate constant [d^{-1}];
- K = Monod (half-saturation) constant [mg COD/L] (indexes g, u and d stand for growth, utilisation and decay, respectively).

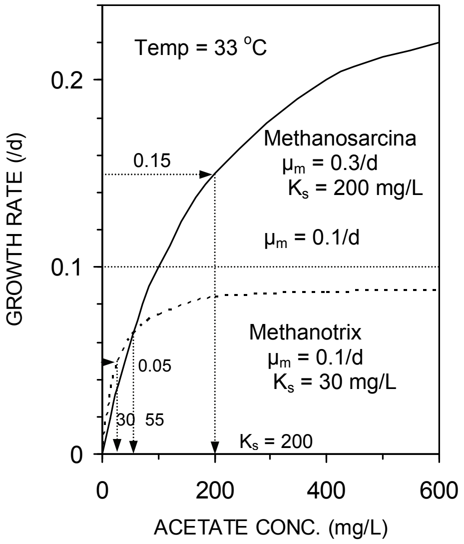
And:

- $(dX/dt)_g$ = growth rate of the micro-organisms
- $(dS/dt)_u$ = rate of substrate (sugars) utilisation
- $(dX/dt)_d$ = decay rate of the micro-organisms
- (dX/dt) = Net production of micro-organisms

Equation (E. 59) shows that, at high substrate concentrations, the Monod ratio $S/(S + K_s)$ approaches unity and the growth rate becomes independent of the substrate concentration, i.e. it becomes a zero-order process. If the substrate concentration is low, the Monod ratio approaches S/K_s and the growth rate is proportional to the substrate concentration, which is characteristic of a first-order process. For intermediate concentrations the growth rate is between zero and first order with respect to the substrate concentration.

Figure 4-41 shows the value of the specific growth rate as a function of the substrate concentration for two types of methanogenic bacteria: *Methanotrix* and *Methanosarcina.* The maximum specific growth rates of these acetate-consuming organisms are μ_m = 0.1 and 0.3 d^{-1}**,** respectively. The specific growth rate is at half its maximum value when the substrate concentration is equal to the parameter K_s, which, for that reason, is called the half-saturation constant or affinity constant. For *Methanotrix* and *Methanosarcina* the values of K_s are 200 and 30 mg/L acetate, respectively. Figure 4-41 shows the importance of the numerical values of the constants for the behaviour of the system: at a low acetate concentration (<55 mg/L), the specific growth rate of *Methanotrix* becomes higher than that of *Methanosarcina* and, ultimately, the methanogenic organism mass will be composed of the former bacteria. By contrast, at acetate concentrations exceeding 55 mg/L, *Methanosarcina* will out-compete *Methanotrix* and become the prevailing acetate-consuming organism.

FIGURE 4-41
GROWTH RATE AS A FUNCTION OF ACETATE CONCENTRATION



The net production of organisms in the treatment system is equal to the difference between bacterial growth and decay. Over longer periods of time, this net production should remain positive. Therefore, to maintain the amount of viable biomass at a constant load, a minimum substrate concentration is necessary, which can be calculated by equalling the net growth rate to zero.

$$\left(\frac{dX}{dt}\right) = (\mu - b)X = 0 = \left[\left(\frac{\mu_m S_{\min}}{K_s + S_{\min}}\right) - b\right]X$$

or

$$S_{\min} = \frac{K_s B}{\mu_m - b} \qquad \text{(E. 61)}$$

$S_{\min}$ is the lowest value of the substrate concentration that can be obtained in the treatment system. For the anaerobic digestion of sewage, there is a series of sequential processes converting the complex organic material to biogas. Under these conditions, the minimum substrate concentration will equal the sum of the minimum concentrations for the different processes.

In sewage treatment practice, the substrate concentration will not be the minimum obtainable, because this would require a very long retention time and hence an unacceptably large treatment process. If the substrate concentration is greater than the minimum there will be a net growth of microorganisms. Naturally, the increase in the micro-organism mass cannot go on indefinitely: after some time of operation the system will be “full” and wastage of the micro-organism mass becomes unavoidable. If it is assumed that the micro-organisms produced in a completely mixed treatment system are wasted at a constant rate, this rate will equal the net production rate. In that case a constant micro-organism mass and concentration, compatible with the organic load entering the system, will establish itself. The rate of wastage is the inverse of the sludge age, which denotes the average solids (microorganism) retention time. Thus for a steady-state system (no accumulation of micro-organisms):

$$\left(\frac{dX}{dt}\right)_w = \left(\frac{dX}{dt}\right)_g + \left(\frac{dX}{dt}\right)_d$$

or

$$\frac{X}{R_s} = X(\mu - b) \qquad \textbf{(E. 62)}$$

Where:

- R_s = sludge age.
- $(dX/dt)_w$ = The rate of micro-organisms wastage

By substituting μ in equation (E.59), the following expression is obtained for the effluent substrate concentration:

$$S = \frac{K_s\left(b + \frac{1}{R_s}\right)}{\mu_m - \left(b + \frac{1}{R_s}\right)} \qquad \textbf{(E. 63)}$$

Equation (E.63) shows that the effluent concentration depends on three constants (K_s, μ_m and b) and one process variable: sludge age, R_s. Figure 4-42 shows the substrate concentration as a function of the sludge age; there is a minimum sludge age for metabolism to take place. For sludge ages below the minimum, the abstraction rate of microorganisms due to sludge wastage and death is greater than the maximum growth rate and therefore the micro-organism population cannot be sustained.

The minimum sludge age can be calculated from equation (E.63) by assuming that no conversion takes place, i.e. the substrate concentration S is equal to the influent concentration S_i.

$$\frac{1}{R_{sm}} = \frac{\mu_m}{\left(1 + \frac{K_s}{S_i}\right) - B} \qquad \textbf{(E. 64)}$$

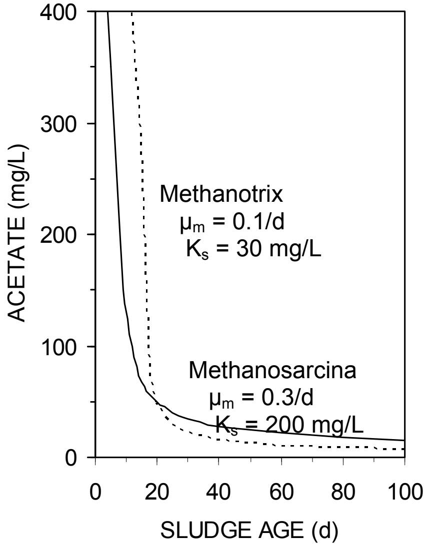
Often the influent substrate concentration is much greater than the half-saturation constant (if this is not the case, removal of the organic matter will be difficult). In that case, equation (E.63) may be simplified to

$$R_{sm} = \frac{1}{\mu_m - b} \qquad \textbf{(E.64a)}$$

Where

- R_{sm} = minimum sludge age

FIGURE 4-42
RESIDUAL SUBSTRATE CONCENTRATION AS A FUNCTION OF SLUDGE AGE FOR *METHANOTRIX* AND *METHANOSARCINA*



Source: Gujer and Zehnder (1982)

Another important kinetic parameter is the specific substrate utilisation rate constant. This constant denotes the maximum mass of substrate that can be metabolised per unit mass of bacteria and per time unit. It can be calculated from the maximum specific growth rate and the yield coefficient as follows:

$$K_m = \frac{\mu_m}{Y} \qquad \textbf{(E. 65)}$$

Where:

- K_m = specific substrate utilisation rate [kg COD/ kg VSS/d].

Table 4-14 shows the most important kinetic constants for acid and methanogenic fermentation.

TABLE 4-14
KINETIC CONSTANTS OF ANAEROBIC CULTURES

Cultures	μ_m(d^{-1})	Y (mg-VSS/ mg-COD)	K_m (mg-COD/ mg-VSS/d)	K_s (mg-COD/L)
Acid-producing bacteria	2.0	0.15	13	200
Methane-producing bacteria	0.4	0.03	13	50
Combined culture	0.4	0.18	2	-

Source: Henzen and Harremoes (1983)

It may be expected that a pure culture of acid formers or methanogens will both metabolise a maximum of about 13 mg COD/mg VSS/d. The acid formers grow 0.15

kg VSS/kg COD metabolised substrate which is complex organic matter, whereas methanogens grow only 0.03 kg VSS/kg COD of methanogenic substrate. Thus, a sludge mass of 0.15 + 0.03 = 0.18 kg VSS/kg COD will be produced when 1 kg of COD of complex organic matter is used anaerobically. Hence, a combined culture of acid formers and methane producers, generated from a complex organic substrate, would typically be composed of 0.03/(0.03 + 0.15) = 1/6 of methanogens and 5/6 of acid formers. This estimate has not taken into account two factors: (1) in fact, the methanogen production will be slightly less because the influent fraction anabolised by the acid formers does not become available for methanogenesis and (2) decay is not taken in account. However, these factors only have a very small effect, so that the maximum rate of methane production per unit mass of combined bacterial mass would be only about one-sixth of that obtained with a pure methanogenic culture, i.e. 13/6 = 2 mg COD/ mg VSS/d.

4.5.6 Factors affecting on anaerobic digestion

Important environmental factors affecting anaerobic sewage digestion are temperature, pH, presence of essential nutrients, and absence of excessive concentrations of toxic compounds in the influent. For sewage, the latter three factors normally do not need consideration. An adequate and stable pH is set by the presence of the carbonic system and no chemicals are needed to correct the pH. Nutrients (both macronutrients, nitrogen and phosphorus, and micronutrients) are abundantly available in sewage. Compounds that could exert a distinct toxic influence on the bacterial population are generally absent in domestic wastewater. The toxic effect of sulphide is not serious and dissolved oxygen can only constitute a problem if the design of the anaerobic treatment system is inadequate.

Influence of temperature on anaerobic digestion

For high strength wastewaters, the operational temperature to a certain extent can be considered as a process variable for an anaerobic treatment system, because within limits it can be controlled by using the produced methane to warm up the wastewater. This is not the case for low strength wastewaters such as sewage, because the heat obtained from the combustion of the produced methane is insufficient for a significant temperature increase. The maximum heat produced from combustion of the methane obtained from the digestion of 500 mg/L of COD (a typical value for raw sewage) is 1.5 kcal/L. Hence an increase in temperature of 1.5°C is theoretically possible, but this maximum value is only reached when the pollutants are completely converted in methane-COD and the heat content of the methane is fully exploited. As a consequence, sewage must be treated at the temperature it arrives in the installation, which is invariably lower than the optimum temperature for anaerobic digestion.

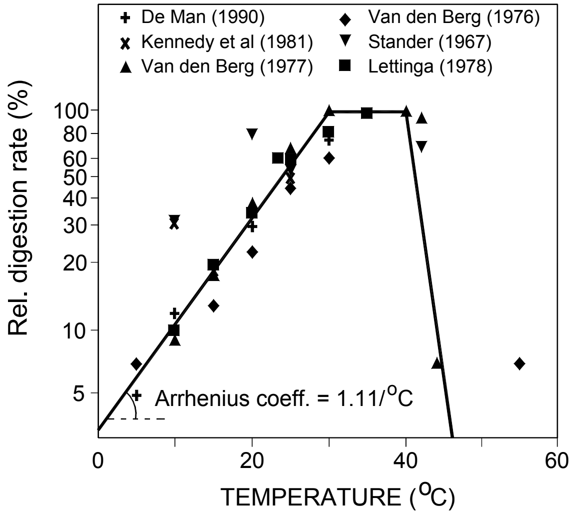
Anaerobic digestion, like other biological processes, strongly depends on temperature. With respect to the conversion rate of digestion processes, there are maxima between 35 and 40°C for the mesophilic range and at about 55°C for the thermophilic range. For sewage treatment only mesophilic digestion is relevant. Figure 4-43 shows a graphical representation of influence of temperature on the rate of anaerobic digestion in mesophilic range. From Figure 4-43 the following conclusions can be drawn: (1) the optimum range is between 30 and 40°C and (2) for temperatures below the optimum range the digestion rate decreases by about 11 % for each °C temperature decrease, or according to the Arrhenius expression

$$r_t = r_{30}(1.11)^{(T-30)} \qquad \textbf{(E. 66)}$$

Where:

- T = temperature in °C and
- r_t, r_{30} = digestion rate at temperature T and 30°C, respectively.

FIGURE 4-43
INFLUENCE OF TEMPERATURE ON THE RATE OF ANAEROBIC DIGESTION IN THE MESOPHILIC RANGE

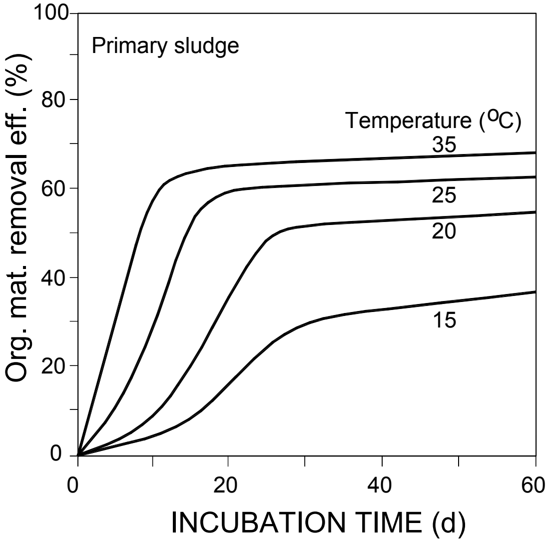


Source: Henzen and Harremoes (1983).

Using equation (E. 66) the calculated rates at 20 and 10°C amount to about 35 and 12 %, respectively, relative to the rate at 30°C.

The effect of temperature on anaerobic digestion is not limited to the rate of the process. The extent of anaerobic digestion is also affected. Figure 4-44 shows the achieved extent of digestion for settled sewage solids (primary sludge) in relation to digestion time at different temperatures (O'Rourke, 1968). This diagram clearly reveals the strong dependence of solids digestion on the temperature. The reduction in the fraction of organic matter degraded can be attributed to a low rate of hydrolysis. In practical terms this means that suspended organic matter can be removed from the water phase at low temperatures, even when it is not metabolised, because it can be entrapped in the sludge bed, consequently becoming part of the sludge mass in the treatment system. After having become part of the sludge, it can be discharged as excess sludge. The excess sludge can be treated in a separate digester, in principle at a higher temperature than for the sewage itself. At all rates, the application of the process is more attractive for tropical (sewage temperature above 20°C) and subtropical (temperature above 15°C) climate conditions than for regions with moderate or cold climates (temperature above 10°C).

FIGURE 4-44
EFFECT OF TEMPERATURE ON ANAEROBIC DIGESTION OF PRIMARY SEWAGE SLUDGE



Source: O'Rourke (1968).

pH in reactor

The value and stability of the pH in an anaerobic reactor is extremely important because methanogenesis only proceeds at a high rate when the pH is maintained in the neutral range. At pH values lower than 6.3 or higher than 7.8, the rate of methanogenesis decreases. Acidogenic populations are significantly less sensitive to low or high pH values, and hence acid fermentation will prevail over methanogenic fermentation, which may result in "souring" of the reactor contents.

The pH value in an anaerobic reactor is established after ionic equilibria of the different acid-base systems present in the system is obtained. The weak acid-base systems have a great influence and in particular the carbonic system is often determinant, because its concentration generally exceeds substantially that of other systems, such as phosphate, ammonia, or sulphide.

Toxic compounds

Apart from the hydrogen ion concentration, several other compounds affect the rate of anaerobic digestion, even at very low concentrations, such as heavy metals and chloro-organic compounds. However, the presence of these compounds at inhibitory concentrations is unlikely in sewage. Potentially toxic compounds that might be present are oxygen and sulphide. Some oxygen may be introduced in the influent distribution system, but it will be used for oxidative metabolism in the acidogenesis process. Thus, no dissolved oxygen will be present in the anaerobic reactor, unless air is entrained together with the influent, so that its introduction will be of no consequence for the performance of the reactor. Sulphide can be formed in the process due to the reduction of sulphate. However, according to results of Rinzema (1989) the sulphide concentration to be expected in anaerobic sewage treatment systems (up to 50 mg/L) is far lower than the minimum concentration for noticeable toxicity. Therefore, toxicity will normally not be a problem in anaerobic sewage treatment systems.

4.5.7 Use and Performance

Advantages of Anaerobic Processes

Anaerobic processes require less energy, produce less biological sludge, require fewer nutrients, and can sustain higher volumetric loadings:

- *Energy production*; the anaerobic treatment produces potential net energy of 10.4×10^6 kJ/d while the aerobic process requires 1.9×10^6 kJ/d (see Table 4-15).

- *Lower biomass yield*; the kinetics of the anaerobic processes lower biomass production by a factor of 6 to 8, which reduces sludge processing and disposal costs.

- *Fewer nutrients required*; if biodegradable BOD is involved in the equation, the amount of needed nitrogen and phosphorus is in the proportion: BOD:N:P = 100:5:1. However, in the anaerobic treatment process, the proportion is BOD:N:P = 350-500:5:1. Wastewater has enough nitrogen and phosphorus and various trace elements to meet the need for nutrition in anaerobic treatment. With less sludge produced, no nutrition or small amounts of nutrition are required. On the contrary, as the aerobic treatment is only applied on organic wastewater, more nutrition addition is required.

- *Higher volumetric loadings*; anaerobic processes generally have higher volumetric organic loadings than aerobic processes (organic loading rates of 3.2-32 kg COD/m^3.d for anaerobic processes compared to 0.5-3.2 kg COD/m^3.d for aerobic processes) (Speece, 1996). More organic substances are removed per volume unit in the reactor.

Disadvantages of Anaerobic Processes

Conversely, anaerobic treatment requires a longer start-up time, alkaline addition, treatment of the effluent, and anaerobic microbes are sensitive to toxic substances.

- *Longer start-up time*; the slow proliferation of bacteria in anaerobic treatment requires a longer start-up time, usually about 8-12 weeks.

- *Need for alkalinity addition*; alkaline concentrations of 2,000 to 3,000 mg/L (e.g., $CaCO_3$) may be needed to maintain an acceptable pH with the high gas phase CO_2 concentration. If this alkalinity is not available in the influent wastewater or cannot be produced by the degradation of proteins and amino acids, there may be a significant cost to purchase alkalinity.

- *Need for further treatment of effluent*; higher loadings, higher volumes of organic substances removed, and higher influent concentrations in anaerobic treatment lead to higher effluent concentrations than in aerobic treatment. The effluent from anaerobic treatment must be specially treated to meet the strict discharge requirements. A series of reactors combining anaerobic and aerobic processes can treat municipal wastewater in warmer climates, lowering energy requirements and sludge production (Goncalves and Avaujo, 1999; Garuti et al., 1992).

TABLE 4-15
COMPARISON OF ENERGY BALANCE FOR AEROBIC AND ANAEROBIC PROCESSES

Energy*	Value/(kJ/d)	
	Anaerobic	Aerobic
Aeration [a,b]		$-1.9.10^{6}$
Methane produced [c,d]	$12.5.10^{6}$	
Increase wastewater temperature to 30°C	$-2.1.10^{6}$	
Net energy, kJ/d	$10.4.10^{6}$	$-1.9.10^{6}$

*Energy required to treat 100 m^3/d of wastewater with strength =10 kg/m^3 and temperature = 20°C
a Oxygen reacquired = 0.8 kg/kg COD removed
b Aeration efficiency = 1.52 kg O_2/kW.h and 3600 kJ = 1 kWh
c Methane production = 0.35 m^3/kg COD removed
d Energy content of methane = 35846 kJ/m^3 (at 0°C and 1 atm)

4.5.8 Anaerobic wastewater treatment processes

Classical anaerobic treatment systems

First developments

The first application of anaerobic digestion for sewage treatment is presumably the air-tight chamber developed by the end of last century in France by M. Mouras. Around the start of the 20th century, several new anaerobic treatment systems were developed, e.g. septic tank by Cameron in England and Imhoff tank by Imhoff in Germany. In both systems, the sewage flows through the system in the upper part, while the anaerobic sludge stays at the bottom of the tank. The settleable solids present in the sewage will sediment and are degraded by the anaerobic sludge. In the septic tank, the efficiency of retention of settleable solids may be hampered to some extent by floating matter rising up from the bottom, or due to the agitation of decomposing solids by biogas bubbles. This will not be the case for the Imhoff tank, where the settled solids sink into a separate digestion chamber and the evolved gas cannot enter the sedimentation zone. In later developments of the Imhoff tanks, the accumulated solids are conveyed to a heated digester, thus increasing the rate of anaerobic digestion. The liquid retention time in the septic and Imhoff tanks for sewage treatment is one to two days, which is enough to remove settleable solids.

Consequently, these systems are in effect primary treatment systems with biological treatment of the settled solids.

In the early anaerobic systems, the removal was based on settling suspended organic matter. As only a fraction of the influent organic matter is settleable (one-third to one-half), the maximum removal efficiency in these systems did not exceed *30-50* % of the biodegradable matter, depending on the nature of the sewage and the settling efficiency.

The low removal efficiency of the primary treatment systems must be attributed to a fundamental design failure. As there is little, if any, contact between the anaerobic micro-organisms in the system and the non-settleable part of the organic matter in the influent, the main part of the dissolved or hydrolysed organic matter cannot be metabolised and leaves the treatment system. The importance of a sufficient contact between influent organic matter and the bacterial population was not recognised at the time. The resulting relatively poor performance of anaerobic systems led to the belief that they were inherently inferior to aerobic systems, an opinion which often still persists today. However, in the mean time, it has been demonstrated that a properly designed modern anaerobic treatment system can reach a high removal efficiency of biodegradable organic matter, even at very short retention times.

Anaerobic ponds

Anaerobic ponds do not differ fundamentally from the early anaerobic treatment systems described above. They are also flow-through systems with anaerobic accumulated sludge at the bottom. Usually, an anaerobic pond is far bigger than a primary treatment system and normally it is not covered. Mixing of the liquid phase (depth 2 - 5 m) may occur due to agitation caused by rising biogas bubbles, but also because of winds and sunshine (mechanical and thermal mixing, respectively). Anaerobic lagoons are extensively used for sewage treatment, particularly as a pre-treatment step in a series of stabilisation ponds. The retention time of sewage in anaerobic ponds (typically two to five days) is often higher than in a primary treatment system and correspondingly the removal efficiency of organic matter tends to be higher. Mara (1976) reported a BOD removal efficiency of 50 - 70 % for raw sewage in anaerobic ponds operated at retention times of one to five days. Figure 4-45 shows the results of several researchers on BOD removal efficiency as a function of the liquid retention time and Table 4-16 summarises operational conditions applied by different workers. Although there is a considerable spread in the experimental data, it is clear that the efficiency tends to improve with increasing retention time. The experimental data allow the derivation of an empirical relationship between the removal efficiency and the retention time. The linear relationship of the log-log plot in Figure 4-45 becomes:

$$E = 1 - \frac{2.4}{HRT^{0.50}} \quad \textbf{E. 67}$$

Where:

- E = efficiency of organic material removal.

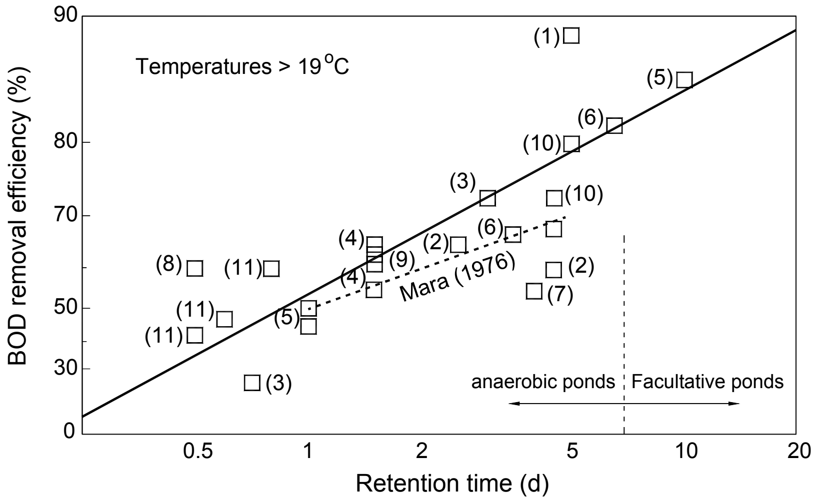
To reach an efficient BOD removal (i.e. more than 80 per cent), a long retention time of approximately six days is required. Below a load of about 1,000 kg BOD/ha.d or

0.1 kg BOD/m^{2}d, a pond tends to be facultative (i.e. with an aerobic top layer) rather than anaerobic. For typical values of the pond depth (2-3 m) and influent BOD (250 mg/L or 0.25 kg/m^3), a load of 0.1 kg-BOD/m^{2}d is reached for a retention time of 0.25 x (2 - 3)/0.1 = 5 - 7 days. Hence, a retention time of less than six days is required to assure anaerobic conditions in the pond.

TABLE 4-16
EXPERIMENTAL CONDITIONS APPLIED WITH SEWAGE DIGESTION IN ANAEROBIC PONDS

	Reference	HRT (day)	Organic load (kg/m^{3}d)	Temperature (°C)
1	Gloyna (1971)	4.5 – 5.5	0.03 – 0.05	23
2	Gloyna and Aguirra (1972)	4.5 – 5.5	0.06 – 0.12	32
3	Marais and Shaw (1961)	0.75	0.23	19
		3.0	0.06	19
4	Lakshminarayana (1972)	1.0 – 2.0	0.053	25
		1.0 – 2.0	0.053	30
5	Parker (1959)	1.0	0.25	19
6	Parker (1970)	5.0	0.23	19
7	Lakshminarayana (1972)	10.0	0.023	19
8	Meiring et al. (1968)	0.5	0.40	
9	McGarry and Pescod (1970)	1.0 – 2.0	0.68	30
		1.0 – 2.0	0.26	30
10	Sastry and Mohanras (1976)	2.0 – 7.0	0.80 – 0.33	
11	Collazos (1990)	0.4 – 0.9	0.46 – 0.25	26

FIGURE 4-45
BOD REMOVAL EFFICIENCY AS A FUNCTION OF RETENTION TIME IN ANAEROBIC PONDS



High rate processes

Figure 4-46 shows schematic reactor configurations of various modern anaerobic treatment systems. Basically, two mechanisms of sludge retention are used:

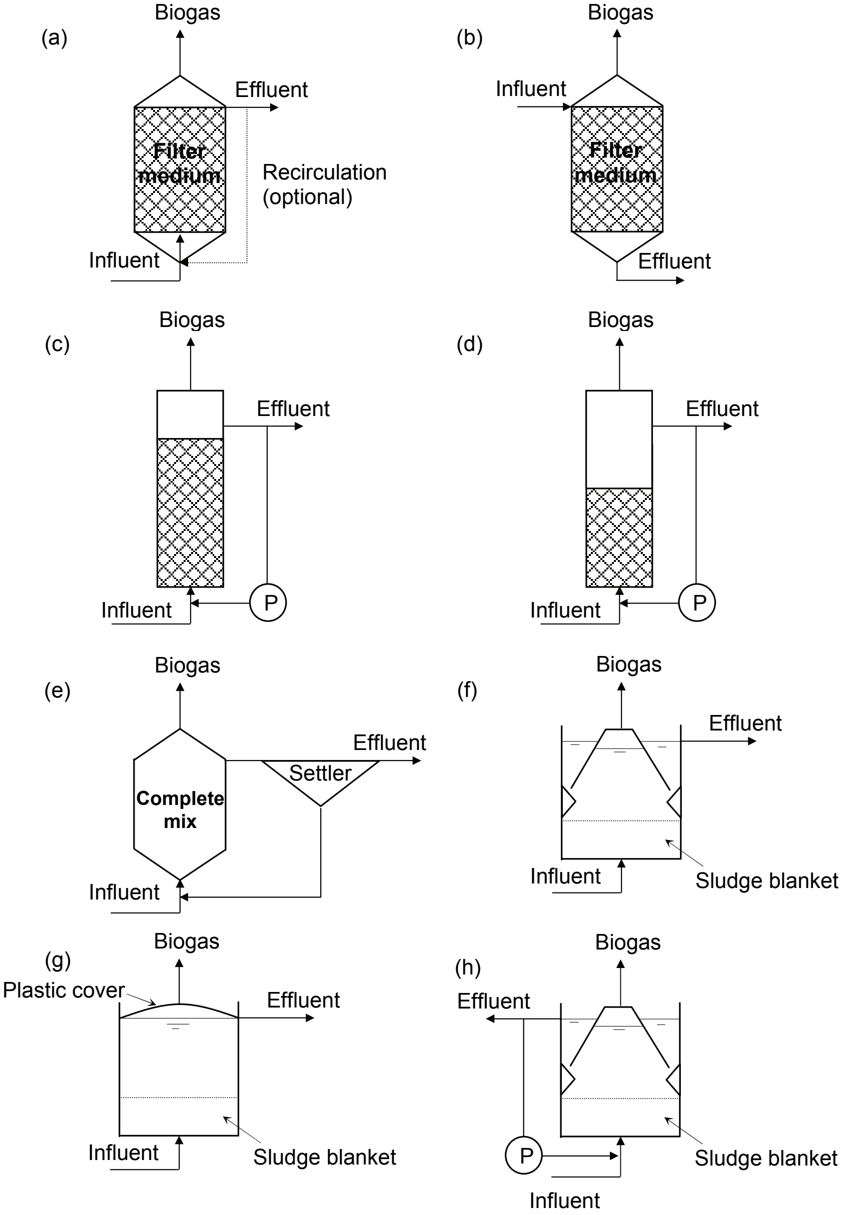
(1) *Immobilisation of the sludge*, e.g. by attachment on solid carrier matter. To this category belong the upflow or downflow anaerobic filter (Figures 4-46a and 4-46b) and sludge bed reactors, such as those using a granular bed operated in either a fluidised (Figure 4-46c) or expanded mode (Figure 4-46d).

(2) Liquid-solid separation with the return of the separated solids to the reactor. In this category fall the contact process, the anaerobic equivalent of the activated sludge process (Figure 4-46e) using an external settler and the conventional UASB reactor, which uses an internal settler, i.e. when rhere is not a special separation device (Figure 4-46g).

The different types of anaerobic treatment systems have been applied to a great variety of industrial wastes, but so far the anaerobic treatment concept is rarely used for sewage so experimental information is scarce. In fact, experimental results of anaerobic sewage treatment in modern systems are restricted to the use of the anaerobic filter, the fluidised and expanded bed reactors and the UASB with and without a liquid-solid separator. For this reason, only these processes will be discussed here.

FIGURE 4-46
SCHEMATIC CONFIGURATIONS OF HIGH RATE ANAEROBIC WASTEWATER TREATMENT SYSTEMS

(a) Upflow anaerobic filter; (b) downflow anaerobic filter; (c) fluid bed; (d) expanded bed; (e) contact process; (f) Upflow anaerobic sludge blanket (UASB) reactor; (g) Anaerobic fluid bed reactor and (h) expanded granular sludge blanket (EGSB) reactor.



Anaerobic filter

The anaerobic filter (AF) is mainly used for industrial wastewater treatment, though at a rather limited scale. Organic loads up to 10 – 20 kg COD/m^{3}d can be applied when the concentration and nature of the organic matter are favourable. An important disadvantage of the AF system is the high price of many carrier materials, which may result in cost of the same order as that of the construction costs of the reactor itself. Full-scale AF systems are operated for treating various types of industrial wastewaters, but for sewage treatment the system is rarely used at a large scale.

Performance data for several pilot and bench-scale AFs (upflow filters with loose fill and with modular media) are in Figure 4-47 a, which plots COD removal efficiency against the hydraulic retention time in a log-log diagram. There is a trend towards the following relationship:

$$\log\left(\frac{S_e}{S_i}\right) = -c_1 \log HRT + c_2$$

or

$$E = 1 - \frac{S_e}{S_i} = 1 - c_2\left(HRT\right)^{-c_1} \quad \textbf{(E. 68)}$$

Where:

- S = substrate concentration (COD)
- E = substrate removal efficiency
- c_1, c_2 = empirical constants.

From the data in Figure 4-47a, c_1= 0.5 and c_2 = 0.87 (*HRT* in hours), and hence equation E.68 becomes:

$$E = 1 - 0.87\ (HRT)^{-0.5} \quad \textbf{(E. 69)}$$

Fluidised and expanded bed systems

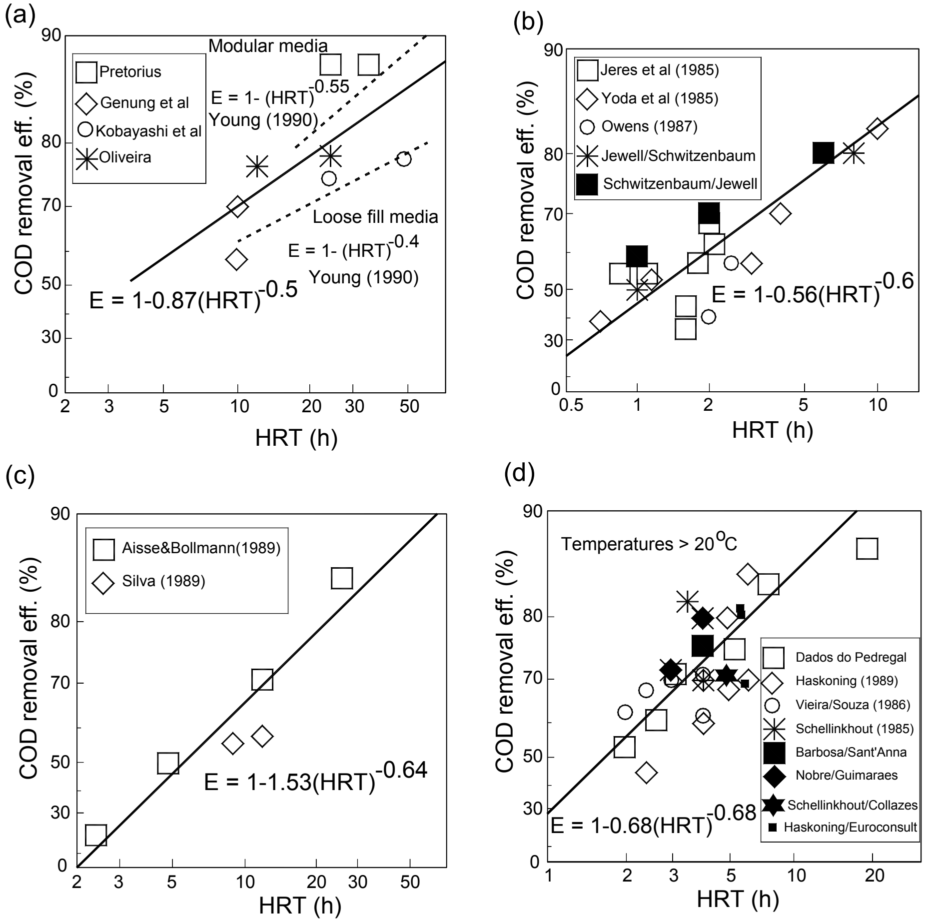
In the fluidised bed (FB) system (Figure 4-46c), the carrier consists of granular medium which is kept fluidised as a result of the frictional resistance of the waste flow. The media used in FB system should have a low density, such as anthracite and plastic, to reduce the required upflow liquid velocity, and consequently the pumping costs. The fluidization needs the diameter of packing materials to be less than 3 mm and an upflow velocity of 20 m/h. The effluent is recycled to provide sufficient upflow velocity. The reactor depth ranges from 4 to 6 m. The large surface area in the fluidized bed ensures high volumes of biomass. FB processes are feasible for organic wastewater with varied concentrations; below 35°C, loading values of 10-40 kg COD/m^3/d result in greater than 90 percent COD removal. FB reactor can provide high biomass concentrations, and relatively high organic loadings and mass transfer characteristics, and handle shock loads due to mixing and dilution with recycle; they do not need much space. The process is best suited for soluble wastewater due to its inability to capture solids. The inlet and outlet must be designed to assure good flow distribution. Disadvantages include the pumping power required to operate the fluidized bed, the costly reactor packing, the need to control the packing level and wasting with bio-growth, and long start-up time.

The fixed film expanded bed reactor (Figure 4-46d) differs from the fluidised bed concept by the much lower upflow velocities applied. To keep the packing materials expanding, part of the effluent is recycled by pumps to raise the upflow velocity. The expanding rate should be in a range of 10%-20%, the height after expanding reaches 50% of the reactor's effective height, and the upflow velocity is about 2 m/h. Such conditions enable the collision among granular particles so that the biological membrane falls off faster. The good packing materials are quartz sand with 0.2-0.5 mm diameter. Activated granular carbon, ceramist and zeolite alike are also suitable.

Figure 4-47b shows experimental results for fluidised and expanded bed reactors in terms of organic matter removal efficiency as a function of the retention time. This relationship can be expressed by the following equation:

$$E = 1 - 0.56\ (HRT)^{-0.6} \qquad (\mathbf{E.\ 69})$$

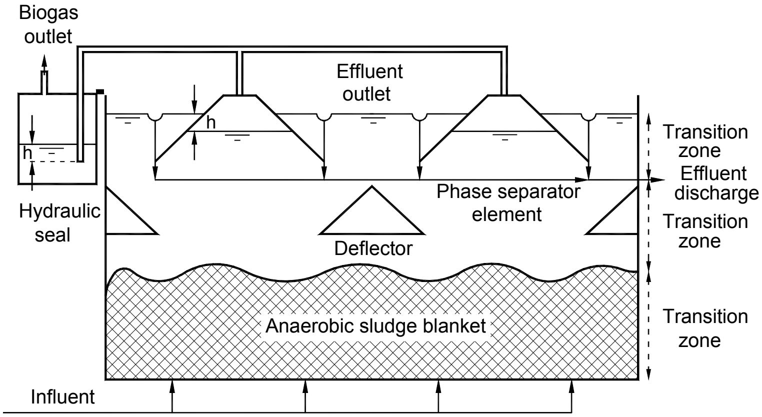
FIGURE 4-47
COD REMOVAL EFFICIENCY AS A FUNCTION OF HYDRAULIC RETENTION TIME
(a) Anaerobic filter. (b) fluidised or expanded beds. (c) Anaerobic fluid bed. (d) UASB



Upflow anaerobic sludge blanket reactor

The upflow anaerobic sludge blanket (UASB) reactor (see Figure 4-46f) was developed in the 1970s by Lettinga and his group at the University of Wageningen, the Netherlands. The UASB reactor is the most widely used high rate anaerobic system for anaerobic sewage treatment. Figure 4-48 is a schematic representation of the UASB reactor with its characteristic devices. The most characteristic device of the UASB reactor is the phase separator. This device, placed at the top of the reactor, divides it into a lower part, the digestion zone, and an upper part, the settling zone. The wastewater is introduced as uniformly as possible over the reactor bottom, passes through the sludge bed, and enters into the settling zone via the aperture between the phase separators.

FIGURE 4-48
SCHEMATIC VIEW OF AN UPFLOW ANAEROBIC SLUDGE BLANKET (UASB) REACTOR



Owing to the inclined walls of the phase separator, the area for the liquid flow in the settling zone increases as the liquid approaches the water surface, so that the upflow velocity of the liquid decreases when the liquid flows towards the discharge point. Owing to the decreasing liquid velocity, sludge flocs drawn into the settling zone can flocculate and/or settle out. At some stage, the weight of the accumulated sludge aggregated on the phase separator will exceed the frictional force that keeps it on the inclined surface and it will slide back into the digestion zone to become, once again, part of the sludge mass that digests the influent organic matter. Thus, the presence of a settler on top of the digestion zone enables the system to maintain a large sludge mass in the UASB reactor, while an effluent essentially free of suspended solids is discharged.

The biogas bubbles rise up to the liquid-gas interface under the phase separator. This interface may be at the same level as the water-air interface in the settler, or at some lower level if a hydraulic seal pressurises the biogas (see Figure 4-48). Sludge flocs with adhering gas bubbles may rise up to the interface in the gas collector, but will settle when the gas bubbles are released to the gas phase at the interface. Baffles, placed beneath the apertures of the gas collector units, operate as gas deflectors and prevent the biogas bubbles from entering the settling zone, where these would create turbulence and consequently hinder the settling of sludge particles.

An important and interesting feature of the UASB process is that a granular type (1-5 mm diameter) of sludge can develop in these systems. These granules have a high density and excellent mechanical strength. The granules combine a high settling velocity and high specific methanogenic activity. A granular type of sludge develops on mainly soluble types of wastewater. The formation of granules is related to the operational condition prevailing in a UASB reactor and to characteristics of wastewater to be treated. So far, granulation has not been observed in any of the existing full-scale UASB reactors treating raw sewage. In all cases, a flocculent sludge developed on raw sewage. Nevertheless, excellent BOD and TSS removal efficiencies were achieved, demonstrating that sludge granulation is certainly not a prerequisite for successful anaerobic sewage treatment in a UASB reactor. However, it is obvious that the use of granular sludge may offer some specific benefits.

To reduce construction costs, anaerobic fluid bed reactors (Figure 4-46g) such as simplified UASB systems have been also used. However, these systems are not equipped with a phase separator, but with a very small in-built settler. The phase separator is an essential device of a UASB reactor, so this system will be considered separately; it can be regarded as an upflow anaerobic pond.

Figures 4-47c and 4-47d show the experimental results obtained with full-scale of pilot plants of anaerobic fluid bed reactors and UASB reactors. These figures yield the following empirical equations:

For anaerobic fluid bed units:

$$E = 1 - 1.53\ (HRT)^{-0.64} \qquad \text{(E. 70)}$$

For UASB units:

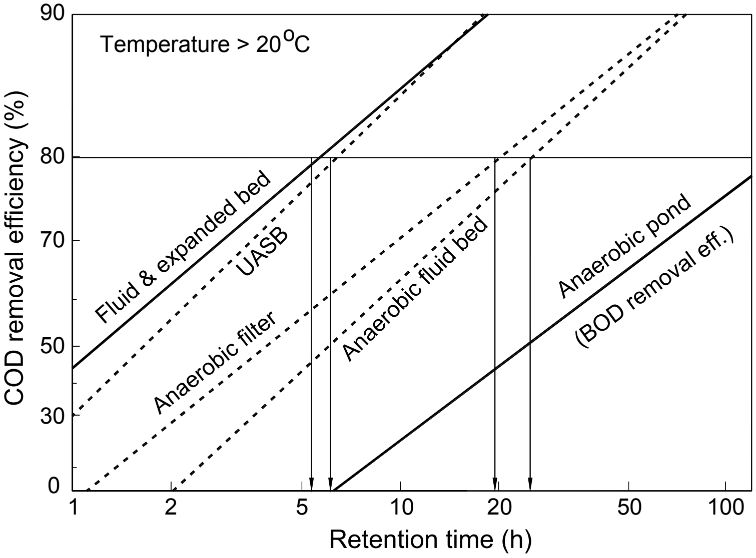
$$E = 1 - 0.68\ (HRT)^{-0.68} \qquad \text{(E. 71)}$$

<u>Expanded granular sludge bed reactor (EGSB)</u>

The expanded granular sludge bed system (see Figure 4-46h), introduced by Van der Last (1991), is characterised by the fact that the granular sludge bed is operated in the expandes mode as a result of a higher upward velocity, i.e. 6 – 12 m/h (less than 1 -2 m/h in UASB reactor). The EGSB reactor is fairly efficient to remove soluble organic matter even at low temperatures, which can be due to the intensive contact between the incoming organic matter and sludge granules. The EGSB system is particularly useful at lower temperatures and relative low strength wastewater, when the production rate of biogas and, consequently, the mixing intensity induced by it, are relatively low. Under these conditions, the higher kinetic energy content of the influent and the extended height of the expanded granular bed contribute to better performance compared to a normal UASB reactor.

An EGSB reactor is inadequate for removing particulate organic matter due to the high upflow liquid velocity. The influent suspended solids are blown through the granular bed and leave the reactor with the effluent. On the other hand, colloidal matter is partially eliminated as a result of sorption on the sludge flocs.

FIGURE 4-49
REMOVAL EFFICIENCY OF ORGANIC MATTER VERSUS RETENTION TIME



Comparison of the performance of anaerobic sewage treatment process

Figure 4-49 combines data from Figure 4-45 (anaerobic pond), 4-47a (anaerobic filter), 4-47b (fluidised and expanded bed), 4-47c (anaerobic fluid bed), and 4-47d (UASB). For all anaerobic treatment systems, the data show a linear relationship between the logarithms of removal efficiency and the applied retention time:

$$E = 1 - c_1 (HRT)^{-c_2} \quad \textbf{(E. 72)}$$

Where the constants c_1 and c_2 are characteristic of the different anaerobic treatment processes. The values of these constants are listed in Table 4-17. It is obvious that the actual efficiency in any particular treatment system can deviate significantly from the predicted value. Despite this, the data show:

- For temperatures over 20°C, a COD removal efficiency exceeding 80% is possible for the systems considered, but the required retention times differ significantly according to the system;

- In the range of practical interest the performance of a UASB reactor and fluidised or expanded bed reactor tend to be similar with the same retention time;

- The performance of well-designed UASB systems is superior to that of the anaerobic fluid bed reactors not equipped with a phase separator and to anaerobic filter systems operated at the same retention time.

To compare the retention time, and hence the volume, of the different treatment systems, equation E. 72 can be written in a more suitable form.

$$HRT = \left[\frac{(1-E)}{c_1}\right]^{c_2} \qquad \textbf{(E. 73)}$$

For illustration, the values of the retention times required to achieve an organic removal efficiency of 80% with the different systems are given in Table 4-17 and Figure 4-49.

TABLE 4-17
EMPIRICAL VALUES OF THE CHARACTERISTIC CONSTANTS AND HYDRAULIC RETENTION TIMES FOR 80% COD REMOVAL FOR DIFFERENT ANAEROBIC SYSTEMS (TEMPERATURE >20^{O}C).

System	c_1	c_2	*HRT* for E= 0.8 (h)
UASB	0.68	0.68	5.5
Fluidised or expanded bed	0.56	0.60	5.5
Anaerobic filter	0.87	0.50	20
Anaerobic fluid bed	1.53	0.64	24
Anaerobic pond *	2.4	0.5	144 (= 6 d)

* BOD removal efficiency.

In practice, the suitability of a treatment system is not only determined by the riquired reactor volume. Other advantages and disadvantages of the treatment options must also be considered. The septic tank and Imhoff tank are unattractive because their removal efficiency is low and required retention time is relatively long. Anaerobic ponds provide a more efficient removal of organic matter and also offer the advantage of a relatively simple construction. However, the required area for the ponds is large and therefore application is not practical in densely populated areas where land is expensive. The AF has drawbacks because of its high construction cost and particulary because of probable operational difficulties due to blockages. From Table 4-17, it is concluded that for the same removal efficiency, anaerobic fluid bed reactor needs a HRT exceeding that of a UASB reactor by a factor of four to five times. Therefore it is highly recommended to equip a sludge bed system with a phase separator. The costs of the separator will be amply compensated by the reduction of the required reactor volume. When comparing the UASB reactor with the fluidised or expanded bed reactors, it is clear that the latter two systems have the important disadvantage of the need for additional pumping. The UASB reactor dispenses with any pumping, provided sufficient head is available. Moreover, the fluidised bed does not seem to be adequate for sewage treatment because of the difficulties of retaining influent suspended solid and maintaining a larger sludge mass in the reactor. Consequently, the UASB concept looks the most attractive and extencive option for sewage.

4.5.9 Design of UASB reactor

Reactor configuration and size

Figure 4-50a shows an unusual basic shape, in which the surface area of the upper (settler) section exceeded that at the lower digester section. The larger settler section could be advantageous for sludge retention, which is important for diluted wastewaters. However, for concentrated wastewaters the organic load rather than the hydraulic load is the determining factor, and there is no need for designs with a larger surface area in the settling section; in fact, the contrary is true, as indicated in Figure 4-50b. In practice, all full-scale UASB reactors under construction or in operation have equal areas for the digestion and settling sections, as shown in Figure 4-50c. Experience has shown that the advantages of constructing vertical reactor walls outweigh the eventual advantages of having a reactor with inclined walls and a larger settling zone. For this reason only UASB reactors with vertical sidewalls will be considered.

For a relatively low strength wastewater such as sewage, the hydraulic rather than the organic load is the most important parameter determining the shape and size of a UASB reactor. Thus it is good practice to design a UASB reactor on the basis of the hydraulic load and then check the performance of the system with respect to the imposed organic load.

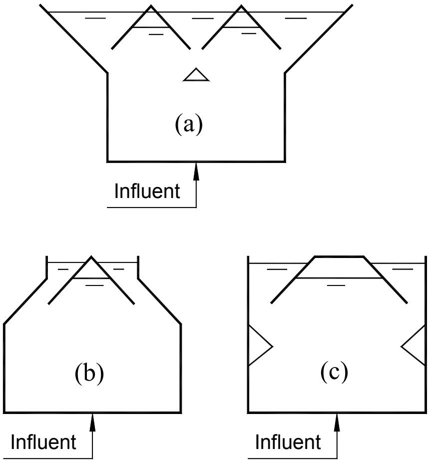
An important design parameter for a UASB reactor is the hydraulic retention time. This parameter cannot yet be assessed accurately from any theoretical question, but from the available experimental results, an average retention time of six hours is sufficient in tropical and subtropical regions ($T > 18°C$) to achieve a satisfactory treatment efficiency in one compartment UASB reactors. Experimental results obtained for moderate climatic conditions indicate that the liquid retention time for conventional designs has to be increased to 12-14 hours for a temperature of 10-12°C (De Man, 1990; Van der Last, 1991). On the basis of the required hydraulic retention time the reactor volume can easily be obtained from the following equation

$$V_r = Q_i . HRT \quad \text{(E. 74)}$$

Where:

- V_r = reactor volume
- Q_i = average sewage flow rate
- HRT = hydraulic retention time.

FIGURE 4-50
BASIC CONFIGURATIONS FOR UASB REACTORS.



For reactor volumes exceeding approximately 1000 m^3, it is beneficial to build systems consisting of more than one unit. This does not only reduce the construction costs, but it also increases its operational flexibility, because such a configuration allows one of the units to be taken out of operation for maintenance or repair, while the remaining reactors continue operating.

The next design parameter to be defined is the height of the reactor. The choice of the appropriate height depends on the required performance and economic considerations. The costs of earth removal increase, with increasing height (or depth) of the reactor, but the land requirement decreases. The economic optimum for the height (depth) of a UASB reactor is 4-6 m and in most cases this is also the optimum range for the performance of the system.

Another important design aspect is the position of the bottom of the reactors relative to ground level. Whenever possible the UASB reactor will be built at such a level that it can be fed without sewage (or effluent) pumping. If the local topography allows, construction costs can be reduced by constructing the reactor partially above ground level. In all cases care must be taken to avoid buoying of the empty reactor due to the Archimedean forces of groundwater.

The reactor height has important implications for the efficiency of organic matter removal. The liquid upflow velocity in the reactor is directly related to the reactor height. As the upflow velocity should not exceed a certain value to retain a sufficient amount of sludge, the reactor height is also limited. On the other hand, a high liquid velocity increases the turbulence in the system at the inlet zone and hence the contact between the biological sludge and the incoming wastewater. The relationship between the upflow velocity and the height of the UASB reactor is given by:

$$V_l = \frac{Q_i}{A} = \frac{V_r}{A.HRT} = \frac{H}{HRT} \qquad \textbf{(E. 75)}$$

Where:

- V_l = liquid upward velocity
- A = surface area of UASB reactor
- H = height of the UASB reactor

For sewage treatment using a conventional UASB system, the average daily value of v_l should not exceed 1 m/h. Hence, for a hydraulic retention time of six hours, the height of the reactor should be less than 6 m. Even when the design hydraulic retention time exceeds six hours, the reactor height is generally between 4 and 6 m and the upward velocity is proportionally lower.

Another consideration concerning the influence of depth on the efficiency of anaerobic digestion is related to the solubility of carbon dioxide as a function of depth under the water surface. Henry's law indicates that the saturation concentration increases with the partial pressure of carbon dioxide in the biogas. Naturally, this partial pressure will increase as the total pressure increases, due to a greater depth. Hence, the deeper the reactor, the higher the dissolved carbon dioxide concentration and therefore the lower the pH. Thus it is conceivable that a high depth can jeopardise efficient anaerobic digestion: the pH may assume a lower than optimum value due to a high carbon dioxide concentration. However, this consideration is not of importance for sewage treatment because the carbon dioxide production is low, due to the relatively low COD concentration, and much of the produced carbon dioxide will remain in solution, even if the biogas pressure is atmospheric (its lowest possible value). Thus, in the case of sewage treatment, the increase in gas pressure does not have an important effect on the carbon dioxide concentration and the pH of the liquid phase.

There are two basic geometrical shapes for the UASB reactor: rectangular and circular (see Figure 4-51). A circular shape offers the advantage of a higher structural stability, but the construction of a round phase separator is more difficult than a rectangular or square unit. For this reason small reactors will generally be constructed in a cylindrical shape, and large units in a rectangular or square shape. Both shapes are applied in practice. Hybrid designs are possible, e.g. with a circular reactor and a rectangular separator. When more than one reactor unit is constructed, the rectangular shape is advantageous because sidewalls can be shared by the different units.

Having assessed the volume and the height of the reactor, the values of length and width must be specified for a rectangular shape. The lowest construction costs will be obtained for a square reactor because the perimeter of a square is smaller than that of a rectangle with the same area. Consequently, the surface area of the sidewalls of a rectangular reactor is larger than that of a square reactor and therefore more construction materials will be required. Figure 4-52 shows the relative increase of the area of the sidewalls as a function of the length/width ratio. The relative increase in the area of a rectangular design becomes significant for length/width ratios exceeding 4: 1.

Figure 4-52 also shows that a round design has an approximately 12% shorter perimeter than a square design. This advantage of the round design will only become important if a single reactor is used. When two or more reactors are constructed (as will often be the case in practice), the rectangular reactors can be constructed with shared vertical walls.

FIGURE 4-51
GEOMETRIC SHAPES OF UASB REACTORS

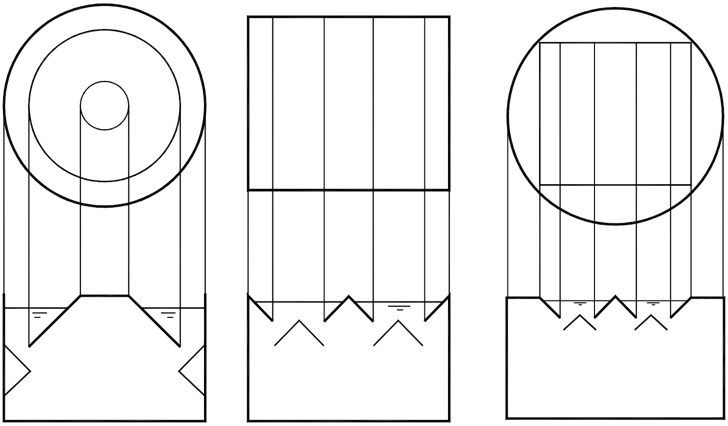
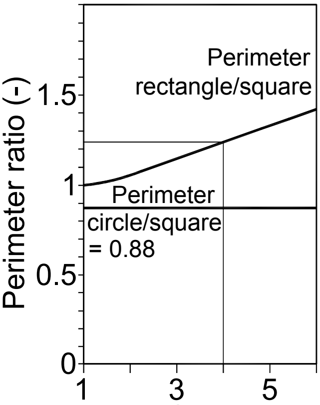


FIGURE 4-52
RELATIVE AREA OF THE SIDEWALLS AS A FUNCTION OF THE LENGTH/WIDTH RATIO FOR UASB REACTORS WITH A RECTANGULAR CROSS-SECTION.



The phase separator

The phase separator is the most characteristic and most important device in the UASB reactor. It serves four functions:

1. it collects the biogas escaping from the liquid phase;

2. it allows settling of the suspended solids in the upper part of the reactor above the separator;
3. it helps to keep the effluent TSS concentration low; and
4. it creates a space above the separator for the sludge bed to accommodate expansion due to temporarily high hydraulic loads.

In the latter case the sludge concentration in the settling zone may become substantially higher than in the expanded bed immediately beneath the separator.

The phase separator separates the three phases present in a UASB reactor: the biogas (G), the liquid (L) and the solids (S). For correct performance of the GLS separator device, the biogas formed in the digestion zone should not reach the settling zone. If this condition is not met, the resulting turbulence in the settler will lead to a decrease in the settling efficiency and loss of the produced biogas as well as the sludge. For these reasons the GLS separator could be composed of a set of gas collector elements at the top of the reactor and a layer of gas deflectors beneath the apertures between these gas collection elements (see Figure 4-53).

The liquid upflow velocity varies over the reactor height and reaches a maximum value where the available area for the flow is at a minimum, which occurs at the level of the apertures between the gas collection elements. From there to the effluent discharge level the surface area available for liquid flow increases and consequently the liquid velocity decreases. In principle, only flocs with a settling velocity smaller than the maximum liquid velocity will be drawn into the settling zone above the GLS separator. In the settler flocs with a settling velocity exceeding the minimum liquid velocity at the effluent discharge level will be retained. These flocs will settle on the GLS separator. When a sufficient amount of mass is accumulated there to overcome the frictional forces, the solids will slide back into the digestion zone. Hence, the liquid velocities of importance are:

$$v_1 = \frac{Q_i}{A_1} = \frac{V_l A}{A_1} \qquad \text{(E. 76)}$$

and

$$v_2 = \frac{Q_i}{A_2} = \frac{V_l A}{A_2} \qquad \textbf{(E. 77)}$$

Where

- v_1, v_2 = upflow velocities of the liquid at the base of the GLS separator and at the effluent discharge level, respectively;
- A_1, A_2, A = areas for liquid flow at these levels and surface area of UASB reactor.

It is important to note that even particles with a smaller settling velocity than v_2 can be retained in the reactor as a result of the occurrence of flocculation of these particles.

The diagrams in Figure 4-54 show that the gas deflectors overlap the aperture. This is necessary because rising gas bubbles tend to oscillate. An adequate overlap for reactors with a total depth of 4-6 m is approximately 100 mm. A larger value can be counterproductive because it results in a further decrease in the surface area for liquid flow through the apertures and hence in an increase in the upflow velocity at this critical level.

The use of a GLS separator consisting of more than two layers, such as shown schematically in Figure 4-54 may be an attractive option. From Figure 4-54a, it is apparent that the maximum ratio between the surface area of the apertures and the cross-sectional surface area of the reactor (not taking into consideration any overlap) is given by $(N-1)/N$ where N indicates the number of layers of separator elements.

The relative increase in the aperture/reactor surface area ratio for an increasing number of layers is plotted in Figure 4-54b. The advantage of a larger aperture area must be weighed against a higher construction cost of such a multi-layer device. It should be borne in mind that in principle the area at the effluent discharge level (and not at the aperture level) will dictate the minimum settling rate of flocs that can still be retained. However, by installing a GLS device consisting of more layers, the flow pattern will become more uniform and the flocculation of small particles passing through the apertures may be enhanced.

The principal design elements of the GLS separator are:

(1) The ratio of the area for liquid flow at the level of the apertures and of the effluent discharge. As shown above these areas indirectly determine the settling velocities of the flocs that will enter into the settling zone and of the flocs that can be retained.

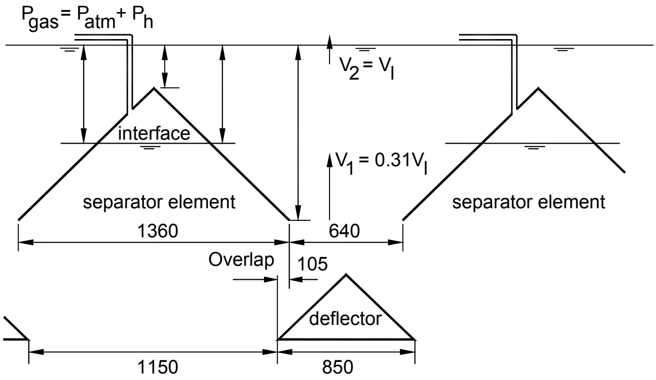
(2) The position of the separator relative to the liquid surface level. The position of the separator in the reactor determines the proportion of the total reactor volume available for digestion (lower part) and for settling (upper part). In most UASB reactors the volume of the settler makes up 15-20 % of the total reactor volume.

(3) The inclination of the phase separator elements. This inclination determines the surface area where the solids can settle out and whence these slide back into the digestion section. The inclination determines the height of the separator elements and the quantity of material needed to construct these. The steeper the inclination, the more material will be needed, but, on the other hand, the easier the settled material will slide back into the digestion section. In practice, the angle of the GLS separator with the horizontal should be in the range between 45 and 60°.

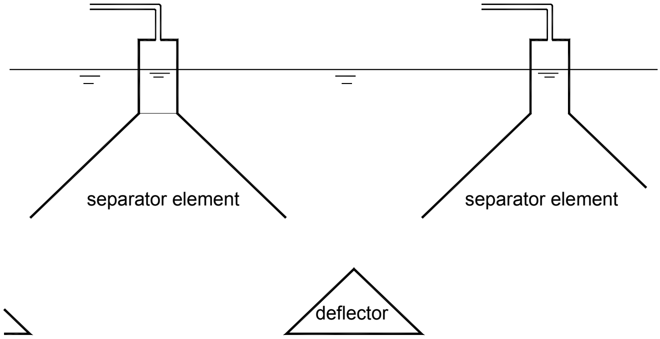
(4) The surface area of the gas-liquid interface under the separator, because it determines the biogas release rate per unit area of interface. When this rate becomes low, there is a tendency to form a floating layer which, with time, may become thick and hard (especially at lower temperatures) and, eventually, may seriously hinder the release of the gas at the interface. A very high gas production rate enhances foam formation at the interface, particularly for wastewaters containing proteins, which may result in clogging of the gas exhaust lines. According to experience obtained with full-scale installations, the gas evolution rate at the interface level should be in the range 1-3 $m^3/m^2/h$

(Souza, 1986), but this rate may not be attained with diluted wastes such as sewage.

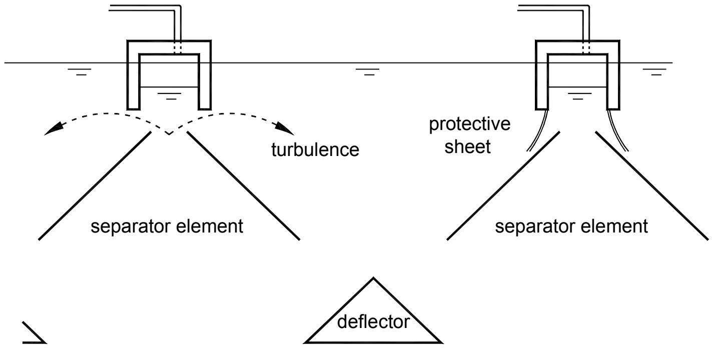
FIGURE 4-53
EXAMPLES OF THE DESIGN OF A GLS SEPARATOR IN THE UASB REACTORS



(a) Submerged separator

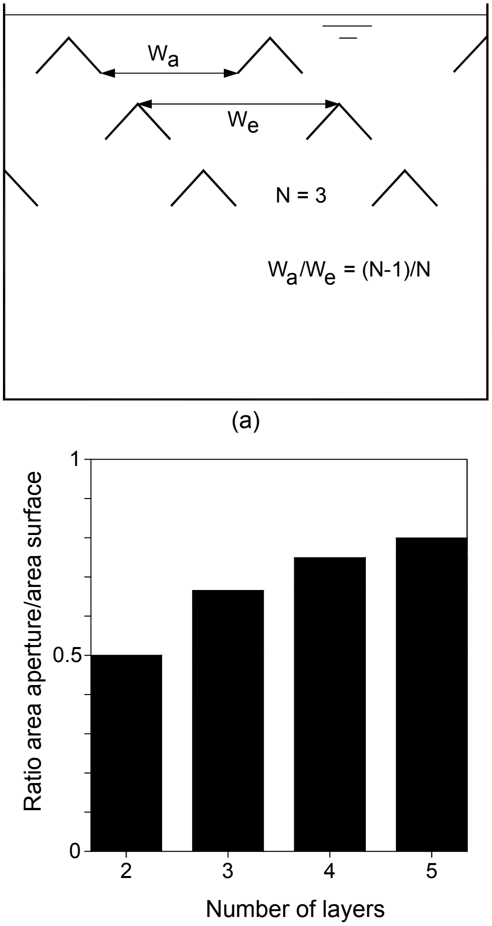


(b) Separator with gas under atmospheric pressure



(c) Hybrid separator with opening for maintenace

FIGURE 4-54
SCHEMATIC REPRESENTATION OF A MULTI-LAYER GLS SEPARATOR AND THE RELATIVE INCREASE OF THE RATIO APERTURE/SURFACE AREA.



The diagrams in Figure 4-53a and b illustrate that there are basically two possibilities to create a gas-liquid interface under the GLS separator:

1. with a submerged separator (Figure 4-53a or 4-54a) it is necessary to use an internal (Figure 72a) or an external hydraulic seal (Figure 4-53a) to create sufficient pressure under the separator to maintain the interface; or

2. when the top of the separator is situated above the water surface, the gas pressure can be atmospheric and a hydraulic seal is not required.

The advantages of the first option are:

- When steel is used for the construction, the occurrence of serious corrosion problems can be reduced by situating the various devices beneath the water surface. Severe corrosion problems will always manifest at the liquid-air interface.

- The entire reactor area is available for solids settling, which maximises the sludge retention.

- The biogas will be released under an overpressure, so that it can be conveyed more easily to its utilisation point.

- When the biogas is flared off, the external seal forms a security device which prevents explosions of gas under the GLS digester.

The advantage of the second option (no hydraulic seal) is the easier accessibility of the separator for inspection, maintenance or repair.

Hydraulic problems may arise when clogging of the gas exhaust piping occurs, because the gas accumulates under the separator. As a result an upward force may build up, so that the structure fixing the separator to the walls of the reactor, or even the structure of the UASB reactor itself, may be damaged. On the other hand, a partial vacuum may be created when, through erroneous operation, liquid is discharged too rapidly from the reactor. When no vacuum release mechanism has been installed, the vacuum created under the GLS separator may cause an implosion. On the other hand, a vacuum relief device can lead to the introduction of air into the gas chamber and hence an explosive biogas-air mixture could be formed.

In Figure 4-53c (left-hand side), a hybrid design is proposed that maintains the advantages of the basic concepts of Figure 4-53a and b, but eliminates their disadvantages. By introducing an opening beneath the height where the gas-liquid interface level is usually situated, an automatic “security valve” will come into action if a gas exhaust pipe is clogged. The gas will accumulate and the gas-liquid interface will descend to the level of the opening where the gas will be released. The escaping gas bubbles serve as an alarm for the operator, indicating that a gas exhaust pipe has become clogged. This separator can be built in two parts: the laterally inclined sides only serve to guide the gas bubbles to the central collection gutter and consequently there is no need to enforce this part of the device. They can be constructed from sheets of non- corrosive materials such as hardwood, asbestos cement, concrete or plastic. The central part has the form of an inverted gutter in which the gas accumulates. This part can be constructed of concrete, with a thickness such that the maximum Archimedean force of the gas displacing water is compensated by the weight of the structure, thus making floating of the gutter impossible.

An important additional advantage of the design in Figure 4-53c is that the gas-liquid interface is easily accessible to remove floating solids that may hinder the release of the produced biogas. As the inverted gutter is kept in its place by its weight, there is no need to fix it to the main structure of the reactor; it rests on concrete beams. If necessary it can be cleaned after inverting it and then be returned to its normal position. Removal of the accumulated solids is much more complicated if the element is constructed in one piece, e.g. the type shown in Figure 4-53a.

A serious drawback of the design in Figure 4-53c (left-hand side) is that the gas production inside the elements will give rise to liquid flows both beneath and (through the opening between the gutter and the inclined side) above the GLS separator. Thus settling will proceed less efficiently. The danger of developing convective currents can be eliminated by placing a plastic sheet film from the inverted gutter on the inclined sidewalls of the separator element in the way indicated in Figure 4-53c (right-hand side). A flexible connection between the upper and lower parts is created and convective currents become impossible. However, the opening still serves as a security valve and can be used for cleaning the interface.

Influent distribution device

To obtain a uniform distribution of the influent over the bottom of the UASB reactor, it is necessary to employ a flow-splitting device to introduce the influent flow at several points on the reactor bottom. The maximum area covered by one inlet point has been subject to extensive experimental investigations and it was established that areas varying between 2 and 4 m^2 per inlet point were sufficient to obtain a satisfactory treatment efficiency for the UASB reactor, which operated at temperatures exceeding 20°C (Haskoning, 1989). However, at temperatures lower than 20°C, volumetric gas evolution is lower and the mixing of sludge and influent is less efficient. Consequently, a higher density of influent points is necessary. De Man (1990) and Van der Last (1991) proposed 1-2 m^2 per inlet point.

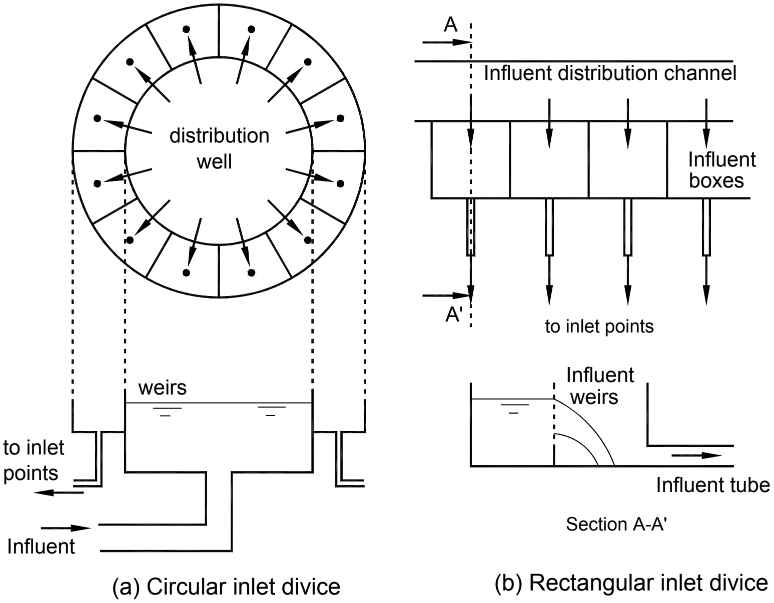
To guarantee a uniform division of the influent the design of the inlet device should be such that:

- it can be verified that the flow to each inlet point actually delivers the appropriate fraction of the total flow to that position;
- eventual obstructions of inlet points should be easily detectable; and
- once an obstruction has been observed, it should be easy to eliminate it.

To verify the uniform division of the influent flow over the different inlet points, it is necessary that each feed inlet line is connected to a separate compartment of the influent distribution system and discharges at only one point. In a manifold system in which several inlet points are connected to one inlet tube, e.g. by using a horizontal tube with orifices on the bottom of the reactor, with time, unavoidably, some of the orifices will become blocked and the influent will then be distributed over the remaining points, leading to an uneven distribution of the feed over the bottom of the reactor.

To ensure that each inlet point receives its due part of the influent flow, it is recommended to use a distribution system situated at a hydraulic level higher than the water level in the reactor. Feeding can then be accomplished using gravity according to the inlet system shown in Figure 4-55, where several small distribution boxes are connected to a distribution well or channel and a feed inlet tube or pipe is connected to each box. The pressure in the boxes is atmospheric, so that they can be opened and easily inspected visually. If necessary loose covers can be placed over the boxes to avoid bad odours and nuisance from flies. It is relatively simple to install an automatic control by employing sensors, for example in the form of an electrical float.

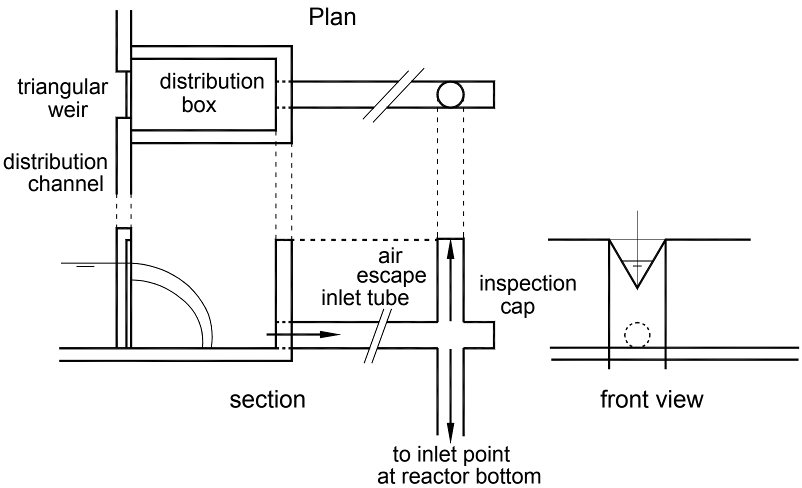
FIGURE 4-55
DISTRIBUTION SYSTEM OF THE INFLUENT



(a) Circular inlet divice (b) Rectangular inlet divice

It is important that each distribution box receives the same fraction of the influent flow. This can easily and reliably be assured by installing a set of triangular weirs between the influent well or channel and the distribution boxes, as indicated in Figure 4-56. After proper adjustment of the weir level in each box, a uniform division of the flow will be obtained.

FIGURE 4-56
SCHEMATIC REPRESENTATION OF A DESIGN FOR A DISTRIBUTION BOX



The height of the water level above the base of the weirs can be estimated as follows. As the area per inlet point is 3-4 m^2 (temperature> 20°C) and the average daily upflow velocity is 0.5-1 m/h, the flow rate to each box is 2-4 m^3/h. By using the equation for a triangular weir (with a right-angle) the calculated maximum water head is 58 mm (corresponding to 4 m^3/h) and the minimum water head is 44 mm (2 m^3/h), i.e. the water level in the inlet well or channel will be about 44-58 mm above the minimum weir level. If occasionally the maximum flow exceeds six times the average design flow (i.e. twice the wet weather flow), provision should be made for a head of 119 (24 m^3/h) to 90 mm (12 m^3/h). These values are sufficiently small to allow the construction of small boxes at almost negligible cost, yet they are big enough to allow an effective control of the distribution of the influent flow.

In the construction shown in Figure 4-56, a vent is present in the inlet tube. This vent is important as it allows entrapped air to escape, so that the distribution system will function properly. It is also helpful during blockages. If the horizontal part of the tube between the box and the vent is clogged, the level of the water in the tube will go down to the level of the UASB reactor. If clogging occurs in the part beyond the vent, the level will be equal to that in the box and in the distribution canal. Hence, when a blockage becomes apparent from a high level in the box, the level of water in the vent tube will indicate the location of the obstacle.

As the feed inlet distribution system is situated at a higher level than the water in the reactor, the inlet tubes should either be bent around the separator or passed through the GLS separator to reach the bottom of the reactor. The alternative of passing tubes through the sidewalls is less attractive. The disadvantage of a bent pipe might be that declogging of the pipes is more difficult than where inlet pipes pass through orifices in the gas separator. If the tube passes through the GLS separator at a level below the gas-liquid interface, the required perforation does not cause any problems, and is even an advantage because it also functions as an emergency escape for the gas in case of clogging of the gas pipe (see Figure 4-57). If the tube passes through the separator at a level above the gas-liquid interface an air-tight guidance tube, reaching below the interface, should be installed, as indicated in Figure 4-57(lower panel). It is important that the guidance tube is fitted in such a way that no gas can escape to the atmosphere. However, due to corrosion leaks may develop through which biogas will escape; perforations in the GLS separator above the gas-liquid interface should be avoided if possible.

If the influent level differs only slightly from the water level in the reactor (e.g. less than 10 cm), obstructions may occur more frequently because insufficient head can build up to eliminate the obstructions. However, these can be eliminated easily by lifting the feed inlet pipe and then immediately releasing it. When the difference between the water level in the box (base of the weir) and in the reactor exceeds about 30 cm, such blockages are rare.

Larger objects present in sewage (wooden chips, plastic bottles, etc.) may also obstruct the inlet tube. Such obstructions can be removed by pushing the obstacles through the tube using a rod. For this there should be a straight tube from the inlet box to the vent and the vent should be positioned directly above the inlet point as indicated in Figure 4-56. The usual cause of blockages is obstruction of the horizontal tube from the box to the vent. To clean this section it may be convenient to have a device as indicated in Figure 4-56: a four- way connection piece with a cap on one of the openings. This cap can be unscrewed when necessary. The construction of Figure 4-56 has the additional advantage that it is very easy to substitute any part of the inlet system that is damaged by mechanical impact or wear and tear.

To some extent air bubbles may become entrapped in the sewage when it passes over the weir through the box and into the tube. Some oxygen will dissolve in the liquid, but this will not result in any notable inhibition of the methanogenic organisms. If a significant amount of air is introduced a potentially explosive gas mixture might be formed with the produced biogas. As gas bubbles of a diameter exceeding about 2 mm rise with a velocity of 0.2-0.3 m/s in water, the liquid velocity in the vertical section of the tube (or at least at the top section of it) should be lower than this value. Assuming a maximum flow through the tube of 3 m^3/h, the required minimum tube diameter D_t at a liquid velocity of v = 0.2 m/s and a flow of $Q_i = 3/3600 = 8 \,.\, 10^{-4}$ m^3/s can be calculated as follows

$$A_t = \frac{3.14 D_t^2}{4} = \frac{Q_i}{v} = \frac{0.0008}{0.2} = 0.004 \quad \textbf{(E. 78)}$$

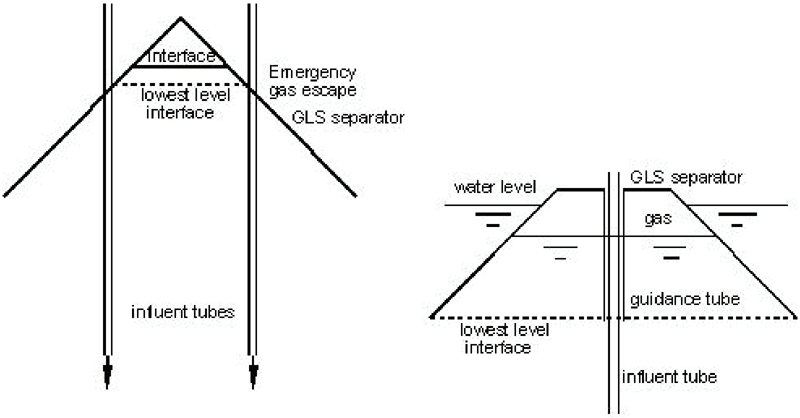
or

$$D_t = 0.072 \text{ m} = 72 \text{ mm}$$

Where:

- A_t = cross-sectional area of the inlet tube.

FIGURE 4-57
POSSIBILITIES FOR PASSAGE OF THE INLET TUBE THROUGH THE GLS SEPARATOR



Hence, under the given circumstances, a tube with an internal diameter of 75 mm is adequate to prevent air bubbles with diameters exceeding 2 mm from entering the reactor.

It may be beneficial to use a smaller diameter of the tube at the bottom of the reactor because it results in a higher liquid velocity and consequently in a higher turbulence and more intense contact between the sludge and influent. To achieve this, the diameter of the tube above the GLS separator could be wider than the part beneath it. Thus the low velocity at the top would allow entrapped air bubbles to escape and the high velocity at the bottom of the reactor would enhance the turbulence for a good contact between the influent and sludge.

To improve the contact between the sludge and wastewater and decrease the frequency of blockages of the influent tubes, it is also recommended to place the influent discharge points 100-200 mm above the reactor bottom. At a flow of 3 m^3/h per inlet tube, with an internal diameter of 40 mm at the bottom end, the discharge velocity of the sewage will be:

$$v_e = \frac{Q_i}{A_t} = \frac{0.0008}{\frac{\left(3.14x0.04^2\right)}{4}} = 0.6 m/h \quad \textbf{(E. 79)}$$

This velocity, which is twice the design velocity for a grit channel, avoids the deposition of settleable solids near the influent discharge point, thus reducing the frequency of blockages.

<u>Effluent collection device</u>

The effluent should collect the treated wastewater at the top of the UASB reactor as uniformly as possible. Most UASB reactors use a device traditionally employed in gravity settlers, i.e. horizontal gutters with V-notches at regular distances, as indicated in Figure 4-58. It is recommended to provide the effluent gutters with a scum baffle as indicated in Figure 4-58 to retain floating solids. Part of the material in the floating sludge layer consists of viable anaerobic active sludge, which rises in the water due to occlusions of biogas bubbles. Once the gas bubbles are released, the sludge will return to the digestion zone of the reactor.

FIGURE 4-58
GUTTERS WITH V-NOTCHES TO COLLECT THE EFFLUENT AT THE TOP OF A UASB REACTOR

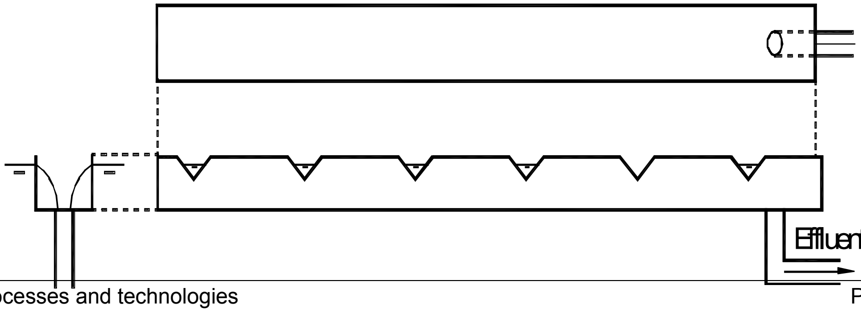
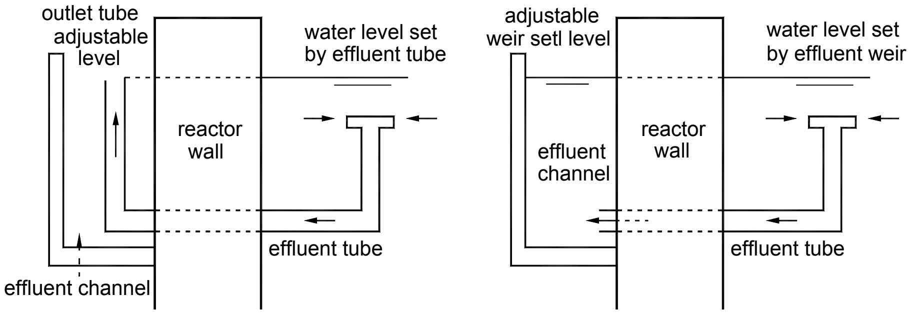
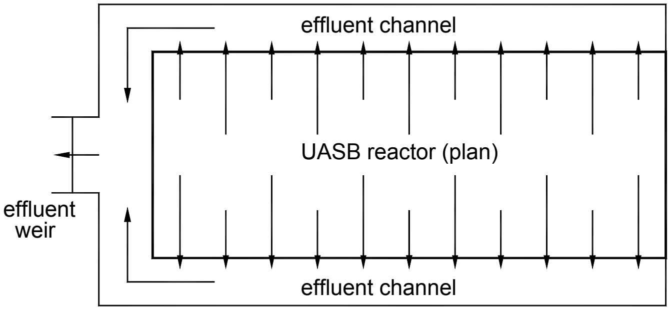


FIGURE 4-59
ALTERNATIVIE DESIGNS FOR EFFLUENT COLLECTION



(a) individual level control (b) level control by a collective effluent weir



(C) UASB REACTOR (PLAN)

A frequent problem in the outlet device is clogging of part of the effluent gutter by floating solids, even if scum baffles are present. This disturbs the uniform effluent discharge. To eliminate or at least to reduce these problems, the head over the weir should be sufficient, probably not less than about 25 mm. Moreover, for a head less than 25 mm it is difficult to regulate the level of the gutters such that the effluent is drawn off uniformly. Using the equation for a triangular weir with a right-angle calculate for a 25 mm layer. $Q_{25} = 1.34 . (0.025)^{5/2} = 0.44$ m^3/h. With the same equation it can be shown that the flow at a head of 25 mm is 75 per cent higher than that at a head of 20 mm. Hence a small difference of only 5 mm in the level over the length of a weir (which is likely to occur in practice, for instance due to a sudden release of biogas accumulated in the sludge), may lead to a difference in discharge rates of 75 per cent. A smaller head causes an even bigger relative error when the weir is not exactly levelled, and operational problems due to blockages of the notches by floating solids will occur more frequently. As the liquid upflow velocity in the UASB reactor is usually in the range 0.5-1 m/h, the number of V-notches must be about (0.5-1)/0.5 or 1-2 V-notches per m^2.

An alternative low cost design for the outlet device is shown in Figure 4-59. In this case no gutters are installed, but the effluent outlet device consists of a number of PVC tubes that draw off the water from beneath the water surface. The outlet level can either be set individually for each tube as shown in Figure 4-59a, or one discharge level can be adopted for all the tubes, as indicated in Figure 4-59b. The first option is slightly more problematic because all the tubes must be regulated individually, but it offers the big advantage that the discharge of the tube is visible and any obstruction can be detected easily. If the same discharge level is used for all effluent tubes, these all discharge into the effluent channel, in which a weir is placed. This weir determines the level in the channel and also indirectly in the reactor itself. The effluent channel can be "flushed" periodically by removing the weir suddenly: the lowering of the level in the channel causes temporarily a very high flow through all the effluent tubes, so that all deposited solids are flushed away. Note that a sudden drop in the water level in the channel, and consequently in the reactor itself, may create a partial vacuum under the separator, which could lead to an implosion in the GLS device if no vacuum relief device has been installed. As with the inlet tubes, the costs of the outlet tubes are small because only a few centimetres of tube (internal diameter 25 mm) are required *per capita.*

Special devices

Sampling points for sludge at different depths

Sampling of the reactor contents to obtain information about the sludge concentration and activity as a function of depth can be done conveniently by using openings in the GLS separator as indicated in Figure 4-60a. A sampler is introduced via such an opening and then samples can be withdrawn at any desired level. Generally it is necessary to use a pump to obtain a representative sludge sample when the sludge bed is very thick. Alternatively, if enough head is available, samples can be withdrawn at different levels by gravity discharge, as indicated in Figure 4-60b. A pump is not necessary when the available head exceeds about 1 m and if the diameter of the sampling tube is 25 mm or more. For smaller heads or diameters the tubes tend to clog, especially those of the lower sampling points, where the sludge is thickest and knowledge about the concentration and activity of the sludge is most important. Sludge samples will generally be withdrawn for assessment of the concentration profile over the depth, and the biological, chemical or physical characteristics of the sludge.

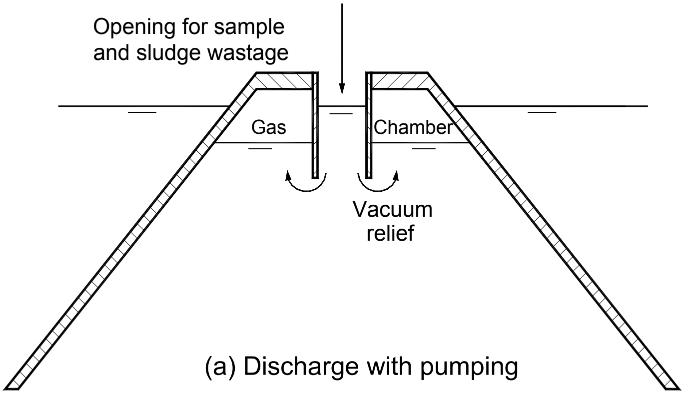
Sludge discharge device

In principle the effluent quality improves as the sludge mass in the reactor increases. However, it is clear that beyond a certain sludge bed height, the retention capacity of the system for suspended solids becomes exhausted. Any sludge produced in the reactor after reaching this maximum height will be washed out and will leave the system together with the effluent. The presence of this excess sludge in the effluent obviously decreases the effluent quality. For this reason it is recommended to discharge the sludge periodically once the sludge bed in the reactor reaches a certain prefixed maximum level. This procedure is particularly recommended when the anaerobic treatment system is not completed by any post-treatment, such as a lagoon or a settler.

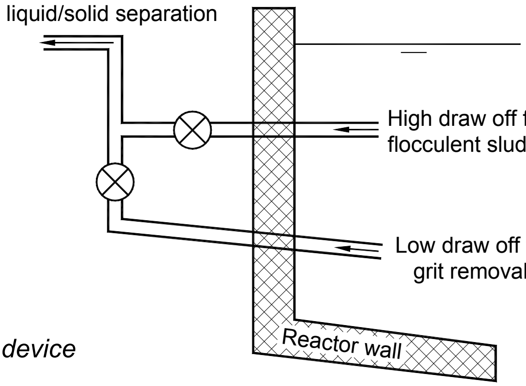
The maximum sludge held in the reactor can best be determined experimentally, because the sludge bed characteristics will depend on the influent composition. Also the maximum sludge mass that can be discharged in one operation without affecting the effluent quality and, consequently, the frequency of sludge discharge can be established experimentally. In general, sludge discharge will follow a preestablished routine schedule in the sense that at regular intervals (for example, weekly) a certain volume of sludge is withdrawn, equal to the amount accumulated during that period. The frequency of sludge discharge may also be influenced by the amount that can be handled on sludge drying beds. A more solid basis is to precede it by a determination of the sludge concentration profile. In principle, there are two methods for sludge discharge: (1) by direct discharge from the desired abstraction level (Figure 4-60b), or (2) by sludge pumping from the reactor though openings in the GLS separator elements, which can be the same openings as those used for sludge sampling (Figure 4-60a).

As to the level at which the sludge should be withdrawn, it is important to “waste” sludge with a lower activity to keep the best sludge in the reactor. For sewage treatment generally a sludge bed will develop which consists of a thick bottom layer and a thinner upper layer of flocculent sludge. Excess sludge should preferably be discharged from the upper part of the sludge bed. If the “heavy” sludge at the bottom of the reactor becomes less active due to the accumulation of grit and fine sand, it is advisable to discharge occasionally sludge from the bottom of the reactor. In this way grit accumulation in the reactor can be avoided, or at least reduced.

FIGURE 4-60
METHODS OF OBTAINING SLUDGE SAMPLES AND DISCHARGING SLUDGE AT VARIOUS DEPTHS



(a) Discharge with pumping



Gas collection device

(b) Gravity discharge

The gas collection device should enable a reliable release of the gas accumulating in the gas chambers, while maintaining a constant level at the gas-liquid interface. Although in sewage treatment the gas production is low (often less than 100 L/m of sewage), the diameter of the gas pipe should be sufficient to avoid clogging due to sludge solids transferred with the gas (foam) into the pipes. It is important to install an additional gas release device to allow gas to escape in case of blockages, thus avoiding large hydraulic forces on the GLS separator structure.

If the gas-liquid interface is maintained below the water surface of the UASB reactor, the gas is released via a hydraulic seal through which a certain gas pressure is set by a water column. Experience has shown that condensed water will accumulate in the hydraulic seal and therefore an outlet for condensed water is necessary to maintain the required water level.

It is of great importance to avoid the development of a partial vacuum in the GLS separator as this can lead to an implosion. This may occur as a result of erroneous operation, e.g. when the sludge flow exceeds the influent flow during the discharge of excess sludge. In that case the water level in the UASB reactor will descend and, consequently, the pressure in the gas chambers will decrease. To avoid damage to the GLS separator it is advisable to equip the system with a vacuum relief device. The device for sludge sampling and discharge may also be used for this purpose, as illustrated in Figure 4-60a.

Construction materials

The choice of proper construction materials is of great importance for the durability of a UASB reactor. As the anaerobic digestion process generates a corrosive environment, the use of metals must be avoided as much as possible. Even noble materials such as brass and stainless steel suffer severe corrosion in anaerobic reactors and paints or coatings only give partial protection.

Generally concrete or concrete reinforced brickwork are the most suitable construction materials for reactor walls. For the construction of specific devices for which concrete is less suitable, non-corrosive materials should be employed, such as PVC for inlet and outlet pipes, sheets of hardwood or asbestos cement for parts of the GLS separator or scum retention baffles, and glass fibre reinforced polyester for feed inlet distribution boxes.

4.5.10 Evaluation of the mechanical stability of the UASB reactor

After completion of the construction of the UASB reactor, it is useful to test if the different parts of the system, namely the inlet and outlet devices, perform properly, i.e. if there is a uniform distribution of the influent flow over the bottom of the reactor and an even discharge of the effluent at the top. If possible, this hydraulic verification should be carried out with water rather than with sewage.

After having established that the inlet and outlet devices function properly, the next step is to verify the quality of the gas collection device. This can be done by blowing compressed air into the gas chambers under the GLS separator. If the gas chamber is totally submerged, leaks can easily be detected by the emerging gas bubbles. For partially submerged separators, the detection of leaks is more difficult. In that case it is convenient to pressurise the gas chambers and wait for a sufficiently long period to check whether the air pressure decreases. When this occurs, it may be possible to find the leak(s) with the aid of a soap solution.

It is of great importance to check the mechanical stability of the separator for blockage of the gas collection device. This can be done by closing the gas outlet and blowing air in under the separator until the level for the emergency escape of gas is reached. The construction of the separator should be such that it is not damaged and remains well fixed to the sidewalls.

4.5.11 Unit cost assessment

Wastewater treatment costs depend on:

- the scale of the wastewater treatment system;
- local labour and material cost;
- complexity of required process, determined by wastewater quality, local discharge standards, required labour protection, and degree of automation;
- energy cost; and
- land cost.

The cost comparison for the 3 cases for which information is available are summarised in Table 4-18 and Table 4-19.

In view of the technical simplicity and the small reactor volume required, the UASB reactor concept is an exceptionally low cost treatment system.

TABLE 4-18
COST COMPARISON OF THREE WASTEWATER TREATMENT PROCESSES

Items	Oxidation pond		UASB+UASB Oxidation pond		Activated sludge (sludge digestion included)	
Investment cost	Z1	Z2	Z1	Z2	Z1	Z2
Construction cost	369	276	950	766	1,026	951
Technology and facility cost	25	21	48	45	585	506
Land cost	2,125	1,300	625	175	525	500
Total	2,519	1,597	1,623	986	2,136	1,957
Investment cost $/population	50	32	32	20	43	39
Annual investment cost	211.8	135.6	154.1	98.8	233.8	212.4
Annual operation cost	74.8	67.6	82.3	74.1	220.0	203.8
Annual total cost	286.6	203.1	236.4	172.8	453.8	416.2
US$ /m^3	0.098	0.070	0.081	0.059	0.155	0.143

Assumptions:

- Designing scale: 50,000 p.e (population)
- Discharge standard: $BOD_5(Z_1)$:20mg/L ; $BOD_5(Z_2)$: 50mg/L
- Land cost: \$25/m^2
- Electricity cost: \$0.1/kWh
- Expected useful life: 20 years
- Interest rate: 8 %

TABLE 4-19

COST COMPARISON OF THREE WASTEWATER TREATMENT PROCESSES (WITH ENERGY PRODUCED)

Items	Oxidation pond		UASB+UASB Oxidation pond		Activated sludge (sludge digestion included)	
	Z_1	Z_2	Z_1	Z_2	Z_1	Z_2
Investment cost	211.8	135.6	154.1	98.8	233.8	212.4
Construction cost	74.8	67.6	82.3	74.1	220.0	203.8
Energy produced (lost)	0	0	-11	-11	-27	-23
Annual total cost	286.6	203.1	224.9	161.5	42.0	393.2
$\text{US\$ /m}^3$	0.098	0.070	0.077	0.055	0.146	0.135

4.5.12 Human resources management

Depending on the scale, automation degree, and operational performance, anaerobic treatment usually requires 5-10 staff, including an administrator with a bachelor’s degree who will be in charge of managing and controlling the wastewater treatment unit; 2-3 positions are for quality inspectors, who must regularly inspect and analyse wastewater quality to ensure treatment efficiency. One position is for an electrician.

4.5.13 Environment impact

Anaerobic treatment has positive impacts on the environment: lower energy consumption, energy (methane) production, less residual sludge.

Further treatment must be done before discharge; bacteria are not entirely destroyed and disinfection of the effluent is needed. Anaerobic treatment also produces NH_3 and H_2S, which worsens the working environment.

4.5.14 References

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5. COLLECTIVE COMPLEMENTARY PROCESSES

5.1 Epuvalisation

5.1.1 Introduction - General considerations

Today, the problems of water and, in particular wastewater, are becoming more and more important. Northern countries face serious problems of water streams pollution and water table contamination with nitrates and phosphates. Southern countries (e.g., Mediterranean countries) suffer from a lack of water supply during at least part of the year and have constantly increasing needs of fresh water for human purpose (drinking water) and for agriculture (irrigation).

Definitions

The epuvalisation name comes from the contraction of two French words: *épuration* (purification) and *valorisation* (valorisation); it uses plants to purify the wastewater and has been applied with success in many Mediterranean countries and in Belgium.

Epuvalisation was born with a first patent on the "Process of purification of organic liquid effluents" in 1985. There was a second patent on the "Continuous Process of purification of methanisable effluents" jointly with the Industrial Institute of Huy (ISI, Belgium) and the Agricultural Technical Center of Strée (CTA, Belgium).

Epuvalisation has its origin in hydroponics. Unlike hydroponics – where plants are cultivated without soil and fed with a nutrient solution to produce vegetable and/or ornamentals, epuvalisation uses the plants' needs and physical characteristics to remove environmentally harmful compounds.

The wastewater flows through channels in which the plants have been placed with bare roots. The system can be used as an opened (only 1 passage) or closed circuit (recirculation). The channels are 50 cm wide and their length depends on wastewater quality. Nitrates and phosphates are taken up by the plants for their growing process and the roots filter the suspended matter and support an abundant bacterial flora. Therefore, the system also acts as a constantly growing trickling filter.

Originally developed to fulfil the need of wastewater treatment solutions for small and seasonal communities, the goals may however vary depending on the conditions of use and the countries concerned. In Mediterranean regions, the aim is to treat and reuse wastewater in irrigation; in dry tropical regions, the emphasis is on increasing yields; in temperate regions, attention focuses on removing nitrates and phosphates responsible for the eutrophication of water streams. The low cost and simplicity of this technique make it appropriate in countries where there is a chronic lack of water supply during at least part of the year and where sanitary problems increase year after year due to the anarchic use of raw wastewater.

Basics of "Plants Using Techniques"

For centuries, water plants and natural wetlands have been known for their "purifying capacities" through filtering, uptake of potentially harmful chemical compounds such as nitrogen and phosphorus but also by trapping many other polluting elements in the sludges and by the complex biological processes in the "water/plant complex".

The aquatic plant system is one of the processes for wastewater recovery and recycling; it stabilises waste and removes nutrients. The main removal mechanisms are physical sedimentation and bacterial metabolic activity as in the conventional activated sludge and trickling filter (USEPA, 1991). Plant assimilation of nutrients and its subsequent harvesting are another mechanism for removing pollutants. Besides reeds, bulrush, cattails and other similar aquatic plants commonly used in constructed wetlands, many other plants can be used for wastewater treatment. Not only are these plants used for purification but also for their end-use production. Here are some examples:

Water hyacinth (*Eichhornia crassipes*) treatment systems are generally known in tropical areas; they operate at high loading rates and their end-use products can be used for mulch and organic fertilizer. Dry water hyacinth petioles can be woven into baskets and purse (Polprasert, 1996).

Lotus is a floating attached plant, which is an important and popular cash crop in many Asian countries. Lotus has multiple uses; for example, stems and rhizomes as fresh vegetables; seeds as dessert and medicine; flowers as religious ornaments, and several parts as raw materials to produce cosmetics (Yi, Lin and Diana, 2002).

Hydrilla is a submerged perennial plant used as mulch, animal feed, and aquarium decoration (Polprasert, 1996). It tolerates a wide range of water conditions and can grow at a lower light intensity. Some research reported that hydrilla and other submerged plants play a major role in taking up and binding N and P in rivers (Vincent, 2001).

5.1.2 Description of the Technique

"EPU"...purification

The technique itself is really simple and consists in plants put in "channels" without soil (bare roots). The wastewater flows in the channels through the plants' root systems (see Figure 5-1 and Figure 5-2).

FIGURE 5-1
OVERVIEW OF EPUVALISATION

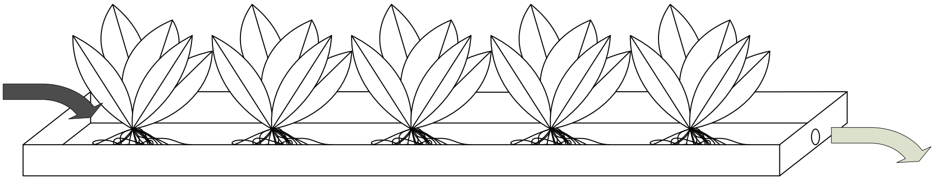
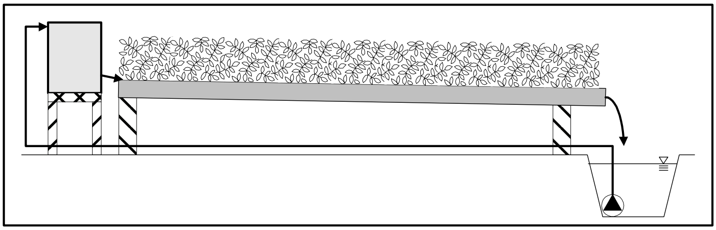


FIGURE 5-2
EPUVALISATION WITH RECIRCULATION (CLOSE CIRCUIT)



The technique initially used the Nutrient Film Technique, (NFT), but was enhanced with the Permanent Nutrition Flow (PNF). In contrast to the shallow film of the NFT, there is a continuous deeper and adjustable amount of water in the PNF.

This method is preferable for several reasons:

- If the conveyance systems break down, an adequate depth of liquid in the channels ensures that the plants do not suffer from lack of water; and

- For heavily polluted waters, the PNF promotes greater and prolonged contact with the plant roots on which an abundant microbial flora has developed. This trickling filter acts as a living and thriving bacteria bed.

The liquid to be treated by epuvalisation is used as exclusive nutritional source and the system can work as an **open** or **closed circuit**. In the open circuit, the liquid to be treated flows only once along a long channel; this is generally used as tertiary treatment for water discharged from wastewater treatment plants. The length of the channels varies according to wastewater quality and the purification level objectives (usually between 20 to 50 meters). The closed circuit is more suitable for heavily charged effluents and is generally used to purify, by depletion, the heavily polluted liquids that often have to be diluted beforehand. A short channel of 10 to 15 m is then enough to achieve the treatment.

Epuvalisation works in three main ways:

1. The roots system acts as a mechanical filter.

2. The roots system supports an abundant bacterial flora which also works as a constantly growing trickling filter. The roots are covered in an abundant microbial flora, which acts as a living and thriving bacterial bed. All surfaces of the channels and accessories in contact with the liquid are also used as support for bacteria.

3. The plant uptake - whether they are nutrients (the plants take up mineralised matter by micro-organisms - nitrates, phosphates,...) or any other compounds considered as "pollutants" (when overdosed in the effluent or toxic elements such as heavy metals).

There are three differences between epuvalisation and stabilisation ponds (Henrard, 1994):

1. A very short retention time of the liquid in the channels, which does not usually exceed 1 to 2 hours whereas retention time in stabilization ponds runs into weeks;

2. Does not require much space and can be set in a greenhouse and kept above freezing by light heating. The technique can be used year round in temperate or cold climates; and

3. Root growth and accumulation of suspended matter around roots leads to silting up channels and overflowing. Plants must be replaced after three to four months of growth, depending on the load of the liquid being treated.

Plant species are chosen according to various specific criteria:

- Their adaptation to hydroponic growth;
- Rooting must be composed of fine rootlets ("hairy" roots) with no tap root; and
- Their ready multiplication by sowing, propagation by cuttings, ratooning, in-vitro, ... to ensure plant replacement.

The plants selected to ensure optimum purification must be specially grown. In the channels, there is no substrate to support them and many require fixation, which is generally provided by mesh. The results obtained by purification are always positive but vary according to a number of factors:

- Fluctuations in the degree of pollution of the liquid;
- Flow rate treated by the channel;
- Vegetative state of the plants; and
- Climate (temperature, luminosity, ...).

The technique is used for:

Physico-chemical aspects: nitrogen and phosphorus removal - principal sources of eutrophication of water streams, suspended solids, COD, BOD_5, heavy metals;

Microbiological aspects: the reduction of pathogen bacteria (faecal coliforms, streptococci, Helminth eggs);

Application Cases

- Complementary treatment of urban wastewater: a 30 meter channel (made of 6 elements of 5 meters each) can treat, on average, 500 litres per hour of liquid which amounts to 12 m^3 /day or 70 to 80 equivalents-inhabitant (Northern European norms) using tertiary treatment of domestic effluents;
- Slurries/manure treatment;
- Landfill leachate treatment; and
- Olive oil mill’s wastewater.

"VALISATION"...valorisation

Besides its "purification" ability, the system can also produce two "valuable" products:

1. Water: the complementary treatment can make the water suitable for non-restrictive use such as irrigation.

2. Plants:

    - "Valuable" plants production (ornamentals, biomass, …);
    - Seed production; and
    - Animal feeding and human feeding *under given and strict conditions* regarding toxic compounds, such as heavy metals or any other compound that could enter the trophic chain.

Materials

The equipment needed consists of easily transportable channel elements, which are light-weight and of convenient width for the operator's arm. The most common types are made of metal sheets coated with a layer of epoxy, which is particularly resistant to aggressive agents, shaped, 50 cm wide and 9 cm deep, with corrugated reinforcements along the lengths. The standard length of each element is 5 m. Placed end to end, channels of any desired length can be obtained. The liquid to be treated flows by gravity along the channels containing the plants.

NB: as a rule, the highest purification occurs in the first 20 m of the channel. Increasing the length to around 50 m further reduces pollution. However, a greater length poses problems for the land, which must necessarily be sloping to avoid raising the elements too high and due to excessive evapotranspiration which can prevent a sufficient quantity of the liquid from reaching the end of the channel.

Figure 5-3 and Figure 5-4 illustrate the simplicity and the "low cost" character of epuvalisation.

FIGURE 5-3
EPUVALISATION WITH ORNAMENTAL PLANTS

FIGURE 5-4
EPUVALISATION CHANNELS

Growth performances

The way plants grow and develop in the system during operation is a good *indicator* of the element uptake and, thus, of the system efficiency (although not correlated).

Under temperate climates, the purification system can only be used in the open from mid-May to the end of October due to the frost. An epuvalisation system can be used all year long if it is placed under a greenhouse. The most efficient species used up to now in epuvalisation are celery, cyperus, watercress, and iris. These four species give excellent results, but their capacity for retaining sludge varies: the iris readily accepts having its roots covered in sludge whereas watercress has much better vegetation when the liquid does not have excessive quantities of sludge. Very satisfactory performances of watercress and celery confirmed observations made for the same species in Belgium, France, and Portugal (see Table 5-1).

TABLE 5-1
GROWTH PERFORMANCE AND PURIFYING CAPACITY FOR VARIOUS SPECIES OF PLANTS

Species performances	Growth	Purifying capacity	Observations
Tobacco	Poor	Not measured	Good plant development, but difficulty in producing a well developed root mat
Tomato	Average	Average	Degeneration of root system after two months growth
Canna	Good	Average	Excessive plant growth due to abundant shoot production
Water cress	Good	Average	Very good development, but tendency to accumulate effluent sludge
Cyperus	Good	Good	Very dense root mat and abundant shoot production
Celery	Good	Good	Very dense root, mat but with the tendency to rot at base at end of cycle

In Belgium, the behaviour and growth performances of several ornamental plants have been assessed (see Table 5-2). Any extrapolation of these growth performances to any efficiency would be hazardous without testing, but a plant showing high growth rates in an epuvalisation system can be assumed to have potential purification efficiency.

TABLE 5-2
GROWTH PERFORMANCES FOR VARIOUS SPECIES OF ORNAMENTAL PLANTS

Plants	Growth performances*	Plants	Growth performances*
Physalis perevianum	100	*Lobelia cardinalis*	80
Iresine sp.	20	*Myosotis palustris*	100
Impatiens sp.	100	*Acorus gramineus*	10
Ageratum mexicanum	100	*Juncus sp.*	10
Mimulus luteus or *guttatus*	100	*Polygonum sp.*	20

* Growth performances of plants in an epuvalisation system compared to normal growth conditions (in soil) in percent of weight.

It could be useful, given these varied vegetation characteristics, to use sequences of different species to enhance global efficiency. Therefore, it is possible to use either one single species or a sequence of species.

Physico-Chemical performances

In general, the reductions in closed circuit are better than those in open circuit. Given that the retention time of the liquid in the channels is longer in closed circuits, the longer contact time of the effluent with the plant roots enables the bacteria to carry out a more thorough nitrification and reduce COD further (Xanthoulis, 1997).

Reduction in physico-chemical pollution is evaluated by measuring SS, BOD_5, COD, NO_3^-, NH_4^+, PO_4^{3-}. These reductions are always substantial, but extremely variable, depending on the quality of the effluent to be treated, and to a lesser extent, on the type of flow used. The species used must also be taken into account as well as appropriate use of intermediary sedimentation basins placed between the channel elements or downstream of the latter.

Open circuit

- *Domestic wastewater;* the results in Table 5-3 have been achieved with effluents from classical purification plants (tertiary treatment - Belgium and Senegal) and from an anaerobic lagoon (secondary treatment - Morocco).

TABLE 5-3
REMOVAL RESULTS WITH VARIOUS TREATED DOMESTIC EFFLUENTS

Parameters	Belgium*		Senegal	Morocco*
	in %	g/m.d **	in %	in %
SS				> 60
COD	48.2	10.31	20-60	> 40
BOD_5	55.0		30-63	> 40
NH_4^+	36.6	1.27	25-40	> 60
NO_3^-	45.3	11.55	25-40	> 60
PO_4^{3-}	30.9	1.71	50-85	

* mean

** results in g. removed per channel meter and per day

Note: Expressing the results in grams of element removed per channel meter and per day (g/m.d) is quite useful for the design of epuvalisation facilities in similar situations.

Experiments also show that most of the purification is achieved in the first 20 to 30 m of the channels. Results in Table 5-4 were achieved in the first 20 m of a 40 m long channel, in percentage of the global purification efficiency (after 40 m).

TABLE 5-4
RESULTS ACHIEVED BY THE FIRST 20 M OF A 40 M LONG EPUVALISATIONCHANNEL

	PNF Channel	NFT Channel
COD	89%[1]	83%
NH_4^+	79%	76%
NO_3^-	82%	78%
PO_4^{3-}	72%	69%

PNF: Permanent Nutrient Flow (liquid depth: a few cm)
NFT: Nutrient Film Technique (liquid depth: a few mm)
[1]: 89% of the COD abatement has been achieved after 20 m in a 40 m long channel.

- *Landfill leachate;* this technique has also been tested on municipal landfill leachate, highly charged with organics and minerals matter, as tertiary treatment after purification by activated sludge secondary treatment (see Table 5-5).

TABLE 5-5
RESULTS OBTAINED FOR VARIOUS PLANTS ON MUNICIPAL LANDFILL LEACHATE

Plant	N-NH4 g/m.d **	N-NO3 g/m.d **	P-PO4 g/m.d **
Celery	1.357	43.648	0.230
Reeds	0.883	23.600	0.148
Rush	0.765	16.674	0.148

** results in g. removed per channel meter and per day

Closed circuit

When the effluent to "epuvalise" is more heavily charged than a common secondary treated domestic wastewater, it is recommended to shift from open to closed circuit.

- *Manure/slurry;* for the treatment of diluted and pre-treated bovine (Belgium) and porcine manures (Portugal), the retention times vary (along with the different trials made) between 1 and 7 days (see Table 5-6).

TABLE 5-6
TREATMENT OF DILUTED BOVINE MANURE (BELGIUM) AND PORCINE MANURE (PORTUGAL)

Parameters	Belgium (in %) *	Portugal (in %)
COD	64.8	from 35.9 to 95.3
NH_4^+	74.3	from 33.7 to 98.7
NO_3^-	88.7	
N_{total}		from 33.9 to 92.1
PO_4^{3-}	66.2	

* mean

Logically, the results show better efficiency than in the open circuit, but closed circuits can treat only low batched volumes (depending on the size of the facilities, from several hundreds litres to max one cubic meter) of effluent. Operating a closed circuit can be more demanding in terms of work and presence since the effluent volume has to be changed frequently (according to the charge, from 2-3 to 7 days).

Heavy metals

Heavy metals consideration is really important for epuvalisation since they can step inside the trophic chain and contaminate every level of this chain resumed by the human. Most the plants generally used in epuvalisation are potential up-takers and can store these elements. Since part of the interest in epuvalisation is the added value brought by the plants themselves (see 2.2. Valorisation ways), this can – in some case – represent a major issue restricting the use of these plants to "non-feeding" ways of valorisation. However, even if the heavy metal issue has to be taken into serious consideration, the deciders should consider epuvalisation since it is proven to efficiently remove those toxic elements from the water.

Table 5-7 shows the results achieved in **Belgium**, in an **open circuit** with a 23 m long channel, fed by a distributor used as a first sedimentation tank followed by a second one. Results are in percentage of heavy metal removed from the water.

TABLE 5-7
HEAVY METAL REMOVAL FOR A 23 M LONG CHANNEL IN OPEN CIRCUIT IN BELGIUM

Metal	Plants and channels			Supplementary materials	
	Root filtration (% removal)	Absorption root part (% removal)	Absorption aerial part (% removal)	Distributor (% removal)	Sediment. Tank (% removal)
Zn	53	4	3	27	13
Cr	62	1.2	0.8	23	13
Ni	62.6	1.4	1	22	13
Cu	65.5	0.9	0.9	19	14
Cd	45	15	10	20	10
Pb	63.3	0.7	0.5	22.2	13.3
All heavy metals	58.6	3.8	2.7	22.2	12.7

65% **35%**

The distributor and sedimentation tank stop 35% of the heavy metals trapped in the sedimentary sludge. Similarly, 58.6% of the heavy metals are trapped in the sludge blocked by the root system of plants. Only 6.5% (3.8 roots + 2.7 aerial part) are taken up by the plants. Experiments have shown the preponderance of heavy metal removal by retention and deposition in sediments compared to the amount taken up by plants. The highest removal rate for Cd and Pb is 99.8%. In **Portugal**, other trials made in a **closed circuit** show the purification efficiency of this system.

The results in Table 5-8 are in percentage of the removed heavy metals. These experiments show that most of the heavy metals are trapped in the sludge and the amount of heavy metals taken up by the plants does not exceed 10%.

TABLE 5-8
TRIAL RESULTS FOR CD AND PB REMOVAL IN PORTUGAL (CLOSED CIRCUIT)

Elements	Trial			
	1	2	3	4
Cd	100.0	99.8	85.7	-
Pb	99.8	99.8	-	78.4

Microbiological

Pathogens are very important when considering the opportunity to reuse treated wastewater for agriculture or other environmentally sensitive use. Table 5-9 shows results of microbial purification in opened circuits of effluents from classical purification plants (as tertiary treatment) and from an aerobic lagoon (as secondary treatment). Most of the time, the microbiological purification is close to the standards for bathing water and has reached those required for fertilising irrigation, which makes the need for chlorinating treated effluents unnecessary.

TABLE 5-9
MICROBIAL PURIFICATION - REMOVAL EFFICIENCY FOR FAECAL BACTERIA

Parameters	Belgium* (in %)	Senegal (in %)	Morocco (in %)*
Faecal coliforms	84.3	80-100%(**)	> 90 %
Total coliforms	79.3	80-100%(**)	> 90 %
Faecal streptococci	88.8	80-100%(**)	> 90 %

* mean
(**) not detected
Note: tests made on the plants and fruits produced by epuvalisation show that there is no contamination of the fruits and of the aerial part of the plants since there is no contact between the effluent and this part of the plant.

5.1.3 Cases of Application and type of treatment

Tertiary treatment; epuvalisation can further refine effluents from urban treatment plants by decreasing nitrogen and phosphorus which contribute to eutrophication of water. Epuvalisation can also further remove heavy metals and micro-organisms and produce a high quality effluent complying with standards for bathing, irrigation, or potable water. One single-pass is sufficient, unless the system is not long enough or the effluent contains too much ammonia nitrogen.

Secondary treatment; treating effluents from a small community is possible if the wastewater flow ensures a constant and sufficient supply to a single channel (4 to 10 m³/d). For this type of application, pre-treatment including oil and grease removal, screening, and grit removal is essential and may be expensive.

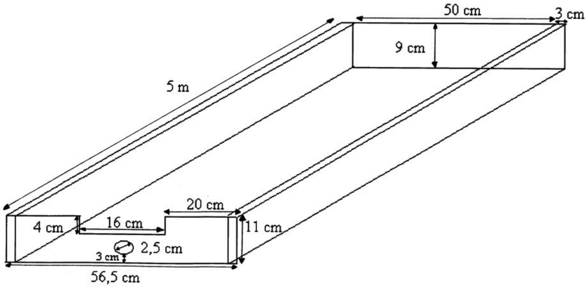
5.1.4 Designing

At this time, there is no mathematical model to design and dimension an epuvalisation system considering all essential parameters: organic and hydraulic loadings, evapotranspiration, received radiation, type of flow, type of influent, etc. Generally, channels are dimensioned and designed according to land availability.

Guide values

Channels have a length of 30 to 50 m (made of a series of 6 to 10 elements of 5 m each), a width of 50 cm, and a depth of 9 cm (see Figure 5-5). One channel can treat 4 to 10 m³ of weakly loaded wastewater per day. The number of channels depends mainly on the quality and type of constituents in the influent and on the wastewater flow rate. The epuvalisation system functions by gravity, and requires a slope of at least 2 to 3%. The planting density varies depending on the species used; for celery, 21 plants/m² has to be considered and for tomatoes 14 plants/m² is suitable.

FIGURE 5-5
DESIGN OF AN EPUVALISATION CHANNEL ELEMENT



Thickness of metal sheet: 1.5 mm

5.1.5 Operation and maintenance

Inflow regulation; the inflow rate into the channel is chosen according to the vegetative development of the plants. The flow must thus be regulated. For example, when young plants are placed into a channel, the flow must be reduced to ensure that plants are not swept along by the current; then the flow needs to be progressively increased.

Control analysis; flow, BOD, COD, suspended solids, ammonia nitrogen, nitrates, phosphorus, and faecal coliforms need to be regularly analysed to follow up the evolution of performances and to asses compliance with the standards. The flow needs to be followed up, a root growth and an accumulation of suspended matter around roots leads to silting up channels and overflowing. The control analysis frequency varies depending on countries and must comply with local standards.

Change of plants; commonly, plants need to be changed every three months; depending on the type of plants, the replacement frequency may vary. To avoid letting a whole channel totally out of use during the period of change and the start of growth, it is useful to change plants by alternating 5 m channel elements.

5.1.6 Conclusion and illustration

Epuvalisation has been refined over a number of years through numerous experiments in closed and open circuits and has resulted in selecting the best species for ensuring the highest treatment rates. The results achieved during the trials clearly show that the system used as tertiary treatment leads to substantial physico-chemical and microbiological reductions. With this technique, the treated effluents meet the standards for discharge into surface water and the quality standards for irrigation water.

The purification technique and the size of the system must however be adapted to the quality of the effluent and space available. Indeed, trials in open circuits have enabled to characterise the purification in reduction per meter of channel and per day, and in closed circuits, in the required retention time of the liquid in the channels to achieve given reductions. These results can be used to set up a purification system. The choice of this technique in open or closed circuits depends of course on the space available, but also on the quality of the effluent to be treated. Although a closed circuit is a valid alternative when available space is fairly limited, it requires a technically heavier and more complex installation. Furthermore, this type of operation seems to be better suited to the treatment of smaller quantities of effluent presenting a higher load of polluting elements.

The main disadvantages are probably the necessity to regularly replace plants, the energy required for recirculation pumps (closed circuit) and the price of a greenhouse if the epuvalisation system is used under temperate climates.

In the current context of search for improving the environment associated with the problems of wastewater treatment costs and water availability in most of the developing and/or emerging countries, epuvalisation is a good alternative for small communities. Indeed, this is easy to use, low cost, flexible, and has shown high purification efficiency.

5.1.7 References

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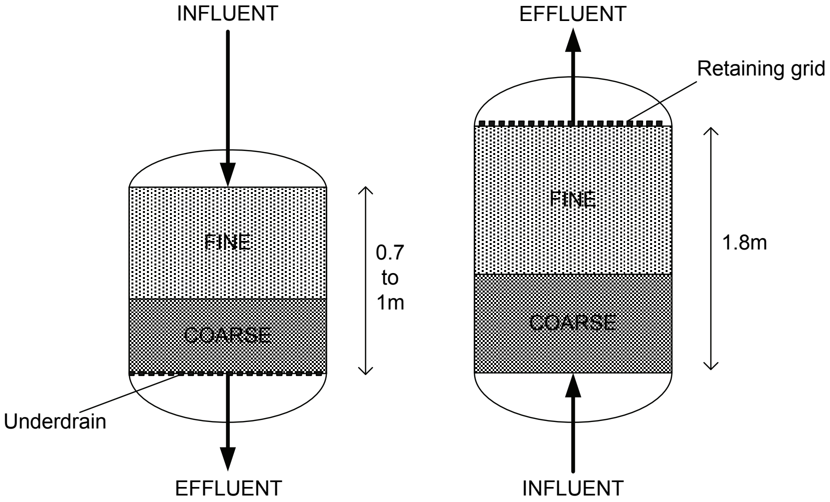
5.2 Sand filters as complementary treatment

Sometimes treatment plant effluents do not meet the local standards for discharge. Treatment plants use rapid sand filtration as an effluent polishing technique to increase removal of BOD and suspended solids. For instance, lagoon treatment systems are not very efficient in producing effluents with low SS concentrations. Generally, effluents from a WSP system have a high algae content. High rate sand filtration can upgrade lagoon effluents (Crites and Tchobanoglous, 1998). Removing algae is one of the most challenging aspects of upgrading pond effluent because of its tendency to clog conventional filter systems. Middelbrooks et al. (2005) also suggest intermittent slow sand filters to upgrade lagoon effluents (see Section 3.2.3 Intermittent sand filters).

5.2.1 Types of rapid sand filters

There are two main types of rapid sand filters (see Figure 5-6): downflow and upflow. The filtration occurring in downflow filters is from fine to coarse sand. In a downflow system, the depth of the sand bed is typically around 0.7-1 m. Upflow filters were first used in Europe to obtain depth filtration. The filtration in upflow filters is from coarse to fine sand (a pump is required to overcome head losses and waterhead). To prevent fluidization of the sand bed, a retaining grid is placed at the top of the bed. Normal filter media depths are generally about 1.8 m.

FIGURE 5-6
MAIN TYPES OF RAPID SAND FILTERS



(a) Downflow **(b) Upflow**

5.2.2 Design

Particle size

For rapid filtration, the typical grain size varies around 0.6-2 mm (sometimes 3 mm). For slow filtration, refer to Section 3.2.3 on intermittent sand filters.

Hydraulic loading rates (HLR)

The HLR strongly affects quality performance. A rate increase tends to decrease suspended solids removal and accelerate clogging. If the sand filter is to upgrade the effluent from a poorly functioning biological treatment unit (providing weak flocs and high concentrations of SS), the quality tends to degrade at rates above 12 $m^3/m^2.h$ (EPA, 1975). For effective algae removal, rapid sand filters need HLR typically less than 5 $m^3/m^2.h$ (Crites and Tchobanoglous, 1998). Slow sand filters require HLR lower than 0.03 $m^3/m^2.h$ to prevent clogging (Middelbrooks et al., 2005).

Area required

$$A = \frac{Q}{HLR} \qquad \textbf{(E. 80)}$$

Where:

- A = Area of sand filter [m^2]
- Q = inflow [m^3/h]
- HLR = Hydraulic loading rate [$m^3/m^2.h$]

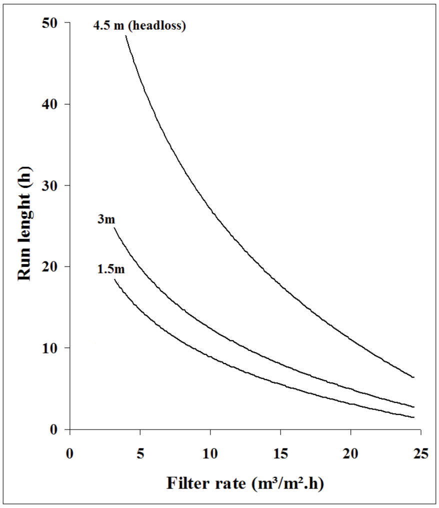
Run length

The length of the filter run depends on the filtration rate, SS content, size of the medium, terminal head loss, and desired quality of the effluent (EPA, 1977). Once a sand filter has been designed and implemented, the filtration rate and head loss control the length of the run. Usually, the run comes to an end when the head loss reaches a predetermined value (see Figure 5-7). For gravity filters, the acceptable design head loss value should be around 1.8-3 m. Pressure filters generally use a higher head loss. When coarse sand is used as a single filtration medium, the head loss may not be such a decisive factor. SS in the filtrated effluent should be monitored and solids breakthrough should indicate when to terminate a filter run (EPA, 1977). Practically, pilot studies should indicate the build-up of head loss with time for various filter rates and for a certain influent solids concentration (EPA, 1975).

5.2.3 Cleaning

Because of the large amount of SS and the presence of organic flocs, sand filters tend to clog rapidly. Rapid sand filters are generally cleaned by an upward flow of water, which fluidizes the filter bed. Such cleaning takes place between runs and is commonly called backwashing. If sand filters receive a high solids load, which stick tenaciously to the filter media, some auxiliary scouring methods or devices might be helpful to obtain a good cleaning. For instance, before backwashing, a concurrent wash with air and water above the fluidization velocity followed by a normal air scour (EPA, 1977).

FIGURE 5-7
RUN LENGTH VERSUS FILTER RATE FOR VARIOUS TERMINAL HEADLOSSES



Source: adapted from EPA, 1975

5.2.4 Overall Performances

For a particle size distribution around 1-3 mm and HLR of 2.5-8 m^3/m^2.h, a sand filter can remove 50-75% of SS (see Table 5-10). According to Middlebrooks et al. (2005), rapid sand filters have shown poor results in removing algae from WSP; the removal efficiency can improve by adding chemicals prior to filtration or pre-treating the wastewater by coagulation and flocculation. The performance of rapid sand filters in treating algae is mixed; it depends on the level of pre-treatment, HLR, time of year, particle size distribution of the sand, size and nature of the algae, and amount of coagulant used. Removals typically range from less than 20 percent to more than 70 percent (Crites and Tchobanoglous, 1998). Without coagulation, algae are too small, have a too low affinity for sand, and are not removed effectively by direct filtration.

TABLE 5-10
FILTRATION RESULTS FROM SECONDARY BIOLOGICAL TREATMENT

Type of Filter Influent source		Bed characteristics			HLR (m^3/m^2.h)	Suspended solids		
		Media	Size (mm)	Depth (m)		In (mg/L)	Out (mg/L)	Removal (%)
Pressure upflow	Activated sludge	Sand	1-2	1.5	8	17	7	60
Gravity downflow	Activated sludge	Sand	0.5-2.5	-	2.9-5.9	12	5	58
Gravity downflow	Trickling filter	Sand	1.1	-	2.5-7.3	20	5	75
Gravity downflow	Trickling filter	Sand	1.5-3	-	3.9-7.8	21	5	75
Upflow	Trickling filter + in line alum injection	Sand	-	-	7.3	40	21	48

Source: adapted from EPA, 1975

5.2.5 References

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6. INDIVIDUAL PROCESSES AND TECHNOLOGIES

6.1 Description

On-site sanitation is often (and should be) the first option for sanitation. Such systems have very distinct advantages, because they are individual systems that dispose of faecal material over a wide area, unlike conventional sewage treatment. One of the main disadvantages of centralized facilities is that when they go wrong, the resulting problems can be very acute. From a health point of view, there is not much difference between any of the different options for sanitation (either on- or off-site) — as long as they all work properly.

It is largely a question of convenience; an off-site system that flushes wastes off the owner's property is more convenient as it gets rid of the problem from the owner's property. Off-site sanitation is usually much more expensive than on-site. There are instances, however, where off-site sanitation is necessary — because of unsuitable ground or housing conditions, or because of a community's commitment to an off-site system. There is a certain amount of prestige in an off-site connection; peer pressure is often a significant motivating force. Once an off-site system has been chosen, sewers are necessary.

Water has a large dispersion, dilution, and carriage capacity, and is, therefore, used as the carriage medium in most sewers. Usually, toilets are flushed with potable water supplied to the house and as much as 40 percent of household water may be used for this. Some countries use dual supply systems where non-potable water (often sea water or natural water) is used to flush toilet, but such systems require more infrastructure and are more costly. Therefore, most sewers are heavy users of precious potable water, which is not good in water-poor areas.

Nowadays, in many countries, EcoSan (Ecological Sanitation) systems are more and more employed; these systems offer indeed many advantages in solving problems relating to environmental protection and sustainable development.

6.1.1 Definition

An onsite wastewater treatment/disposal system is the means by which an individual home or a cluster of homes cleans and disposes of its wastewater. This is usually known as a septic system. A conventional system consists of a septic tank for pre-treatment and a drain-field for disposing of the wastewater. Each system, however, must be designed according to specific site conditions to ensure proper treatment. In Vietnam or in developing countries, generally, there are other means besides septic tanks, such as *Pit latrine, Ventilated Improved Pit (VIP), Double Vault latrine and Ventilated Improved Double Pit (VIDP)* (see Table 6-1).

For biological treatment of less than 15 m^3/day of wastewater, the following facilities are used:

- Filtration trenches and underground filtration beds;
- Wetlands and constructed wetlands;
- Sand filtration beds;

- Oxidation ponds or channels;
- Biofiltration; and
- Filtration hole or well, for less than 1 m^3/day of wastewater.

TABLE 6-1
LATRINE TYPES FOR ON-SITE OPTIONS IN VIETNAM

Types	Name	Application conditions	Remarks
Dried Latrines	***Pit latrine and bucket latrine***	Used in mountains, highland zones where there is a lack of water and a low level of ground water	Unused in areas prone to flooding or next to water sources
	Ventilated Improved Pit / latrine/ (VIP)	Suitable for households in highland zones with a lack of water and low incomes	Used in small schools in highland areas
	Simple Latrine	Used for households with narrow land, lack of water or high level of ground water	Recommended to install ventilation pipe
	Ventilated Improved Double Pit (VIDP)	Used in residential zones with needs to fertilize for plantation or agriculture	Used for groups of households in common houses
Wet Latrines	***Sulab***	Used in zones with permeable soil, low population, no risk of ground water pollution, high income or relative high level of life, no need to fertilize for plantation	May be used in small clinics or schools located in areas rich in water.
	Septic Tank without filter	Used in the areas with water sources and high income (urban areas)	Outlet water from septic tank could be discharged to trench with gravels or ponds or to combined sewer
	Septic tank with aerobic or anaerobic filter	Used in areas with water sources, high income and enough space, good management conditions.	
	Anaerobic digestion	Used in areas with high income and livestock	

6.1.2 Dried processes (pit latrine, VIP, or ventilated improved double vault latrine)

Pit latrine

Until the end of the 19th century, urban areas in developing countries used pit latrines. At that time, water came from surface water or shallow wells and the risk of water pollution was real. Pit and sunken latrines are the simplest type of dried latrines, with a round or square-shaped surface. Faeces is stored in the excavation, which is reinforced by bamboo or wood in case of soft ground. The protruding part, with a reliable floor, conceals the excavation tightly; the toilet hole has a cover.

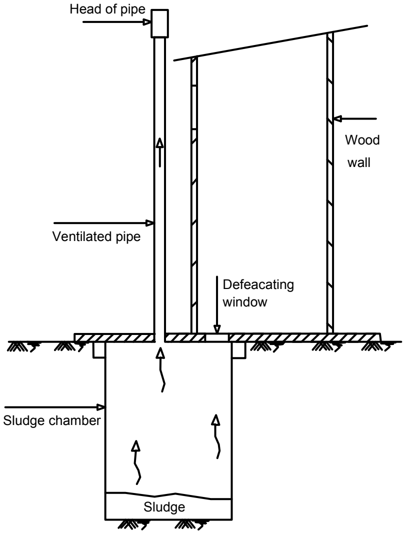
The latrine surroundings are enclosed with basic materials (no construction); it is not compulsory but better having roof for the latrine. After using the toilet, users put down ash and soil to overlay faeces. It is necessary to start a new excavation and move the protruding part to the new one when the old one is full.

Ventilated improved pit/latrine (VIP) (see Figure 6-1)

The first significant change to urban sanitation in developing countries came at the beginning of the 20th century with the introduction of the bucket latrine system. By the 1960-1970s, water pollution and hygiene were no longer a major concern in urban areas. Then the Ventilated Improved Pit/Latrine (VIP), Double Vault Latrine, and Ventilated Improved Double Pit/Latrine (VIDP) were introduced.

The latrine in Figure 6-1 is an improved dried and sunken latrine. This is a simple excavation or the soil surface, with the addition of a pipe for ventilation to reduce bad odours, improve evaporation, and prevent flies.

FIGURE 6-1
VENTILATED IMPROVED PIT/LATRINE (VIP)



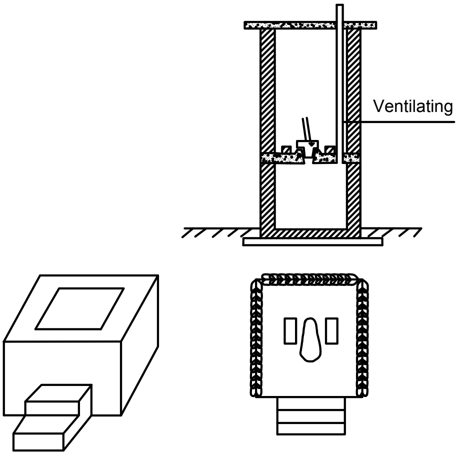
Ventilated Improved Pit with urine-separating toilet (see Figure 6-2)

One type of VIP is the urine-separating toilet, in which urine is collected separately and stored for about half a year before being used for agriculture.

Ventilated Improved Double Pit (VIDP) (see Figure 6-3)

The VIDP is almost the same as the VIP but with two separate chambers; while one is used, the other is used for faeces fermentation or composting. To remain in good working conditions, the chamber should stay dry and without flies. This latrine is a special type of dried latrine, for both toilet use and on-site faeces composting. This type of latrine uses each chamber one by one. When the first chamber is full, faeces from the first chamber is composted during six months and then used as fertilizer.

FIGURE 6-2
VENTILATED IMPROVED PIT

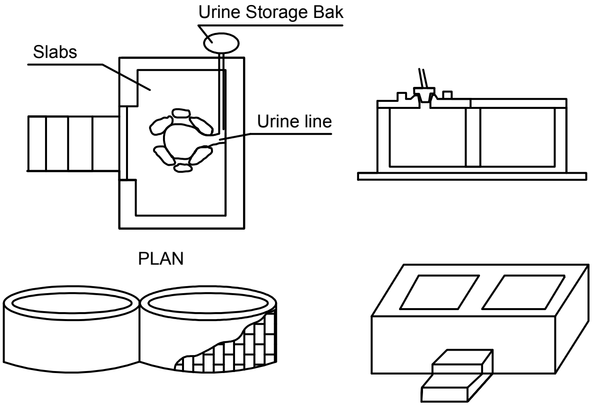


Space Schem of VIP

Plan

Elevated Urine –
Separating toilet in VN

FIGURE 6-3
VENTILATED IMPROVED DOUBLE PIT (VIDP)



Round VIDP

Rectangular VIDP

6.1.3 Wet processes (Sulab, septic tank without filter, septic tank with aerobic filter, baffle septic tank with anaerobic filter, filtration hole/well, filtration trench, biogas)

Sulab (see Figure 6-4)

This is the simplest type of wet latrine (firstly used in India meaning as sulab) users flush the toilet by hand, faeces is stored in a pit, and the liquid from the faeces tank goes to the ground automatically. The faeces tank is in the ground, with surroundings built (or supported by bamboo or wood) with tight cover and ventilation pipe. The walls and bottom are not enclosed and let the water go to the ground automatically.

The protruding part of all sulabs has the same structure: a sitting platform and a siphon (on the concrete floor) lead faeces into the storage tank. The protruding part can be set vertically on the storage tank. The siphon prevents odours from going up. After use, the toilet is flushed with water, faeces stays in the storage tank, and the liquid percolates to the ground gradually.

Septic tank without filter

Traditional Septic Tank

This type of latrine uses water to flush the toilet. Micro-organisms in the storage tank treat the wastewater. The sludge is stored and fermented in the tank; the liquid passes through the chambers and flows out. This is actually a *semi septic tank* because the treatment process is not thorough; it just keeps, ferments, and disintegrates sludge/sediment that does not dissolve and is easy to deposit. The sludge storage tank is underground and has two or three communicating chambers, with surrounding walls and bottom to keep the liquid inside the tank and prevent seepage into the ground. A ventilation pipe is located on the toilet roof. The part containing sludge/sediment is made of bricks, stones, concrete, or composite plastic.

After use, the toilet is flushed with water, faeces stays in the storage tank, and sediment/sludge fermentation and disintegration happen simultaneously. The liquid passes gradually to other settling chambers and then flows out into the filter chamber. If there is no filter chamber after the septic chamber, the liquid discharges into a filtering trench or the sewer (see Figure 6-5 b and Figure 6-5 c).

Double Floor Septic Tank

Double floor septic tanks are assembled Imhoft tanks (named by German creator), but smaller in size; they prevent gas bubbles to contact with resettled water, which improves the quality of effluent from the septic tank. Figure 6-6, Figure 6-7, and Figure 6-8 show three types of double floor septic tanks.

FIGURE 6-4
COMPONENTS OF SULAB

1- Toilet
2, 3 - Storage Chambers
4- Water tank

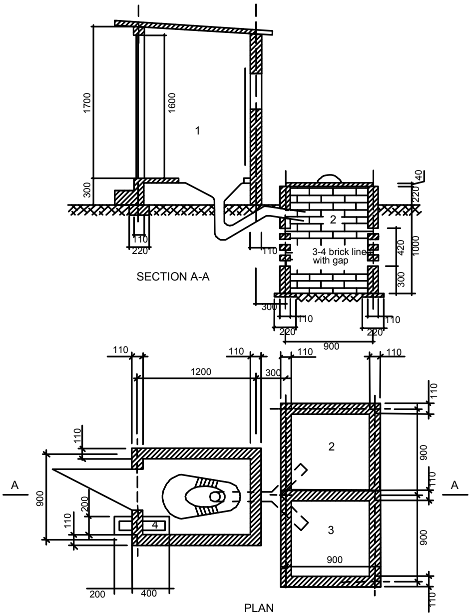


FIGURE 6-5
SEPTIC TANKS WITHOUT FILTER

a. With filtration hole; b. Effluent discharged into channel; c. Effluent discharged into sewer

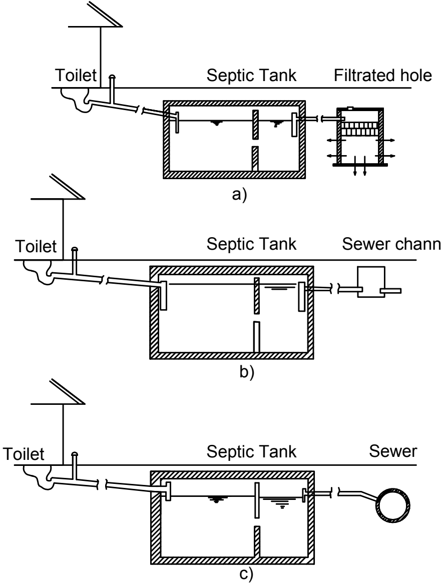


FIGURE 6-6
DOUBLE CEILING SEPTIC TANK (TYPE I)

a. One chamber; b. Two chamber;

1.Settling chamber; 2. Hole ; 3. Sludge discharged pipe; 4. Control pipe; 5. Gas pipe; 6. Fermentation chamber; 7. Wall; 8. Outlet pipe; 9. Inlet pipe.

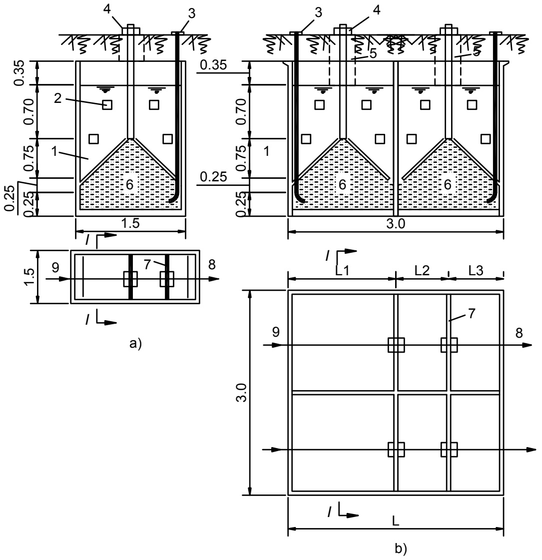


FIGURE 6-7
DOUBLE CEILING SEPTIC TANK WITH CONIC BOTTOM (TYPE II)
a. One chamber; b. Two chamber;
1. Settling section; 2. Hole; 3. Control pipe; 4. Sludge discharge pipe; 5. Fermentation part ; 6. Wall; 7. Outlet pipe; 8. Inlet pipe

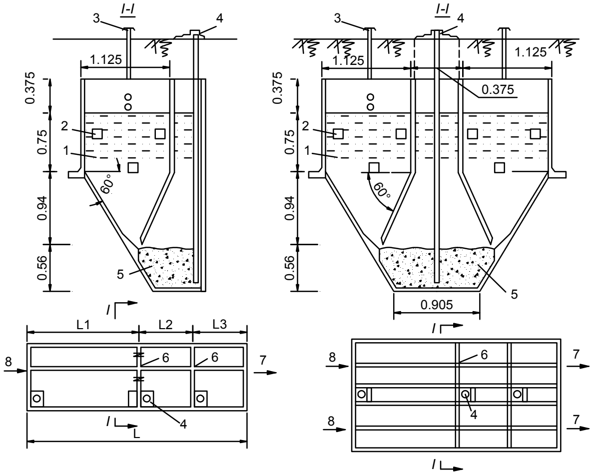
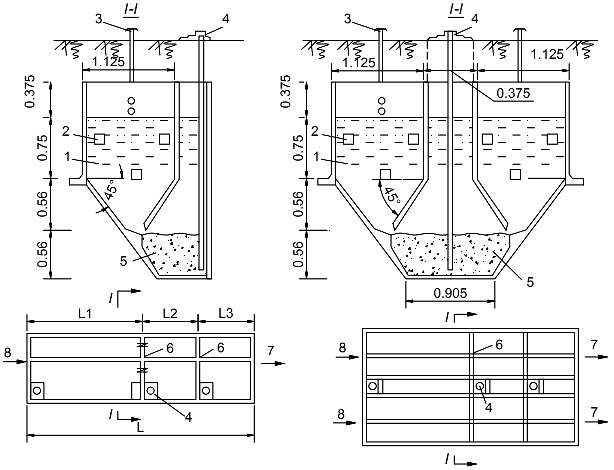


FIGURE 6-8
DOUBLE FLOOR SEPTIC TANK WITH PYRAMID BOTTOM (TYPE III)
a. One chamber; b. Two chamber;
1. Setlling section; 2. Hole; 3. Control pipe; 4. Sludge discharge pipe; 5.Sludge storing section; 6. Wall



Septic tank with aerobic and anaerobic filter

This is the best type of water flushing latrine; it is a septic tank (storage, settling and fermentation chambers) with a filter. Filter materials include charcoal, macadam, broken brick, gravel and soft materials, etc. --filters can be aerobic (see Figure 6-9) or anaerobic (see Figure 6-10). The faeces liquid goes to the septic tank after

settling and filtration and flows out. Such septic tanks are difficult to maintain because filters have to be changed periodically. This is why septic tanks are more popular than septic tanks with aerobic filters. Septic tanks with anaerobic filters are used to meet the requirement that the bottom of the discharge pipe be higher than the one on the street (see Figure 6-10).
Figure 6-11 shows a baffled septic tank with anaerobic filter (BASTAF).

FIGURE 6-9
SEPTIC TANK WITH AEROBIC FILTER

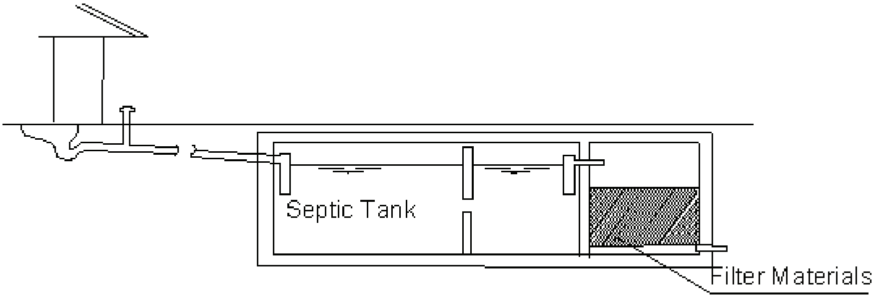


FIGURE 6-10
SEPTIC TANK WITH ANAEROBIC FILTER

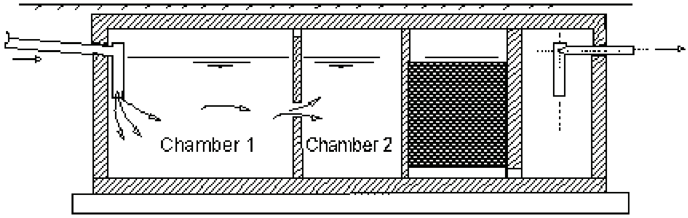
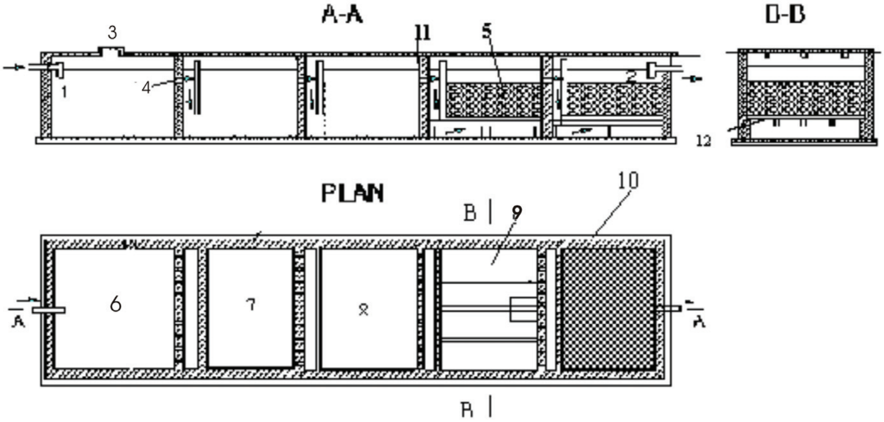


FIGURE 6-11
BAFFLED SEPTIC TANK WITH ANAEROBIC FILTER

1. Inlet pipe; 2. Outlet pipe; 3. Window for taking sludge; 4. Hole; 5. Filtration media; 6. Storage chamber; 7. Settling chamber; 8, 9, 10, 11. Filtration chamber 1, 2, 3, 4; 12. Ventilation window; 13. Cement concrete slabs



6.2 Use and performance

VIP: in general, a pit has a surface area of 0.8-1.0 m^2 and a depth of 1.0-1.2 m, (described on section 6.1.2). A concrete slab supports the seat and a pipe vents odours through the roof. If geological conditions are good, the pit may be underground; if not, the pit should be above ground. The walls of the pit are lined with bricks; the back wall of the pit has a door to empty fermented faeces. As mentioned above, in the 1960s, pits or latrines with urine separating toilets started to develop.

VIDP: bigger surface areas (1.2-1.4 m^2) than VIP, but about the same depth.

Wastewater treatment processes in septic tank

In septic tank occur the basic wastewater treatment processes: settling, sludge fermentation, and wastewater stabilization. The main sources of sewage and waste matters flowing to septic tanks are from toilets, bathrooms or kitchens. Because of the long residence time of liquids in the tank and slow stream velocity, most sediments stay in the tank. The removal of suspended solids in wastewater can reach 55 to 60 percent. Organic substances in the sludge will be fermented in anaerobic conditions during the retention time. Because the septic tank works in an unstable and no mixing environment, the fermentation in the tank is acid and generates gas bubbles of H_2S –that does not dissolve much-- and CH_4, --that does not dissolve at all. These gas bubbles rise to the surface, bring with them some SS together with some kinds of grease that stay in the wastewater and form scum on the surface. The scum gets thicker day after day and can contaminate back the wastewater.

6.3 Design criteria and materials

6.3.1 Septic tank

Traditional Septic Tanks (TST)

TST treat domestic wastewater from one or more households. The effluent from TST passes through filtration trenches, holes or wells, aerobic filtration bed soak-sand filtration, or oxidation ponds. TST have a volume of 1.5-25 or even 50 m^3; the inlet pipe should have a minimum diameter of 100 mm with a minimum slope of 0.03. The ventilation pipe should have a diameter of 75-100 mm. TST may have:

- One chamber when the amount of domestic wastewater (Q) is less than 1 m^3/day;
- Two chambers when Q is less than 10 m^3/day (first chamber takes place of 75% of total volume, second one 25%); and
- Three chambers when Q is less than 25 m^3/day (first chamber takes 50% of total volume, second and third take 25% each).

Table 6-2 shows the volume of TST depending on the number of households.

TABLE 6-2
VOLUME OF TRADITIONAL SEPTIC TANK

Number of Households	Volume of TST (m^3)
1 or 2	3.0
5 or 6	5.5
More	From 7.5 to 13

Septic tanks are usually made of bricks, reinforced concrete, composite, etc and have the shape of a square or circle. The tank has two or three chambers. The first chamber has a minimum width of 0.9 m and a minimum length of 1.5 m. The depth of the tank ranges from 1.2 to 1.8 m. Septic tanks should be easy to empty, chambers should have ventilation doors and the tanks should have ventilation pipes.

Septic tank capacity can be designed as follows:

- When the wastewater volume Q is less than 5 m^3/ day, the tank volume W is:

$$W= 1.5\ Q \qquad \textbf{(E. 81)}$$

- When wastewater Q is more than 5 m^3/day, the tank volume W is:

$$W = 0.75\ Q + 4.5 \qquad \textbf{(E. 82)}$$

The volume of sludge (W_0) is:

$$W_c = \frac{\left[a.T.(100 - P_1).b.c.N\right]}{\left[(100 - P_2).1000\right]} \qquad \textbf{(E. 83)}$$

Where:

- a = The amount of sludge per capita per day, a = 0.5 – 0.8 L/Cap.day;
- b = Coefficient of decreasing sludge volume in fermented storage chamber of TST, b = 0.7;
- c = Coefficient counting the amount of fermented sludge that should be rested after each empty (20%), c = 1.2;
- T = Time between two empties, T = 360 - 720 days;
- p_1 , p_2 = Humidity of fresh and fermented sludge, e.g., 95 and 90%;
- N = Number of served people.

The wastewater treatment facility after the septic tank can be an aerobic filter, anaerobic filter, soak well, underground trench filter, oxidation pond, circulating oxidation canal, etc. As the wastewater flow after the tank is relatively stable, the calculated flow in the coming facilities is usually the average flow. Under the country's weather conditions, sludges are fermented for three months. Therefore, sludges should be taken out of septic tanks after 3 to 6 months. Sludges left after each suck/empty make up 20 percent of the total sludge volume.

Double Ceiling/Floor Septic Tanks

Double floor septic tanks are assembled Imhoft tanks, but smaller in size. These tanks prevent gases bubbles to contact with the resettled water, which improves the quality of effluent from the septic tank. There are three types of double floor septic tanks (see Figure 6-6, Figure 6-7, Figure 6-8, Table 6-3, Table 6-4 and Table 6-5).

Double floor septic tanks consist of two parts separated by an inclined floor: the settling or clarified part is on top and the storage section is under the floor. The edge of the inclined floor lets the settled matter slip down to the storage section. The tank has a pipe to discharge the sludge. The diameter of the sludge discharge pipe is 150-200 mm. The inclined intermediary floor prevents gases from the fermentation section to go to the above clarified section and dissolve in the effluent.

Double floor septic tanks can be designed as follows:

- Useful capacity: at least equal 2.5 or 3 times the daily flow.
- Amount of settled daily sludge: 1.2 to 2 litres/capita. The humidity of the fresh sludge is 97.5%, of the fermented sludge 90-92%.
- Effect of organic sludge degradation: about 50%. Calculated sludge per capita per day: 0.1875 litre.
- Flow per capita: 150-200 L/d
- Number of people: 5 - 100
- Residence time in settling section: 1.5-2.5 days
- Volume of sludge fermentation section:

$$W_{Sludge} = \frac{0{,}1875.N.365}{1000} \quad \textbf{(E. 84)}$$

Where

- N = number of people

- Height of fermented sludge layer at the end of the calculated period of time:

$$H_{Sludge} = \frac{W_{Sludge}}{F} \quad \textbf{(E. 85)}$$

Where

- F = area of tank on plan.

- Volume of settled section is accepted no less than twice the daily flow.
- Useful height of the tank: 2.2-2.5 m
- Width of one unit: 1.5 m.

There are three types of double ceiling/floor septic tanks:

1. Type I (Table 6-3 - Figure 6-6) with a plate bottom and inclined floor of 45^0 (compared to horizontal plate) used to treat wastewater with soap.

2. Type II (Table 6-4 - Figure 6-7) with an inclined bottom and inclined floor used to treat domestic wastewater with soap liquid equal to 50% of total quantity of wastewater. This type is also used for both dry and wet soil foundation.

3. Type III (Table 6-5 - Figure 6-8) with an inclined bottom and inclined floor of 60^0 (compared to horizontal plate) used to treat domestic wastewater with soap liquid equal to 50% of total quantity of wastewater. This type is also used for both dry and wet soil foundation. Type III is also used to treat hospital wastewater.

For a wastewater flow less than 5 m^3/day, there should be one unit divided into 1-2-3 sections in series along the long flow in the tank. For a wastewater flow from 5 to 15 m^3/day, there should be two units. The size of the tanks and technological schemes are to be limited with multiple 10. For quick construction, it is recommended to produce in series with prefabricated concrete. The length of the tank is the changeable parameter

6.3.2 Septic tank with aerobic filter

The head chambers are as described in the TST above. The last chamber is an aerobic filter. The four filtration layers should be at least 600 mm (each layer 150 mm). The layers' materials are ground pieces of bricks or stones, gravels, coal, or plastic. The layers should have the following sizes (1 being the lowest to 4 the highest): Layer 1 (50 – 30 mm), Layer 2 (35 – 25 mm), Layer 3 (25 – 15 mm), and Layer 4 (15 – 10 mm).

6.3.3 Anaerobic filter and Baffled Septic Tank with Anaerobic Filter (BASTAF)

Anaerobic Filter: the structure of layers is the same as for aerobic filters. The only difference is that the outlet pipe is higher than the surface of filtration media layers.

BASTAF: F/M = 0.24 - 0.31 g COD_{in}/g VSS.d and Organic Load Ratio (OLR) = 0.35 – 0.92 g COD/L.d. The average effectiveness is as follows: $BOD_{5\ total}$ (64.39%), COD_{total} (64.71%), and SS (78.84%). Parameters to be selected for BASTAF are as follows:

- Upflow velocity in the chambers: v = 0.3 m/h
- Hydraulic residence time in sediment-storage chamber: 12-24 h
- Hydraulic residence time in baffled chamber: 36 –48 h
- Hydraulic residence time in anaerobic filter: 12 – 24 h

Table 6-6 shows the determination of BASTAF volume depending on the number of served people.

To treat black water from WC, the following BASTAF scheme is recommended:

Storage and settling chamber ---→ 3-4 Anaerobic chambers ---→ 2 Anaerobic filters with coal ash media.

TABLE 6-3
TECHNOLOGICAL PARAMETERS AND SIZES OF DOUBLE FLOOR SEPTIC TANKS -- FIRST TYPE

Number of people (N)	Average daily flow Q (m^3)	Volume of settled section W_{set}, (m^3)	Volume of fermented section $W_{Ferment}$ (m^3)	Volume of float scum W_K, (m^3)	Total useful volume W_t, (m^3)	K –Hydraulic residence time (days)	Number of chambers (n_K)	L	l_1	l_2	l_3
Double floor septic tank- one unit											
5	0.75	1.5	0.375	0.563	2.81	3.75	1	1.0	-	-	-
30	4.5	9.0	2.10	3.2	16.40	3.64	3	5.6	2.8	1.4	1.4
Double floor septic tank- two units											
40	6.0	12.0	2.76	4.12	21.64	3.62	3	3.7	1.7	1.0	1.0
80	12.0	24.0	5.55	8.35	43.45	3.62	3	7.4	3.7	1.85	1.85
100	15.0	30.0	7.10	10.6	54.80	3.65	3	9.4	4.7	2.35	2.35

Source: Vacilenco, 1974

TABLE 6-4
TECHNOLOGICAL PARAMETERS AND SIZES OF DOUBLE FLOOR SEPTIC TANKS - SECOND TYPE

Nbr of people (N)	Average daily flow (Q, m^3)	Vol. of settled section W_{Set}, m^3	Vol. of fermented section $W_{Ferment}$ (m^3)	Vol. of float scum W_K, (m^3)	Total useful volume W_t, (m^3)	K –Hydraulic resident time (days)	Nbr of chambers (n_K)	L	l_1	l_2	l_3
Double floor septic tank- one unit											
5	0.75	1.265	0.147	0.715	2.397	3.2	1	1.1	-	-	-
30	4.5	7.65	2.42	4.30	14.37	3.2	3	6.6	3.3	1.65	1.65
Double floor septic tank- two unit											
40	6.0	12.0	2.76	3.64	18.40	3.07	3	5.2	2.6	1.3	1.3
80	12.0	24.0	5.50	8.40	37.90	3.15	3	10.4	5.2	2.6	2.6
100	15.0	30.0	6.8	10.4	47.2	3.15	3	12.8	6.4	3.2	3.2

Source: Vacilenco, 1974

TABLE 6-5
TECHNOLOGICAL PARAMETERS AND SIZES OF DOUBLE FLOOR SEPTIC TANKS – THIRD TYPE

Number of people (N)	Average daily flow (Q, m^3)	Volume of settled section W_{set}, m^3	Vol. of fermented section $W_{Ferment}$ (m^3	Vol. of float scum W_K, (m^3)	Total useful volume W_t, (m^3)	K –Hydraulic resident time (days)	Number of chambers (n_K)	L	l_1	l_2	l_3
Double floor septic tank- one unit											
5	0.75	1.23	0.41	0.81	2.45	3.23	1	0.9	0.9	-	-
30	4.5	7.45	2.45	4.9	14.8	3.28	3	5.45	2.25	1.1	1.1
Double floor septic tank- two unit											
40	6.0	14.4	2.76	6.05	23.21	3.88	3	5.2	2.6	1.3	1.3
80	12.0	28.6	5.53	12.3	46.43	3.86	3	10.4	5.2	2.6	2.6
100	15.0	35.7	6.9	15.2	57.8	3.86	3	13.0	6.5	3.25	3.25

Source: Vacilenco, 1974

TABLE 6-6
DETERMINATION OF ANAEROBIC FILTER AND BASTAF VOLUME DEPENDING ON THE NUMBER OF SERVED PEOPLE

Number of people (N)	Average daily flow (Q) L/day	Water from WC Q_{WC}, L/day	Volume of settled chamber (V) L	Number of anaerobic chambers	Total volume of anaerobic chambers L	Number of Anaerobic Filters	Total volume of anaerobic Filters L	Total useful volume W_t, (m^3)	Total useful vol. V_{tot} (m^3), (in accounting with vol. of baffled channels)	Per capita Volume (m^3/cap)
4	600	160	427	4	427	2	213	1.07	1.49	0.37
10	1500	400	1067	4	1067	2	533	2.67	3.73	0.37
20	3000	800	1600	4	2133	2	1067	4.80	6.72	0.34
100	15000	4000	5333	3	8000	2	5333	18.67	26.13	0.26

Source: ANH N.V, NHUE T.H., 2001

6.3.4 Filtration Hole/Well

Filtration holes/wells filter wastewater through sand and gravel layers and anaerobically disintegrate organic substances absorbed in the sand and gravel layers. After treatment, wastewater percolates to the ground and stays there for a long time, which eliminates all kinds of pathogens. To keep the hole operating, wastewater must be treated in septic tanks. Filtration holes are used only when ground water is deeper than 1.5 m to ensure the penetration effect and prevent ground water pollution. The soil permeability should be between 34 L/m^2.day and 208 L/m^2.day. Figure 6-12 shows a filtration hole, with a circular shape and a minimum diameter of 1.2 m, made of bricks or reinforced concrete. Filtration holes/wells can be made of well pipe too. The well's concrete wall has a minimum thickness of 100 mm and lays on a strong concrete foundation. The well's area depends on the types of soil and water discharge.

FIGURE 6-12
DETAIL OF FILTRATION HOLE/WELL

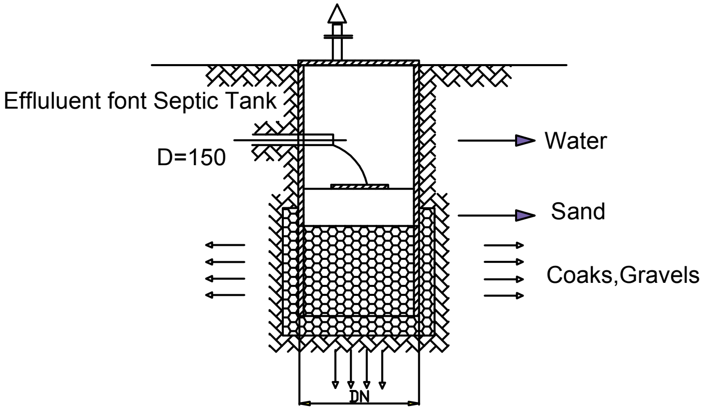


Table 6-7 shows the filtration area needed for one person. Filtration wells are filled in with gravel, macadam, etc that are smaller from beneath to above. The upper most layer is filled in with fine sand and protected from erosion by the covered material. To increase the well's water permeability, gravels are added around the well. Cleaning and clearing are done through a water discharge pipe or separated ventilation pipe.

TABLE 6-7
FILTRATION AREA NEEDED BASED ON LOADING UNIT AREA

Soil type	Loading per unit area (L/m^2.day)
Sand	80
Clayish sand	40

6.3.5 Underground trench

Underground trenches are suitable for areas with high ground water tables where it is not possible to build soak wells. Wastewater must be preliminary settled by mechanical treatment before going through underground trenches. The soil of underground trenches will absorb dirt from wastewater during filtration and then oxidize it biologically. Aerobic oxidation usually occurs in the top soil layer while the anaerobic respiration of organic substances happens in the layer below. As the soil layer is relatively thin (from 0.6 to 0.9 m), tree roots absorb a large volume of wastewater and only a small volume of water flows. The activities of the plants also contribute to the supply of oxygen to the ground.

Table 6-8 shows the design parameters of underground trenches. The useful area of underground trenches depends on the type of soil.

TABLE 6-8
PARAMETERS OF UNDERGROUND TRENCH DESIGN

Design parameter	Value	
	Minimum	Maximum
Number of water pipelines	1	
Length of each pipeline, m	-	30
Width of trench bottom, m	0.46	0.9
Distance between pipelines, m	1.8	-
Thickness of top soil layer above the pipe, mm	300	-
Slope of trench, mm/m	Horizontal	25
Thickness of filter materials under water pipe, mm	300	-
Thickness of filter materials above water pipe, mm	50	-

As shown in Figure 6-13, underground trenches include a wastewater distributing system and a water collecting system. Underground trenches have a ventilation pipe. The distribution system is located inside the trench, 1 m minimum from the ground water level. Figure 6-14 shows an onsite sewage treatment system with a septic tank and underground trench.

FIGURE 6-13
FILTRATION TRENCH FOR SEWAGE TREATMENT

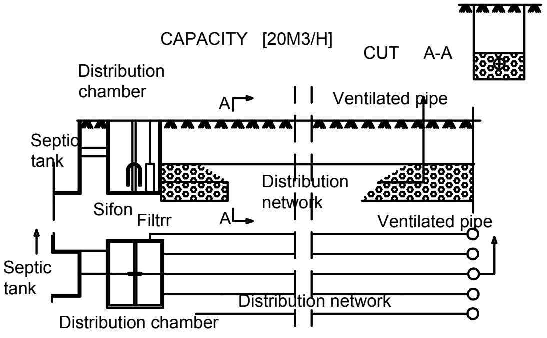
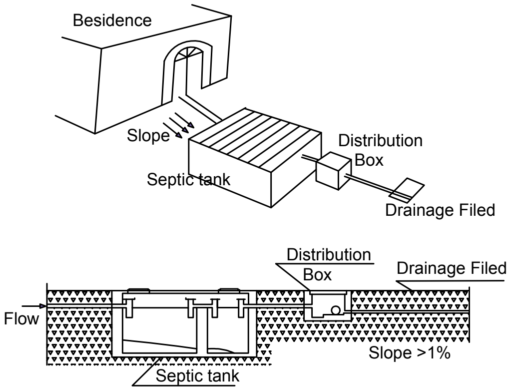


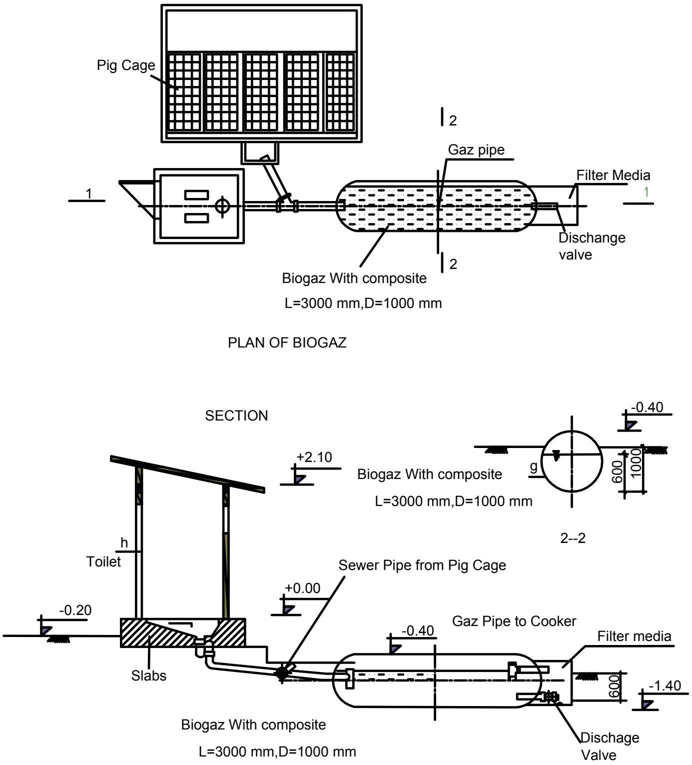
FIGURE 6-14
ONSITE SEWAGE TREATMENT BY SEPTIC TANK AND TRENCH FILTRATION SYSTEM



6.3.6 Anaerobic digestion

In developing countries there are many pig farms. Anaerobic digestion can treat sewage from these farms (see Figure 6-15). Biogas is produced and can be reused to produce energy.

FIGURE 6-15
ANAEROBIC DIGESTION SYSTEM



6.4 Ecological Sanitation

The new approach for sanitation is to develop systems that would save water, prevent water pollution, and recycle the nutrients of human excreta. These new solutions should also save money and optimise the financial resources in cities, towns. *This new approach is called “ecological Sanitation” or “Eco-San”.*

Ecological Sanitation is based on three fundamental principles:

1. Preventing pollution rather than attempting to control it after we pollute;
2. Sanitising the urine and faeces; and
3. Using safe products for agriculture.

Urine and faeces are separated, stored, and processed, and then, if necessary, further processed off site until they are free of disease organisms. The nutrients in the excreta are then recycled in agriculture. An essential part of eco-san is to separate and contain human excreta (urine and faeces) before they are recovered and reused. Usually human faeces contain agents of diseases more than urine. So the faeces are to be treated by dehydration and decomposition.

Dehydrating or drying faeces is easier if they are not mixed with urine and water. When faeces are decomposed or anaerobically fermented, the pathogens in them, such as viruses, bacteria and worm eggs die and are broken down or destroyed. Only theses faeces can be recycled.

Urine is usually safe enough for agriculture without further treatment, or only after a short period of storage. Urine contains a lot of nitrogen, phosphorus, and potassium, and could act as valuable fertiliser.

Ecological sanitation closes the loop of nutrients contained in wastewater with agriculture. Besides providing adopted technology solutions, it also contributes to local food security, which is important in many developing countries. *Ventilated Improved Pit with urine-separating toilet (see* Figure 6-2*) and Ventilated Improved Double Pit (VIDP) (see* Figure 6-3*) in Vietnam, and then in China and many other developing countries are examples of eco-san.*

Countries, such as Sweden and Nordic countries, have developed different kinds of urine separating toilets, composting toilets, and urine storage. Eco-San offers many advantages to the environment, agriculture, households, families, and municipalities. In an ecological sanitation system, a separation and effective anaerobic treatment of these wastes is to be implemented. So, it is not only producing energy in the form of biogas, but also ensuring a hygienic nutrient reuse and protecting water resources.

It is possible to digest faeces in a biogas digester. Urine does not produce any biogas. Therefore, source separation could be a valuable solution to upgrade sanitation systems.

Unlike conventional sanitation systems, ecological sanitation controls the direct hygienic risks to the population and protects the natural environment. In making the organics, nutrients and trace elements available to agriculture, soil fertility is preserved and long-term food security is safeguarded.

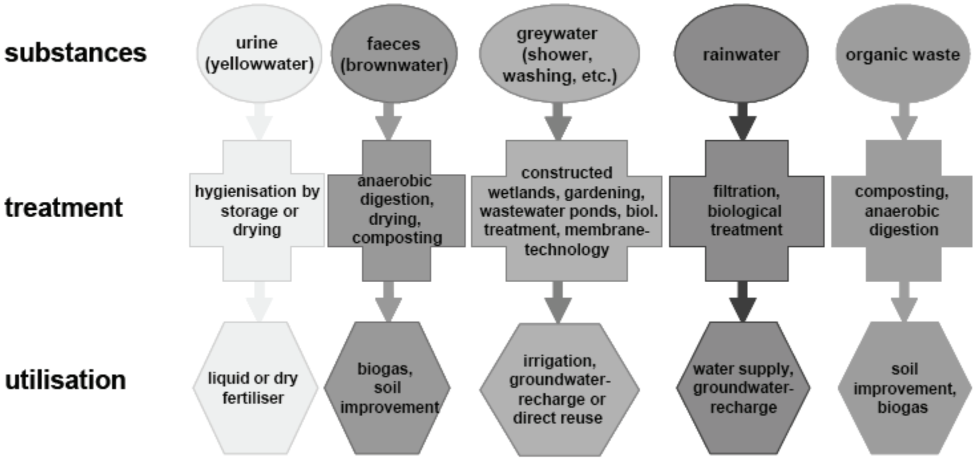
In practice, the commonly applied ecological sanitation strategy of separately collecting and treating faeces, urine and grey water minimises the consumption of valuable drinking water and enables treatment of the separate wastewater flows at low cost for subsequent reuse in soil amelioration, as fertilizer, as service or irrigation water or for groundwater recharge.

Sustainable ecological sanitation restores a significant natural balance between the quantity of nutrients excreted by one person in one year and that required to produce their food, and therefore can greatly help in saving limited resources.

Ideally, sustainable ecological sanitation could recover all of nutrients, trace elements and energy contained in household wastewater and organic waste, and their productive reuse in agriculture. By this way, they support preserving soil fertility and safeguarding long-term food security.

Heinz-Peter Mang has carried out ecological sanitation in China and has shown good experiences in separating substances (see Figure 6-16).

FIGURE 6-16
SEPARATION OF SUBSTANCES AND EXAMPLES OF POSSIBLE ECOLOGICAL SANITATION ELEMENTS



Source: Heinz-Peter Mang

Waterless toilets with urine separation are installed in households and for the public. The faeces are preferably powdered with ash after defecation and collected in containers or digestible bags placed in a dry fermentation plant with biowaste, manure and other digestible biomass from the community and agriculture; a preliminary hygienisation through a pH increase and drying takes place. Urine is collected separately in containers and stored. Urban households have very little garden and the need for fertilizer is minimal, therefore it is feasible to incorporate farms, a flower producers or urban landscaper for biomass delivery. These enterprises at the same time have a fertilizer demand and therefore can use compost: organic compounds for soil improvement and nutrients for plant growth.

In practice, the collected and partly dried and hygienised faeces are mixed with other organic substrates suitable for dry digestion (grass cuttings, plant waste, manure, straw, bio waste, food waste). The substrates complement each other in their qualities; through co-digesting all the substrates together, an optimal fermentation takes place. Important parameters for dry fermentation are: organic dry substance, pH value, C/N ratio, Redox potential, volatile fatty acids, moisture content, “acidity and alkalinity“, substrate structure. Dry fermentation, as the core part of the system is hygienising, homogenising and producing compost, which is used in the fields and gardens in a small closed loop for nutrients and organic matter. Biogas can be used directly for burning (cooking, lighting, heating cooling) or in a cogeneration plant for power and heat production. The additional liquid phase of urine is collected and stored for six months for sanitation and can be used as additional fertiliser. If urine is needed, locally collected grey water and rainwater can serve as process water for flooding or percolation. The authors also conducted an *experience in improving fertiliser value of compost by enriching with urine* in China and concluded that:

Enriching compost from easy biodegradable organic household waste or from human excrements improve the nutrient content of the compost. Technologies and experience confirm this fact. Calculations in China proved the market value of stored treated liquid urine as fertiliser.

6.5 Operation and maintenance

To operate and maintain wastewater treatment facilities, see Table 6-9.

TABLE 6-9
OPERATION AND MAINTENANCE OF WASTEWATER TREATMENT FACILITIES

Facility	Operation and Maintenance
1. Pit Latrine	▪ Tidy up regularly, put on the lid after toilet use. ▪ When the old pit is full, start the new one and compost the old one. ▪ Check regularly the steadiness of the supporting floor and sitting cover to avoid a broken supporting floor. ▪ Only use fertilizers that have composted for a long time (6 months to 1 year).
2. VIP: Simple	▪ Tidy up regularly, put on the lid after toilet use. ▪ Check regularly the steadiness of the supporting floor and sitting cover to avoid a broken supporting floor. ▪ Check the tightness between the floor slab and faeces storage pit. ▪ Maintain, inspect, and clean ventilation pipe ▪ Only use fertilizers that have composted for a long time (6 months to 1 year).
3. VIP: Urine Separating with Bricks	▪ Tidy up regularly, put on the lid after toilet use. ▪ Continue using after taking out all the faeces when the tank is full, covering tightly the faeces tank door. ▪ Maintain, inspect, and clean ventilation pipe ▪ Only use fertilizers that have composted for a long time (6 months to 1 year).
4. VIDP	▪ Tidy up regularly, clean the floor, and put on the lid after use. ▪ Store enough padding agent (ash, sawdust, powder soil, etc). ▪ Do not use two chambers at once. ▪ Do not let urine flow to faeces chamber. ▪ Compost faeces for 6-12 months.
5. Sulab	▪ Have enough water to flush the toilet. ▪ Tidy up regularly, clean the floor, and keep tightly covered. ▪ Prevent blocking siphon, leaks ▪ Keep the storage tank tightly
6. Traditional Septic Tank	▪ Use enough water to flush the toilet. ▪ Tidy up regularly, clean the floor. ▪ Prevent blocking siphon, leaks ▪ Suck sediment / empty sludge periodically. ▪ Keep toilet paper in place to prevent blocking siphon.
7. Double Floor Septic Tank	as above
8. Septic Tank with Aerobic Filter	as above and periodically wash filtration materials

Facility	Operation and Maintenance
9. Septic Tank with Anaerobic Filter and BASTAF	as above and periodically wash filtration materials

6.6 Unit cost assessment

TABLE 6-10
UNIT COSTS OF INDIVIDUAL WASTEWATER TREATMENT FACILITIES

Facility	Unit cost (US$/m^3)	Life span (years)	Emptying frequency (years)
1. Pit Latrine	10 – 15	10-15	0.5
2. VIP Simple	30 – 60	20-30	0.5
3. Urine Separating with Bricks	32- 65	20-30	0.5
4. VIDP	60 – 90	20-30	0.5 – 1
5. Sulab	35 – 60	15-20	1
6. Traditional Septic Tank	80 – 120	30 and more	0.5 – 1
7. Double Floor Septic Tank	90 – 130	30 and more	0.5 – 1
8. Septic Tank with Aerobic Filter	100 – 150	30 and more	Wash filter media
9. Septic Tank with Anaerobic Filter	110 – 160	30 and more	Wash filter media
10. Other biological facilities	90 – 100	20 and more	

6.7 Human resources

TABLE 6-11
HUMAN RESOURCES

Facility	Level of skill
1. Pit Latrine	Low
2. VIP Simple	Low
3. VIP : Urine Separating with Bricks	Low
4. VIDP	Low
5. Sulab	Low
6. Traditional Septic Tank	High
7. Double Floor Septic Tank	High
8. Septic Tank with Aerobic Filter	High
9. Septic Tank with Anaerobic Filter	High

6.8 Environmental impact (positive and negative)

TABLE 6-12
ENVIRONMENTAL IMPACT

Facility	Advantages	Disadvantages
1. Pit Latrine	▪ Simple structure; ▪ Easy to build, low investment cost; ▪ Home-made built; ▪ Operates without water, easy to collect faeces, cattle hardly approach faeces, etc.	▪ Only storage, no treatment; ▪ High risk of transmitting disease; ▪ Bad odour and flies; ▪ Need to build latrine far away from homes and water supply sources; ▪ High risk of polluting water supply and soil; ▪ Inadequate construction could result in broken supporting floor likely to injure users; ▪ When the pit is full, need to bring faeces to treatment and build new excavation.
2. VIP Simple	▪ Prevents cattle and flies from approaching faeces, reduces bad odour; ▪ Simple structure, easy to build; ▪ Low investment cost, home-made built; ▪ Operates without water; ▪ Easy to collect faeces, to used urine –separating toilet; ▪ Can be easily changed to sulab toilet if conditions are suitable.	▪ Only storage, no treatment; ▪ High risk of transmitting disease; ▪ Bad odour and flies; ▪ Need to build latrine far away from home and water supply sources; ▪ High risk of pollution for ground water and soils.
3. Urine Separating with Bricks	▪ Simple structure and low cost that the residents can build themselves; ▪ Does not take much space; ▪ Steady and safe to use and control; ▪ No pollution of soil and ground water; ▪ Longer lifespan of latrine because no renewal when the tank is full; ▪ Little odour if good maintenance; ▪ Prevents cattle and flies from approaching faeces; ▪ Meets fertilizer demands.	▪ Only storage, no treatment; ▪ Risk of transmitting disease; ▪ Bad odour and flies; ▪ Need to treat/compost faeces when tank is full; ▪ High risk of polluting environment in case of bad maintenance.
4. VIDP with Bricks	▪ Simple low-cost structure that residents can build themselves; ▪ Does not take much space; ▪ Suitable and safe for depression and flooding area; ▪ Steady and safe to use and control; ▪ Dry, clean, less odour and flies, and no pollution of air, soil, and ground water; ▪ Longer lifespan of latrine because of continuous use; ▪ Good treatment if well maintained; ▪ Meets fertilizer demands.	▪ Must be built according to technical instructions (urine-separating); ▪ Need to store enough padding agent (ash, charcoal, etc); ▪ Need to use and maintain latrine appropriately; ▪ High risk of pollution if poorly maintained.
5. Sulab	▪ No flies, bad odour; ▪ Convenient, clean, can be built inside the house;	▪ Needs water to flush and toilet paper; ▪ Toilet building requires highly

Facility	Advantages	Disadvantages
	▪ Does not need much water; ▪ Steady and safe to use and control; ▪ Longer lifespan of toilet; ▪ No bad odour if properly maintained.	skilled workers; ▪ Waste of faeces source; ▪ High investment cost and complicated maintenance; ▪ Not suitable for areas needing fertilizers.
6. Traditional Septic Tank	▪ Convenient, clean, can be built inside the house; ▪ Preliminary treatment of domestic sewage; ▪ No flies and bad odour; ▪ Little impact on water sources.	▪ Needs water to flush and toilet papers; ▪ Toilet building requires highly skilled workers; ▪ High investment cost and complicated maintenance; ▪ Need to empty sludge periodically.
7. Double Floor Septic Tank	as above	as above
8. Septic Tank with Aerobic Filter	as above	as above
9. Septic Tank with Anaerobic Filter	as above	as above
10. Biogas	as above	as above

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7. NATURAL TECHNIQUES FOR SLUDGE TREATMENT

7.1 Introduction

Surplus sludge generated from biological and chemical wastewater treatment needs further management before it can be finally disposed or used as an agricultural resource. Traditional sludge dewatering practices reduce its volume, increase its dry matter content, and consequently minimise transportation and management costs. Several successful and well-documented methods are available, but their capacity and operation vary, as well as the level of technological sophistication, infrastructure requirements, and needs for operational labour skills.

The first three sludge dewatering systems in Table 7-1 produce sludge of similar dry matter content. These systems generally require the addition of conditioning chemicals (e.g. coagulants and/or polyelectrolyte), the input of energy, and the operations require highly qualified personnel. The latter two systems are considered low technological solutions because they consume less energy and are relatively simple to construct and operate. Drying beds and planted beds for sludge dewatering and mineralization systems can also stabilise, even mineralise the sludge, and therefore produce a final product that can be safely disposed or used for agricultural purposes. Additionally, as released water from the sludge percolates through the bed, the systems can reduce the typical high concentrations of COD and BOD by 60%, nitrify up to 80%, and reduce enterobacterias by 2 to 3 orders of magnitude (Heinss and Koottatep, 1998).

TABLE 7-1
DEWATERING POTENTIAL OF VARIOUS SLUDGE THICKENING SYSTEMS

Dewatering method	*Centrifuge*	*Filter belt press*	*Filter press*	*Sludge Drying beds*	*Planted beds for sludge dewatering*
% Dry matter	23 (15-20[a])	24 (15-20[b])	32	10[b]	30 - 40

[a] Normal observed values
[b] Value dependent on treatment duration
Source: modified from Nielsen, 2003

7.1.1 Definition and types of sludge

Sludge is the semisolid by-product of wastewater treatment that contains the compounds removed from wastewater and those that are added during the process. Sludge from wastewater includes primary and secondary sludge depending on where it was produced during treatment. These two types of sludge have different characteristics due to do the nature of the solids that they contain.

Primary sludge comes from primary treatment, for example from a sedimentation tank designed to remove inorganic particles (sand or grit) as well as some dense organic and colloidal particles that can precipitate from raw wastewater. The amount and characteristics of primary sludge depend on the sedimentation tank's capacity and hydraulic performance and on the quality of the influent water.

Secondary sludge comes from secondary treatment (biological) and results from the conversion of organic compounds and substrates to biomass and microorganisms.

Secondary sludge may also contain solids, which were not removed during primary treatment. The quantity and characteristics of the sludge vary depending on the process used, the efficiency of the primary treatment, the organic matter concentration of the water, and the local climatic conditions. In general, secondary sludge has high organic concentration, low relative density made up by flocculent particles, and low concentrations of inorganic solids. Due to its inherent characteristics, secondary sludge is more difficult to treat.

Combined sludge comes from wastewater treatment systems that do not use primary settling; it has the mixed characteristics of primary and secondary sludge. Treatment of combined sludge is difficult since the sludge characteristics vary; therefore, there is no standard protocol for treatment.

Chemical sludge results from the chemical treatment of wastewater and contains salts, polyelectrolyte, and chemicals used to enhance the removal of solids and precipitate nutrients. The characteristics of the chemical sludge depend on the precipitation agents used for treatment, the treated water quality, and the operation parameters of the plant.

7.1.2 Sludge characteristics

The general characteristics of sludge are physical, chemical, and biological.

Physical characteristics include solid content, volatile solids, and particle size distribution. The solid content is the solids dry weight divided by the total weight of sludge. Volatile solids (VS) measure the content of organic matter in the sludge by gravimetric methods. The VS are determined by bringing a weighted dry sample to a temperature of 550°C to volatilise the organic material. The particle size distribution describes the granulometry of the sludge, which affects the tendency of the sludge to retain water.

Chemical characteristics mostly depend on the wastewater origin; they describe the chemical compounds in the sludge and indicate the potential for sludge reuse after stabilisation. The common parameters analysed are odour, organic material, and metal content. If reuse is expected, additional compounds such as nitrogen, phosphorous, specific metals, and possible toxic compounds should be evaluated so that the final product can comply with local regulations.

Biological characteristics determine the pathogens in the sludge, which is expensive and difficult as it implies identifying viruses, bacteria, protozoan, and helminths that might cause diseases. If reuse is the goal, the detection of certain pathogens can be mandatory.

Sludge treatment is necessary for health, environmental, and economic reasons. Sludge can be a serious health hazard since it contains a wide variety of pathogens and risky substances that can affect the population exposed to the material. Raw sludge also produces unpleasant odours and is a potential source of vectors. Therefore, it is necessary to immobilise pathogens and control substances. Volume reduction may also be necessary to reduce costs and make reuse economically attractive.

7.1.3 Types of natural sludge treatment systems

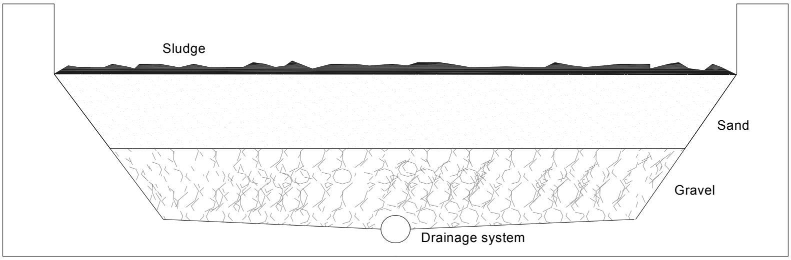
Process levels can be described by the solid concentration of the sludge. Sludge thickening is mostly *in-situ*, generally with technical systems, to remove some liquid and increase solid concentration to around 5%; the sludge retains its “liquid characteristics”. Sludge dewatering removes more water to increase solid concentration to at least 20%. The resulting sludge is expected to behave like a solid. Dry sludge has very low water content; depending on the treatment selected and sludge characteristics, 100% of the water can be removed. Sludge stabilisation transforms biological solids to non-cellular products. Natural sludge treatment systems improve the quality of the product, reduce the potential drawbacks of sludge, and produce a final product that can be safely reused; they include drying beds, composting, land application, planted reed bed systems, sludge drying lagoons, and lime stabilisation.

Sludge drying beds

Sludge drying beds built on sand filters have been operational for several decades; they are considered relatively easy to operate and to design and can produce a stable dewatered final product (WEF, 2003). They are recommended for small facilities and can be used under most climatic conditions. Although they require large areas and intensive labour, they are economically competitive in places where land and labour are affordable.

Sludge is mainly dewatered by drainage and evaporation of the liquid phase; water is freed from the sludge by gravity, percolates through the sand to the bottom of the bed, and is collected and removed from the bed via underlaid pipes. Some of the sludge water that cannot percolate will form a supernatant that along with the precipitation can be evaporated. The sludge will accumulate on top of the bed with a dry matter content of around 10% (WEF 2003), depending on the duration of the drying process. Figure 7-1 shows a diagram of a typical sludge drying bed.

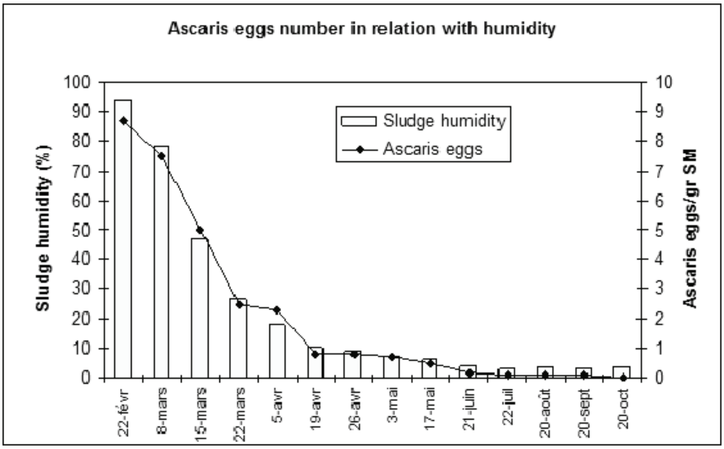
FIGURE 7-1
SLUDGE DRYING BED



Walls with enough freeboard (0.5 to 0.9 m) to stock up the sludge should enclose the sludge drying bed. The bottom layer of the bed consists of coarse gravel (3-25 mm in diameter), of a depth of 200 to 500 mm, to enclose the drainage system. On top of the gravel and separated by geotextile, the system has a sand layer of 200 to 500 mm filled with clean, hard, durable sand with granulometry between 0.3 and 0.8 mm and recommended uniformity coefficient of ca. 3.5 but no higher than 4.0. The drainage system has perforated pipes of at least 110 mm in diameter made of inert material (vitrified, PVC, etc.) and placed across the bed with a downward slope of no less than 1% to allow rapid and effective collection and drainage of released water. The sludge pumped or transported to the drying bed has to be distributed uniformly on top of the surface and fill the entire bed. A typical system consists of several beds that are loaded sequentially to allow sufficient time for effective water drainage and drying. The number and size of beds depend among others on the size of the wastewater treatment system, the physical-chemical properties of the sludge, and the local climatic conditions.

Additionally to dewatering, while the sludge is spread on the surface of the beds and as water is drained, the loss of humidity contributes to the death of pathogens in the sludge. Tests conducted at Ouarzazate in Morocco (Xanthoulis, 1996) show that the eggs of parasites disappear completely from the sludge after 8 months in the drying beds (Figure 7-2). This sludge has been spread in a layer of 400 mm in thickness. As the parasite eggs are the most time resistant, the standards for faecal coliforms and Salmonella will comply.

FIGURE 7-2
EVOLUTION OF SLUDGE HUMIDITY AND NUMBER OF ASCARIS EGGS



Rem.: gr = gram

Composting

Composting is an aerobic process where organic solids are biodegraded into carbon dioxide and water (IWA, 2006) and as a result produce a stable material (compost) that can be used as an agronomical and soil amendment. The reactions that occur in composting generate relatively high temperatures that have to be maintained throughout the process if good quality compost is desired. Composting is an alternative to stabilize sludge and can produce a useful material and reduce pathogens. Composting requires some preparation and relatively high labour input. Since sludge has a high water content, before the actual composting begins, the sludge requires dewatering and conditioning by adding a bulking agent (wood chips, straw, solid organic waste, etc.) to increase the solid fraction of the sludge to at least 35% (Ministry of environment and energy, 1996).

The most common composting methods are aerated static piles, turn piles, and closed systems. Aerated static piles are stacks of prepared sludge of ca. 2.0 m in height where air is mechanically injected through pipes under the piles. Composting requires sludge preparation, structures, and equipment. To maintain good porosity and facilitate air transfer; a layer of porous wood chip is placed between the aeration system and the sludge pile. The air is injected intermittently to prevent cooling the pile and affect composting. Turn piles is similar; conditioned sludge is piled on stacks of 1.0 to 2.0 m, but the air is drawn in by mixing and turning the sludge stacked in the piles (Crites *et al.,* 2006). This method generates obnoxious odours. Closed systems are closed vessels, mostly used to overcome unfavourable climatic conditions and to optimise the processes where composting operation parameters are controlled.

Depending on the climatic conditions, as well as the sludge characteristics and the composting method used, the process takes between 4 and 8 weeks. After sludge stabilisation, additional storage time is needed for maturing and drying. The storage time has economic and operational implications; the longer the residence time, the larger the facilities should be.

Land disposal

Land disposal consists in applying sludge (liquid, dewatered, or dry) on the soil surface or buried for agricultural use, and for forest and restoration purposes. Surface application generally involves spreading liquid sludge on the soil surface by pressurized aspersion, drainage into furrows or spreading with hoses. Dewatered sludge can be either buried or ploughed in the soil. Dry sludge can be in bags or bulk and applied on the surface either manually or mechanically.

Land application of sludge for agriculture can reduce the amount of fertilizer used by farmers and improve soil conditions. Local laws regulate land application of sludge for agriculture; in general, they limit the metals concentrations that can be applied and may also limit and restrict pathogens and organic compounds for ground water protection. For land application, liquid sludge might be preferred, if permitted, since the nutrient concentration in dewatered and dry sludge is lower.

Planted reed beds for sludge dewatering and mineralization

Planted drying beds can be categorised as a water-solid separation technology, which contribute to an effective dewatering of sludge and additionally produces a mineralised product that can be used as a soil amendment product and as a potential source of nutrients for agriculture. As the result of research in several countries there are several technological options for planted dewatering systems. The principal characteristic is the combined use of plants and gravel-sand filled beds that are loaded with sludge sequentially to allow the physical-chemical and biological processes to dewater and stabilise the sludge. Traditionally, the selected plants for this type of systems have been reeds (*Phragmites australis*), but other helophytes are likely to be used. German documented experiences include also the use of grass planted beds denominated humification beds (More information in Pabsch, 2004).

Planted reed beds for sludge dewatering and mineralization consist of several filled gravel vegetated beds, where sludge is distributed evenly on the surface. The vegetation, soil, sun, and gravity separate solids and liquids from the sludge. The solid fraction of the sludge stays on the surface of the bed while some of the water is drained and trickles down through the gravel. After each load, a dewatering period is allowed before a new layer of sludge is discharged on top of the dewatered sludge. This process continues until the bed is filled with dewatered sludge and has to be emptied (after about 10 years). The water drained from the sludge percolates through the sand and gravel; the prevailing oxic conditions in the non-saturated filter and the filtering effect of the media reduce the concentration of pollutants in the released water, which is sent back to the wastewater treatment plant for treatment.

The dewatering occurs as the water drains from the sludge by gravity. Further dewatering involves the release of capillary water. Simultaneously, the sludge volume is reduced due to the loss of water (drainage and evapotranspiration) and the mineralization of the organic matter in the sludge making the sludge a safe and homogenous material. The dewatering process of the sludge is further optimised by the contribution of the plants. The continuous growth of the reeds and the aggregated mechanical effect of the wind on the stems of the plants causes that new pathways for water drainage are created and consequently increase the drainage of water and counteract clogging.

FIGURE 7-3
EFFECT OF PLANTS ON THE SURFACE OF A PLANTED REED BED FOR SLUDGE DEWATERING AND MINERALIZATION

The design and operating scheme of a system depend on several factors, including the nature and biological, chemical, and physical characteristics of the sludge. Other factors include local climatic conditions, the volumes of sludge to be treated, water discharge requirements, the sludge's final use, and the local regulations for these types of systems.

Figure 7-4 shows a diagram of a typical bed. The bed includes an impermeable basin to host the bed, plants, several layers of specific types of gravel, sand and soil, distribution system, a drainage system, and a passive aeration structure to maintain the airflow to the bottom of the bed and the media. Any system should have several (a minimum of eight) beds to alternate the loading and provide enough time between loadings so that the biological and physical processes can take place and avoid clogging the beds. Each bed requires emptying after a period of operation of about 10 years, after which the bed can be reloaded (Nielsen, 2003).

FIGURE 7-4
PROFILE OF A PLANTED REED BED SLUDGE MINERALIZATION SYSTEM

The figure shows the components of the system

There are three periods in the operation of a planted reed bed system. During start-up (about two years), sludge loading should be less than the designed loading. After start-up, the plants are fully developed and the bed can be loaded with the designed load. In the third period (after about eight years of operation), the beds are emptied to remove accumulated dewatered sludge. The beds that need emptying (maybe two out of eight) will not be loaded during the (dry) summer period to maximise dry matter content of the sludge. The beds are then emptied successively; depending on the needs and number of beds, it will take about four years. Once the bed is empty, a new start-up period begins (see Figure 7-5). The construction and operation of planted reed beds are relatively inexpensive and do not require highly qualified staff; reed beds are robust and can handle varying qualities of sludge.

These systems are used widely and successfully in temperate climates, where they have been thoroughly documented. Applications in subtropical and tropical areas are not as common, however, and therefore there is very little information available. These systems are likely to perform better in warmer climates due to the more benign and stable temperatures, which should accelerate the rate of biological processes and avoid fluctuations that can affect these processes.

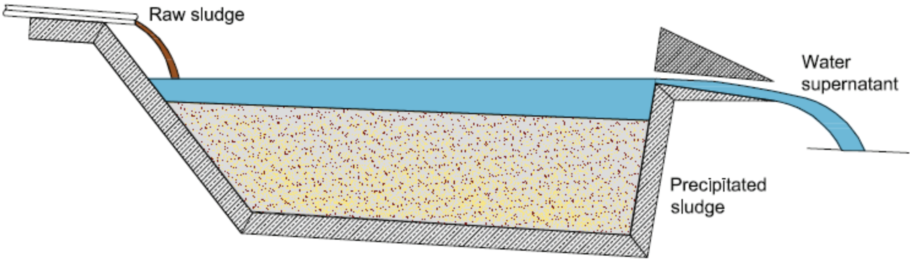
FIGURE 7-5
LOADING OF PLANTED REED BED AFTER SLUDGE HAS BEEN REMOVED

In the background, an empty bed and beds with fully-grown plants.

Sludge drying lagoons

In sludge drying lagoons, sludge from wastewater treatment is simultaneously stored, dewatered, and dried (see Figure 7-6). Gravity and flow separate, settle, and consolidate the solid component of sludge in the bottom. The process requires a relatively long residence time of the sludge in the lagoon. As the solids precipitate and consolidate on the bottom of the lagoon, the supernatant from the lagoons is removed continuously and/or intermittently, and the evacuated water is sent back to the head of the wastewater treatment plant for treatment. Once the consolidated solids retained on the bottom of the lagoon reach a predetermined height, the lagoon is drained and the solids are dried (Peavy *et al* 1986). Once the sludge is sufficiently dry, it is removed form the drained lagoon and properly disposed.

FIGURE 7-6
SIDE VIEW OF A SLUDGE DRYING LAGOON



A sludge drying lagoon typically consists of a lined basin (permeable basins can pollute ground water) that can store sufficient sludge, and with hydraulic conditions to facilitate sludge precipitation. Since sludge drying lagoons require resting periods to allow the sludge to dry, more than one sludge drying basin must be built. The number and dimensions of basins depend on the characteristics and volume of the sludge and the climatic conditions of the site.

Lime Stabilization

Lime stabilization controls nuisances such as odour and bacteria removal. Additionally, chemical stabilization improves the sludge condition so further dewatering and treatment can be effectively performed. Stabilization involves adding alkaline products (e.g., lime) to increase pH for sufficient periods to inactivate micro-organisms and therefore limit producing odours and avoid attracting vectors. Additionally, lime can act as a bulking agent and enhance sludge dewatering.

Some of the design considerations include the sludge characteristics and volume, contact time, pH and temperature, alkaline chemicals selected for stabilization, blending methods, and testing. Lime can be injected as liquid or added as dry lime in the form of pellets or powder. Chemical dosages depend on the feeding system, sludge volume and characteristics, and desired sludge quality. Continuous testing can determine further chemical dosing adjustment and sludge quality optimization.

7.1.4 Climatic considerations and operational site requirements

Due to the operating principles of extended sludge treatment processes, the magnitude of the surface required for treatment depends on the climatic conditions of the place of establishment. Further adaptations due to the climate may be needed during the operation to optimise the quality of the final product.

7.2 System design considerations

7.2.1 Sludge quality and characterisation

Sludge disposal is one the most expensive operations in wastewater treatment. Additionally, the disposal and the reuse of sludge for agriculture are increasingly restricted by regulations and controls on discharges and reuse of biological material. Therefore, it is important to properly treat and condition sludge when designing and operating a wastewater treatment system.

Sludge from wastewater treatment includes the suspended solids and materials in wastewater and depends highly on the wastewater origin. Besides the typical organisms of biological treatment (activated sludge), the sludge includes chemicals added during treatment. To calculate the amount of sludge generated by the wastewater treatment plant, a good approach is to do a solid mass balance for all of the operations of the wastewater treatment plant. The mass balance should include the transformations in the process that can affect the total amount of solids. Some of the parameters to take into account include BOD_5, total suspended solids, flow, recycling schemes, nitrogen and phosphorous balances, and chemicals added during treatment. Computing a precise sludge mass balance during the design stage is difficult and some adjustments will be necessary once the plant begins operation. According to Spinosa L. and Vesilind P. A. (2002), the sludge produced from typical domestic wastewater is about 0.25 kg/m^3 of wastewater treated --more details from Metcalf and Eddy (2002).

The characteristics of the sludge vary from place to place as well as the rate at which sludge can release water. Sludge amounts depend on the place of origin (primary or secondary, see Table 7-2), the technology used for treatment and operating schemes, the type of water (percentage of industrial wastewater), chemical precipitants and coagulants used during treatment, and the local climatic conditions and hydraulic operating cycles.

TABLE 7-2
PRIMARY AND SECONDARY SLUDGE CHARACTERISTICS

Parameter	Primary sludge Concentration dry-weight basis	Secondary sludge Concentration dry-weight basis
Total solids (TS), %	2.0 - 8.0	0.4 - 1.2
Total volatile solids, % of TS	60 – 80	60 - 85
Grease, % of TS	5.0 - 8.0	5 - 12
Phosphorous, % of TS	0.8 - 2.8	1.5 - 3.0
Proteins, % of TS	20 – 30	32 - 40
Cellulose, % of TS	8 – 15	
Nitrogen, % of TS	1.5 - 4.0	2.4 - 7.0
pH	5.0 - 8.0	6.5 - 8.0

Source: modified from WEF, 2003

Sludge production volume and characteristics ultimately depend on the water origin and the type and efficiency of the wastewater treatment process. The quantity of solids on a dry mass basis for primary sludge can be estimated by the following equation:

$$M_{ps} = \xi.TSS.Q \quad \textbf{(E. 86)}$$

Where:

- M_{ps} = total dry mass of primary solids [kg/d]
- ξ = efficiency of the primary treatment
- TSS = total suspended solid in the effluent [kg/m^3]
- Q = flow rate [m^3/d]

Production of biosolids form the secondary treatment can be estimated by the following equation:

$$M_{SS} = \gamma.BOD_5.Q \quad \textbf{(E. 87)}$$

Where:

- M_{ss} = total dry mass of primary solids [kg/d]
- γ = factor that relates BOD_5 incorporated in the system into biomass [kg/kg]
- BOD_5 = BOD_5 removed by the secondary treatment [kg/m^3]
- Q = flow rate [m^3/d]

7.2.2 Treatment selection

The treatment system should have the flexibility to handle the volumes of sludge produced, including possible operational peaks, and not always use the entire capacity. The system should also produce a final product with aggregated value so that the treated sludge is a resource and final disposal is not an economic and environmental burden. Odour generation is often one of the usual complaints, so some odour control and/or plant isolation is recommended. The sludge treatment technology selected should be limited to the level of treatment needed.

7.2.3 Site selection

Sludge treatment systems for economic and environmental reasons are often located within or close to wastewater treatment systems. Some sludge treatment systems are designed to handle the sludge generated from more than one wastewater treatment plant and their location will highly affect sludge transportation costs.

7.2.4 Sludge reuse

Raw sludge should not be freely disposed of in the environment since there is a risk of transmitting diseases associated with the pathogens in the sludge. Even if the sludge has been treated and biologically stabilized, it may require additional treatment before it can be reused or disposed. If metals and toxic compounds are present, the sludge might not be suitable for reuse or even sent to a disposal site (e.g., landfill, incinerator). The final fate of the sludge depends on the local regulations for disposal. The most common practices for sludge reuse are land application (land disposal) and the use of composted sludge (see Section 4.1.3).

Land application of sludge for agricultural purposes, is the disposal of sludge at rates that can benefit the vegetation. These rates depend on the plant’s nutrient needs (forage crops and/or forests), the soils, and the possible effect on the surrounding ecosystem.

Composted sludge has been successfully used as soil conditioner in agriculture, horticulture, and forest management. Compost provides nutrients to the soils; due to its high organic carbon, it benefits the soil structure by increasing soil aeration, water percolation, and root growth. Before use, composted sludge should be analysed for pathogens that could harm workers handling the sludge; composting is expected, however, to eliminate this threat. Another concern when using composted sludge is the presence of heavy metals and toxic compounds.

Another sludge reuse alternative is the application of sludge for environmental rehabilitation (e.g., mines, highway landscaping, and landfill covers).

If high concentrations of metals or toxic compounds restrict the reuse of sludge, sludge has to be disposed of in a landfill or incinerated. Sludge disposed of in a landfill might have high concentrations of metals and care must be taken so that leachate does not pollute ground water. Incinerating sludge requires energy and therefore is expensive; given that some metals and toxic substances can also volatilise, gases from the incinerator have to be treated (Hammer M.J, 1995).

7.2.5 Excess water treatment

Water content in the sludge varies significantly depending on the types of sludge and processes. Any sludge treatment process generates excess water. The sludge's origin and characteristics determine the quality of excess water, which can contain high concentrations of pollutants. Water drained from the sludge is collected and treated if the sludge treatment is located within the wastewater treatment plant. The ideal solution might be to collect and pump back the excess water to the start of the process and mix it with the raw wastewater. If the sludge system is decentralised, a plant for treating the released water may be needed.

7.2.6 Odour control

Raw sludge from wastewater has a characteristic strong odour that depends on the type of sludge, the level of sludge treatment, and the local climatic conditions. Anaerobic organisms mostly generate odours; to avoid unpleasant odours, sludge should be under aerobic conditions, which means that the sludge treatment should not be overloaded. Another passive measure to minimise the impact on the community involves isolating the site by planting trees in buffer zones.

7.3 Location and establishment

7.3.1 System layout and size

The surface area needed and system layout and size depend on the sludge treatment selected, the amount and type of sludge to be treated, and the local climatic conditions.

7.3.2 Environmental impact

Like any other project, the construction of a sludge treatment facility requires an environmental impact study. The nature of the process is likely to generate some local community resistance. Therefore, the community should participate in the environmental assessment.

7.4 Costs

According to Peavey et al (1986), the construction of sludge disposal facilities may represent between 40 to 60% of the construction costs of a wastewater treatment systems. Aggregated to the capital cost, the operating costs of sludge management might account for as much of 50% of the total operations costs of the wastewater treatment plant and as such, this should be budgeted in the total operation costs.

7.4.1 Capital costs

Capital costs include the costs of designing the system and the costs of the materials used for constructing the system. Since costs change from place to place, the evaluation should use local prices and a detailed breakdown of all the expenses generated by the entire process; extrapolating costs and expenses from other sites is likely to generate errors.

7.4.2 Operation and maintenance (O&M) costs

O&M costs also depend on local economic conditions. Most O&M costs for sludge management are labour related and depend on local wages. Operation includes quality follow up and flow control. Maintenance includes pumps and hydraulic structures maintenance, weed control, plague control, aesthetic maintenance, signs, and fencing.

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8. REUSE OF TREATED WASTEWATER

8.1 Introduction

Wastewater reclamation and reuse for agricultural (e.g., crop irrigation), industrial (e.g., cooling water), residential (e.g., sanitary flushing) or urban (such as for park irrigation) purposes, is an excellent way to preserve and extend existing water supplies and is becoming more and more frequent throughout the world (see Table 8-1). The main objective of treated wastewater reuse is to provide more water by speeding up the natural cycle of water to ensure the stability of the water cycle and protect the environment.

TABLE 8-1
APPLICATIONS FOR REUSING TREATED WASTEWATER

Category of reuse		Examples of applications
▪ Urban	Unrestricted	Landscape irrigation of parks, playgrounds, school yards, golf courses, cemeteries, residential, green belts, snow melting
	Restricted	Irrigation of areas with infrequent and controlled access
	Other	Fire protection, disaster preparedness, construction
▪ Agricultural	Food crops	Irrigation for crops grown for human consumption
	Non-food crops and crops consumed after processing	Irrigation for fodder, fibre, flowers, seed crops, pastures, commercial nurseries, sod farms
▪ Recreational	Unrestricted	No limitation on body contact: lakes and ponds used for swimming, snowmaking
	Restricted	Fishing, boating, and other non-contact recreational activities
▪ Environmental enhancement		Artificial wetlands creation, natural wetland enhancement, stream flow
▪ Ground water recharge		Groundwater replenishment for potable water, salt water intrusion control, subsidence control
▪ Industrial		Cooling system water, process water, boiler feed water, toilets, laundry, construction wash-down water, air conditioning
▪ Residential		Cleaning, laundry, toilet, air conditioning
▪ Potable reuse		Blending with municipal water supply, pipe to pipe supply

Source: Asano and Levine, 1998

8.2 Types of reuse

8.2.1 Agricultural reuse

The major type of wastewater reuse is agricultural reuse. Treated wastewater has a fertilizer contribution because it contains a certain amount of nitrogen, phosphorus, potassium, organic matter, and other valuable micronutrients required for agricultural crops. Thus, wastewater reuse for crop irrigation increases yields and benefits farmers.

Wastewater quality parameters

Parameters of health significance

There are two kinds of health hazards associated with direct and indirect wastewater use:

1. Health and safety of those working on the land or living on or near the land where the water is used; and

2. Risk that contaminated products from the wastewater use area may subsequently infect humans or animals through consumption or handling of the foodstuff or through secondary human contamination by consuming foodstuffs from animals that used the area (WHO, 1989).

Two types of contaminations constitute health hazards:

1. The possible accumulation of certain toxic elements (organic and inorganic) of wastewater (e.g., heavy metals, pesticides, nitrates, and other toxic elements) in plants and the intake of potentially toxic material through eating the crops irrigated with contaminated irrigation water (FAO, 1992); and

2. The presence in wastewater of pathogenic viruses, bacteria, protozoa and helminths that may subsist in the environment for long periods of time, which is a great health concern (see Table 8-2). The most common pathogenic parameters tested out for wastewater reuse are faecal coliforms (*Escherichia*, *Enterobacter*, *Klebsiella*, etc.) and intestinal nematodes eggs (*Ascaris*, *Trichuris* and hookworms).

In case that the irrigation in not conducted in the best way clean water can be polluted. Irrigation can be used with wastewater (quite) free of pathogens (See: Regulations and guidelines for reuse of wastewater).

Parameters of agricultural significance

To protect plant health and crop yields, the physicochemical quality of treated wastewater used for irrigation should comply with FAO's recommendations. For agricultural reuse, only a few parameters are generally considered:

TABLE 8-2
SURVIVAL OF EXCRETED PATHOGENS AT 20-30°C

Type of pathogens	Survival times in days*			
	In faeces, night soil, and sludge	In fresh water and sewage	In soil	On crops
Viruses				
Enteroviruses	< 100 (< 20)	< 120 (< 50)	< 100 (< 20)	< 60 (< 15)
Bacteria				
Fecal coliforms	< 90 (< 50)	<60 (<30)	< 70 (< 20)	< 30 (< 15)
Salmonella spp.	< 60 (< 30)	<60 (<30)	< 70 (< 20)	< 30 (< 15)
Shigella spp.	< 30 (< 10)	<30 (<10)	-	< 10 (< 5)
Vibrio cholerae	< 30 (< 5)	<30 (<10)	< 20 (< 10)	< 5 (< 2)
Protozoa				
Entamoeba histolytica cysts	< 30 (<1 5)	< 30 (< 15)	< 20 (<10)	< 10 (< 2)
Helminths				
Ascaris lumbricoides eggs	Months	Months	Months	<60 (<30)

* Figures in brackets show the usual survival time in days.
Source: Feachem & al., 1983

- *Electrical conductivity* (EC)

EC expressed in milliSiemens per centimetre or deciSiemens per metre at 25°C measures total dissolved solids and gives a precise idea of the salinity hazard. Excessive salt concentrations reduce crop yields. The accumulation of salt into the soil depends on the quality of the irrigation water. There are two types of electrical conductivity: EC_w is the electrical conductivity of the irrigation water and EC_e is the electrical conductivity of the soil saturation extract.

- *Sodium absorption ratio* (SAR)

High sodium concentration can modify the physical structure of the soil and affect the infiltration rate of water into the soil (reduces permeability). The effect of sodium also depends on calcium and magnesium concentrations. When sodium is present in the soil in an exchangeable form, it can replace calcium and magnesium cations and induce slaking of aggregates and dispersion of clay particle. A follow-up of exchangeable sodium present in the soil is consequently required for a sustainable management of the soil quality. SAR measures the relative sodium concentration and sodium hazard of irrigation water as follows:

$$SAR = \frac{Na}{\sqrt{\frac{(Ca + Mg)}{2}}} \quad \textbf{(E. 88)}$$

Where Na, Ca, and Mg are in milli equivalents per litre [me/L]

SAR represents Na^+ in the irrigation water and relates to ESP (Exchangeable Sodium Percentage) which represents Na^+ in the soil:

$$ESP = \frac{Na.100}{\sum cations} \qquad \textbf{(E. 89)}$$

Where:

- Na = Concentration of Na^+ [me/100gr]
- $\Sigma\ cations$ = Sum of concentrations of all cations [me/100gr]

- *Nitrogen (NO_3-N)*

Nitrogen can affect and reduce crop yield if the concentration is too high. Most crops are not affected by concentrations up to 30 mg N/L, but some susceptible crops can tolerate only up to 5 mg N/L.

- *Phytotoxic ions*

The most common phytotoxic ions in treated wastewater that can cause toxicity are boron (B), chloride (Cl), and Sodium (Na). *Boron* (B) can be toxic if its concentration is too high. Some plants such as lemon or blackberry are very sensitive to boron and do not tolerate concentrations above 0.5 mg/L. *Chloride* (Cl) is taken up by the crop and accumulates in the leaves; if its concentration in the leaf is too high, it can dry the leaf tissues or burn the leaves.

- *pH*

The normal irrigation range is from 6.5 to 8.4. A pH value outside this range means that the water quality is non-standard.

- *Trace elements and heavy metals*

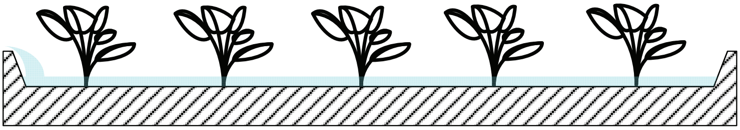
A trace element is a chemical element whose concentration is usually less than a few mg/l in common irrigation water. Heavy metals are included in trace elements. Heavy metals have densities higher than four times the density of water. Living organisms require trace amounts of some heavy metals, but excessive levels can be detrimental to the organism and may cause health hazards. A particular attention should be paid to heavy metals because they can get in food through plant uptake.

Irrigation system

The systems and methods to irrigate crops can be organized into five different classes depending on how and where the water is applied:

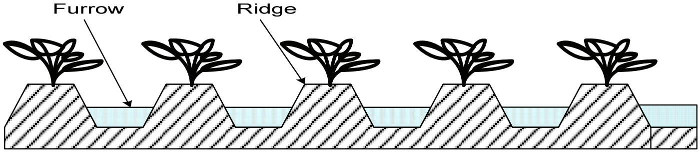
<u>Flood irrigation</u>: it may be the easiest and most common method to irrigate crops. Water is applied over the entire field, flows along the ground among the crops, and infiltrate into the soil (see Figure 8-1).

FIGURE 8-1
FLOOD IRRIGATION



Furrow irrigation: furrows are parallel channels between ridges that carry irrigation water into the field (see Figure 8-2). The water is applied in the furrows and the water reaches the plant roots located in the ridges by capillary movement.

FIGURE 8-2
FURROW IRRIGATION

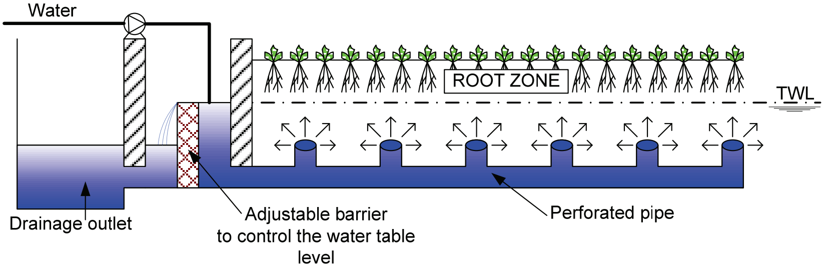


Sprinkler irrigation: sprinkler irrigation is like watering your lawn at home, spraying water in all directions with a hose (see Figure 8-3). A sprinkler is a pressurised nozzle that sprays the water in the air and let if fall down on the crop like rainfall. The flow rate has to be adjusted not to pond the surface of the field. A sprinkler system can have one or more sprinklers, connected to a main pipe which brings the irrigation water. Sprinkler irrigation is largely used, but this system often loses a lot of water to evaporation.

FIGURE 8-3
SPRINKLER IRRIGATION USED WITH WASTEWATER FROM AGRO-FOOD INDUSTRY (I.E. WITHOUT PATHOGEN)

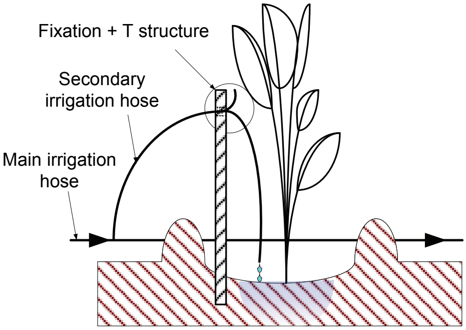
Sub-irrigation: water is applied beneath the root zone to artificially raise the water table level and wet the root zone by capillary movement (see Figure 8-4). Sub-irrigation can be performed by burying a pipe into the ground just under the root zone.

FIGURE 8-4
SUB-IRRIGATION SYSTEM SKETCH



Drip irrigation: water is delivered locally and slowly at the base of plants; it only wets the root zone, but keeps fruits and stems away from any contact with irrigation water (see Figure 8-5). This irrigation method minimises water losses due to percolation, runoff, and evaporation.

FIGURE 8-5
DRIP IRRIGATION SYSTEM (WITH ADJUSTABLE HEIGHT TO REGULATE THE IRRIGATION WATER FLOW RATE)



Crop Selection

Salinity management

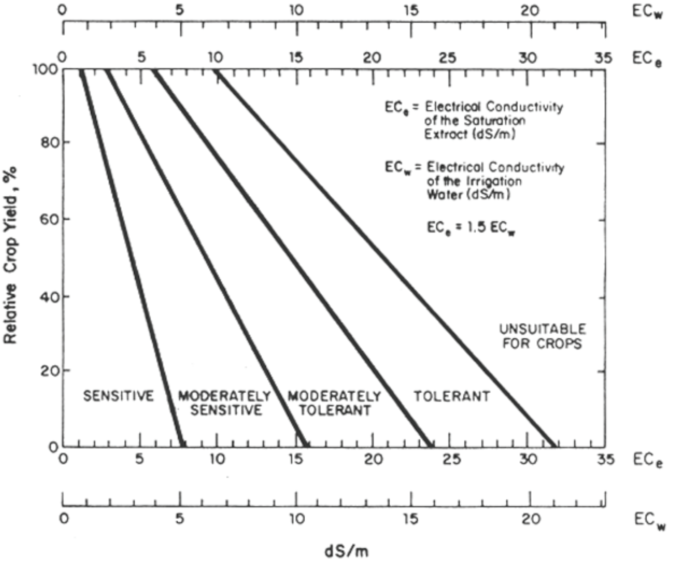
Salt accumulation reduces crop yields and may lead to total loss and uncultivable fields, if not controlled. Appropriate drainage and leaching can control salt accumulation into the root zone. Drainage is the ability of a soil to remove excess water. A poor drainage and hot climatic conditions can lead to soil salinisation. When the water table is shallow, ground water may rise into the root zone by capillarity and transport salts to the surface. The crops then use that water and evaporate it at the surface, thus accumulating salt into the soil. An appropriate drainage system can solve this salinisation problem by helping to control the level of the water table. Leaching is the process by which salts are washed out from the root zone into a lower layer of soil. Sometimes, it is necessary to apply more irrigation water onto the field than what the crops need. This excess water percolates through the root zone and removes the salts which have accumulated. For a selected crop, knowing the crop tolerance to soil salinity and the irrigation water salinity, it is possible to estimate the leaching requirements.

Salt sensitivity and tolerance vary from a plant to another. There are four classes of crops depending on their relative sensitivity or tolerance to salinity:

1. Sensitive (Bean, carrot, onion, …);
2. Moderately sensitive (Rice, sugarcane, cabbage, potato, …);
3. Moderately tolerant (Soybean, artichoke, wheat, …); and
4. Tolerant (Asparagus, barley, sugar beet, …).

Maas (1984) presented a relationship between relative crop yield and electrical conductivity of the soil saturation extract for various crop sensitivity classes (see Figure 8-6). Here, EC_e is assumed to be 1.5 x EC_w which is a standard relationship for soils with adequate drainage and good irrigation practices.

FIGURE 8-6
SALT TOLERANCE RATINGS OF AGRICULTURAL CROPS



Source: Maas, 1984

Irrigation water with an EC_w less than 0.7 dS/m is suitable for growing all crops to a full relative crop yield. With water of moderate salinity (0.7-3 dS/m), it is still possible to reach a 100% relative yield by applying the required leaching fraction. The required leaching fraction helps to keep the salinity of the soil within the crop tolerances. At higher levels of salinity (>3.0 dS/m), the required leaching fraction might be huge and it might not be possible to provide the amount of water needed to reach that leaching fraction. When using high salinity water, it is recommended to choose salt-tolerant crops and to grow them on permeable soils. The amount of water needed to reach the required leaching fraction decreases when soil permeability increases.

Toxicity management

Toxicity and salinity may cause reduced yields and crop failure, but are two different problems. Salinity restricts the availability of water to plants while toxicity is due to an uptake and an accumulation in plant leaves of certain ions. As for salinity, not all plants are equally sensitive to toxic ions. The most common toxic ions are boron, chloride, and sodium. Relative tolerance tables for boron chloride and sodium are presented below.

Sprinkler irrigation may enhance sodium and chloride toxicity because those ions can be directly absorbed by plant leaves and cause special problems. Generally trace elements do not cause any problems because their concentration in treated wastewater is too low. Nevertheless heavy metals, especially in urban treated wastewater, can be found at harmful concentrations for plants and may reduce crop yields. Thus, heavy metals require a particular attention to avoid any accumulation into the soil or plant tissues. Any wastewater use project should include monitoring of soil and plants for toxic material (FAO, 1992).

Human health management

Irrigation with treated wastewater may lead to some health hazards for the consumers and also for any exposed agricultural worker or the general public. Health hazards depend on who can potentially access the field and on how crops are consumed (eaten raw or cooked). WHO classifies crops and cultivated plants according to the exposed groups and the consumption mode:

Category A:

- Exposed groups: consumers, agricultural workers, and general public.
- Irrigation of crop likely to be eaten uncooked, sports fields, public parks.

Category B:

- Exposed groups: agricultural workers only.
- Irrigation of cereal crops, industrial crops, fodder crops, pasture, and trees.
- Not eaten raw, processed before consumption.
- Includes also crops grown well above the ground and not contaminated by irrigation (sprinkler).

Category C:

- Exposed groups: none.
- Drip irrigation of crops in category B if exposure to workers and the public does not occur (protected area).

Category A requires treated water of a high microbiological quality for irrigation, especially for vegetable eaten uncooked. A lower quality may be used for irrigating certain crops such as crops that are normally cooked. To protect consumers, workers, and the general public, WHO has established specific guidelines for each crop category. (See: Regulations and guidelines for reuse of wastewater).

Selection of irrigation methods

Selecting an irrigation system depends on the quality of the wastewater, selected crop, past traditional usage, experience, skills, ability to manage irrigation methods, potential environmental risk, and health of the workers and general public. Table 8-3 evaluates common irrigation methods (i.e., furrow, border or flood, sprinkler, and drip) according to the use of treated wastewater.

TABLE 8-3
EVALUATION OF IRRIGATION METHODS ACCORDING TO USE OF TREATED WASTEWATER

Parameters of evaluation	Furrow irrigation	Border irrigation	Sprinkler irrigation	Drip irrigation
1 Foliar wetting and consequent leaf damage resulting in poor yield	No foliar injury as the crop is planted on the ridge	Some bottom leaves may be affected but the damage is not so serious as to reduce yield	Severe leave damage can occur resulting in significant yield loss	No foliar injury
2 Salt accumulation in the root zone with repeated applications	Salts tend to accumulate in the ridge which could harm the crop	Salts move vertically downwards and are not likely to accumulate in the root zone	Salt movement is downwards and root zone is not likely to accumulate salts	Radial salt movement along the direction of water movement. A salt wedge is formed between drip points
3 Ability to maintain high soil water potential	Plants may be subjected to stress between irrigations	Plants may be subjected to water stress between irrigations	Not possible to maintain high soil water potential throughout the growing season	Possible to maintain high soil water potential throughout the growing season and minimise the effect of salinity
4 Suitability to handle brackish wastewater without significant yield loss	Fair to medium. With good management and drainage, acceptable yields are possible	Fair to medium. Good irrigation and drainage practices can produce acceptable levels of yield	Poor to fair. Most crops suffer from leaf damage and yield is low	Excellent to good. Almost all crops can be grown with very little reduction in yield

Source: Kandiah, 1990

Clogging of sprinklers, micro sprinklers, drippers, and subsurface irrigation systems can be a serious problem. Clogging is created by development of bacteria, biological and mineral deposit, accumulation of solid particles and salts in sprinklers, pipes and irrigation puncture holes. Worst cases of clogging generally appear with drip irrigation, which is considered to be the best irrigation system for sanitary conditions and plant contamination. Using a drip irrigation system can be extremely complicated if irrigation water contains a lot of suspended solids.

If treated wastewater does not comply with WHO guidelines (1989), certain safety measures have to be followed (Xanthoulis 1996):

- Sprinkler irrigation (sprinkler, micro sprinkler, etc.) should only be used for fodder crop, fibre, and seed production;
- Sprinkler irrigation lawn or area with limited access can be carried out during night time; and
- Sprinkler irrigation is not recommended in windy weather conditions. The wind can carry the mist (eventually containing pathogens) produced by the sprinkler, which represents a health hazard for workers and the neighbourhood.

Border irrigation (also called flood irrigation) and submersion in basins involve a complete flooding of the soil with the treated wastewater and a contamination of crops which are growing near the ground or in the ground. With that method, farmers are directly in contact with the effluent. This method will only be accepted for fodder crops, cereals or fruit crops (category B) and workers should avoid any contact with the wastewater during irrigation periods.

Furrow irrigation does not wet the entire surface area of the soil, which may reduce crop contamination because plants grow on ridges, but a total sanitary protection cannot be guaranteed.

Besides sanitary hazards due to leaching losses, *surface irrigation* is more dangerous than other irrigation methods for soil and ground water pollution.

Sprinkler irrigation is suitable for low saline wastewater after secondary treatment. Additional precautions like filtration or adjustment of the nozzle diameter should be taken. Sprinkler irrigation has less clogging problems than drip irrigation, but is potentially risky for crop contamination because the wind can drift away sprinkled water. This method can be used for industrial crops and crops which are not eaten raw.

Drip irrigation is the most appropriate method due to its low health hazards; it requires good filtration of wastewater and frequent maintenance to prevent clogging.

To ensure proper operation and an effective management of an irrigation system using treated wastewater, all materials must be well maintained. The irrigation system must include sieve filters, sand filters, drainage valves, etc. It is important to check up the system and verify that all of its components work well. Regular reports are important to prevent any breakdown or failure of the system.

Yield impact

Wastewater nutrients

Treated wastewater usually contains undesirable trace elements and pathogens, but also many useful nutrients (macronutrients: N, P, K, Ca, Mg, …; micronutrients: Fe, Zn, Cu, Mn, …) directly available for plants. Irrigating with wastewater is like fertigating, i.e., fertilising fields with irrigation water; this is economically interesting because it reduces the fertilisation costs. A strong application of nutrients through wastewater irrigation may lead to a nutritional imbalance; mineral elements (N, P, K) in wastewater are generally present in higher quantities than crop needs. That excess may result in abnormalities like excessive vegetative growth and alteration in product quality. A periodical control of elements in the effluents is thus necessary to limit quantities of fertiliser elements and to avoid abnormalities.

- *Nitrogen*

Wastewater has three forms of nitrogen: organic, ammonium, and nitrate. The relative proportions of these forms depend on the origin and wastewater treatment. Ammonium (NH_4) is the main form and its concentrations vary from 5 to 40 mg/L. The organic fraction is either soluble or insoluble in small suspended particles. All organic forms can be converted into ammonium by micro-organisms in wastewater or in soils. In aerobic processes, a portion of the ammonium of treated wastewater is converted into nitrates by nitrifying bacteria. Nitrate concentrations vary between 0 and 30 mg/L. If water containing ammonium is frequently applied on a soil, nitrifying bacteria increase.

Excess nitrogen leads to excessive vegetative growth, delayed maturity, and reduced crop quality. Certain crops are highly effective to consume nitrogen and prevent any accumulation and leaching in the soil. If the effluent contains too small amounts of nitrogen, additional nitrogen must be applied to reach optimum crop yield. For example, Table 8-4 shows that the total quantities of applied nitrogen to a tomato crop irrigated with urban wastewater from the city of Ouarzazate (Morocco) are higher than needed.

TABLE 8-4
APPLIED NPK (KG/HA) FROM IRRIGATION WATER FOR A TOMATO CROP REQUIRING 6,500 M^3/HA OF IRRIGATION WATER

Mineral elements	Treated wastewater	Untreated wastewater	Theoretical needs
N	225	334	175
P	99	145	75
K	155	111	175

Source: Xanthoulis, 1996

- *Phosphorus*

Like nitrogen, phosphorus is essential for plants. The phosphorus content of an effluent from secondary treatment varies from 6 to 15 mg/L (15 to 35 mg P_2O_5 /L). This concentration of phosphorus in treated wastewater might not be sufficient at the beginning of the growth to ensure a satisfactory yield. Reactions of phosphorus with soils form complexes. The absorption of phosphorus into the soil depends on its concentration; an excess of phosphorus in irrigation water does not lead to any problem.

- *Potassium*

Potassium in wastewater should not have any toxic effect on crops. That macronutrient has a positive impact on the fertility of a soil, crop yields, and quality. The potassium content of an effluent from secondary treatment varies between 10 and 30 mg/L (12 to 36 mg K_2O /L). The establishment of a fertilization program must take into account that concentration.

Salinity and potential yield

Plants tolerate a certain value of salinity without any impact on crop yield. Above a critical value of salinity, specific to each crop, yields begin to decrease linearly with salinity increases (FAO, 1985). That critical value is called the salinity threshold value. Mass and Hoffman (1977) give the equation expressing the linear decrease of crop yield when salinity increases:

$$Y = 100 - b \cdot (EC_e - a) \qquad \textbf{(E. 90)}$$

Where:
- Y = relative crop yield [%]
- EC_e = salinity of the soil saturation extract [dS/m]
- a = salinity threshold value [dS/m]
- b = yield loss per unit increase in salinity [%m/dS]

The yield loss per unit increase in salinity (b) which represents the slope of the linear decrease of crop yield can be determined as follows:

$$b = \frac{100}{EC_{e0\%} - EC_{e100\%}} \qquad \textbf{(E. 91)}$$

Where:
- $EC_{e0\%}$ = salinity of the soil saturation extract at 0% yield [dS/m]
- $EC_{e100\%}$ = salinity of the soil saturation extract at 100% yield [dS/m]

$EC_{e100\%}$ equals the salinity threshold value (a).

For example, the potential yield for a rice crop ($EC_{e0\%}$ = 11 dS/m and a = $EC_{e100\%}$ = 3 dS/m) growing on a field irrigated with wastewater (EC_w = 4 dS/m) would be:

At a 15–20 percent leaching fraction, the salinity of the applied water (EC_w) can be used to estimate the soil salinity (EC_e) using the general rule of thumb EC_e = 1.5 x EC_w. EC_e can be estimated to 6 dS/m (1.5 x 4 dS/m).

The yield loss per unit increase in salinity (b) equals 12.5% ($b = \frac{100}{11-3}$).

Thus, $Y = 100 - 12.5 \cdot (6 - 3) = 62.5\%$

Therefore, the potential yield of a rice crop grown in those conditions is 62.5%.

Monitoring requirement

Monitoring has three different purposes:

1. Validate or prove that the system meets its design requirements;
2. Monitor routine operation or indicate that processes are working as expected; and
3. Verify or show that the end product meets treatment and health-based targets.

These three functions of monitoring are each used at different times. Validation takes place at the beginning, when a new system has just been implemented, to prove that the system can meet the specified targets. Operational monitoring shows through a series of simple measurements and analyses that the system works as it should. Verification occurs periodically on the final product to prove that the system meets its targets. Operational monitoring uses short interval measurements that can be rapidly interpreted so that a specific decision can be made immediately whereas verification monitoring collects data over a certain period of time and shows the overall efficiency and the different trends of a system (WHO, 2006).

A monitoring program must be defined and should at least:

- Specify the parameters to be monitored;
- Define appropriate sampling locations; and
- Specify sampling frequencies.

8.2.2 Ground water recharge

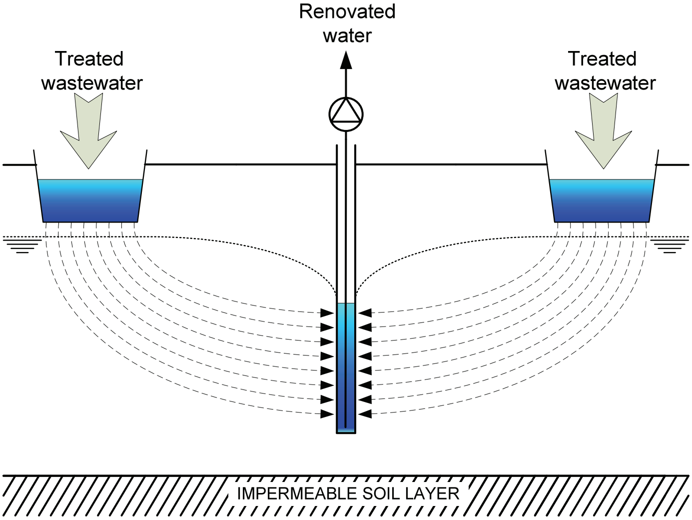
Ground water aquifers are very important because they can provide freshwater through water wells. Recharging ground water with reclaimed water or treated wastewater can:

- Avoid saltwater infiltration in coastal freshwater aquifers;
- Provide additional treatment for future reuse;
- Provide reclaimed water storage for future reuse;
- Increase potable or non potable aquifers; and
- Control or prevent ground subsidence.

Soil-Aquifer Treatment (SAT)

The soil can be a natural treatment to polish pre-treated wastewater. In infiltration basins, treated wastewater is filtered by percolating into the soil towards ground water. The vadose zone acts like a natural filter and can further remove BOD, suspended solids, nitrogen, phosphorus, bacteria, viruses, trace elements, and other elements. SAT systems basically consist of infiltration basins that are first flooded with treated wastewater. Then, treated wastewater infiltrates into the soil, passes through the vadose zone, reaches ground water, and the basin undergoes a drying period. At the end, renovated water is recovered from a drain, a well or a lower elevated lake (see Figure 8-7). SAT is a cyclical operation with wetting and drying periods; a normal cycle life is between 8 hours dry-16 hours flooding and 2 weeks dry-2 weeks flooding (FAO, 1992). Drying periods are important to restore infiltration rates and aerate the soil. Long drying periods prevent clogging layers and ensures a long aeration with a complete nitrification of the ammonium in the soil. SAT systems are usually located in permeable soils to have high infiltration rates and low evaporation. Soils do not have to be too permeable and must provide a fine filtration to give a satisfactory polishing treatment.

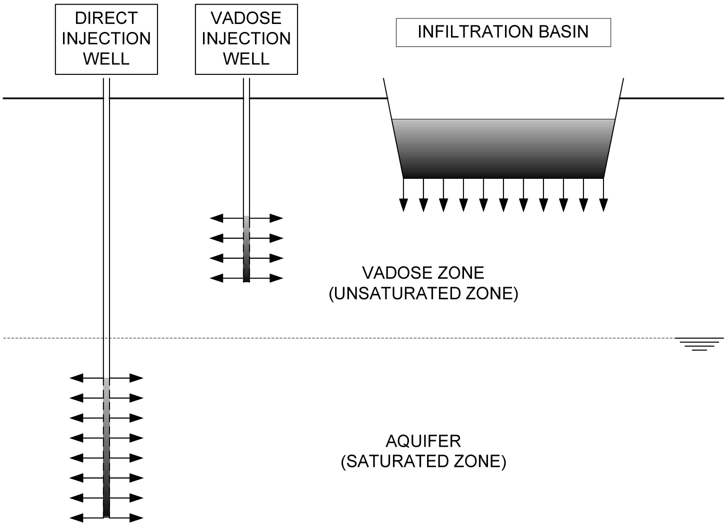
FIGURE 8-7
SOIL AQUIFER TREATMENT WITH RENOVATED WATER RECOVERED FROM A WELL



Methods of recharge

Infiltration basins are the most common method for ground water recharge. Two other methods are direct injection into the saturated zone or the vadose zone (see Figure 8-8).

FIGURE 8-8
COMMON METHODS FOR GROUND WATER RECHARGE WITH TREATED WASTEWATER



Infiltration basins have low costs, but they require space. Direct injection allows to reach confined aquifers and requires only limited space, but high technology pre-treatment. Vadose injection is an emerging technology that combines the advantages of direct injection and infiltration basins (UNEP, 1999). In some cases, like a confined aquifer or an unconfined aquifer with an inconvenient access, direct injection is the only option to reach the aquifer. However, direct injection is more expensive than low technology alternatives (see Table 8-5).

TABLE 8-5
MAJOR CHARACTERISTICS OF AQUIFER RECHARGE METHODOLOGIES

Characteristic	Infiltration Basins	Vadose Zone Injection Wells	Direct Injection Wells
Aquifer type	Unconfined	Unconfined	Unconfined or Confined
Pre-treatment requirements	Low Technology	Removal of Solids	High Technology
Capital costs	Land and Distribution System	\$25,000-75,000 per well	\$500,000-1,500,000 per well
Capacity	1000-20,000 m^3/ha.d	1000-3000 m^3/well.d	2000-6000 m^3/well.d
Maintenance requirements	Drying and Scraping	Drying and Disinfection	Disinfection and Flow Reversal
Estimated life cycle	>100 Years	5-20 Years	25-50 Years
Soil aquifer treatment	Vadose Zone and Saturated Zone	Vadose Zone and Saturated Zone	Saturated Zone

Source: UNEP, 1999

For infiltration basins, the major costs parameters are infiltration rates, land area requirements, and treated wastewater conveying facilities to transport water into infiltration basins. To determine hydraulic loading rates, average infiltration rates must be calculated considering cyclical operations that include flooding and drying periods. Hydraulic loading rates usually vary from 15 to 100 m/year and depend on the type of soil, climate, quality of treated wastewater (suspended solids content), and frequency of basin cleaning (FAO, 1992).

For example, a ground water recharge project with a treated wastewater production of 10,000 m³/day and a hydraulic loading rate of 50 m/year requires 7.3 ha of infiltration basins.

$$Area = \frac{10{,}000.365}{50} = 73{,}000m^2 = 7.3ha$$

If the land costs around $20,000 per ha, the total cost will be about $150,000. That cost does not include and could be seriously increased by treated wastewater conveying facilities. This is why infiltration basins should be close to a water conveyance system.

8.2.3 Industrial reuse

Industries use water for cooling, washing, transportation, as solvent, and may incorporate it into the finished goods. The two major water consumers are thermal and nuclear power plants, which need large amounts of cooling water to evacuate excess heat. Metal-working industries, chemical plants, refineries, and other industries may benefit from reclaimed water for cooling and for different process uses (as industrial process water). In addition to the general environmental benefits discussed in earlier sections, industrial water reuse has the following specific benefits:

- Potential reduction in production costs from the recovery of raw materials in wastewater and reduced water usage;
- Heat recovery; and
- Potential reduction in costs of wastewater treatment and discharge.

Industrial water reuse and recycling ranges from simple housekeeping to advanced technology implementation (see Table 8-6).

TABLE 8-6
TYPES AND EXAMPLES OF INDUSTRIAL WATER REUSE

Types of water reuse	Examples
Reuse of municipal wastewater	Cooling tower make-up water Once-through cooling Process applications
Internal recycling and cascading use of process water	Cooling tower make-up water Once-through cooling and its reuse Laundry reuse (water, heat, and detergent recovery) Reuse of rinse water Cleaning of premises
Non-industrial use of effluent	Heating water for pools and spas Agricultural applications

Source: Asano and Levine, 1998

Cooling water

There are two types of cooling water systems:

1. Once-through cooling water systems: water passes one time through a heat exchanger and then returns to the original water source. There is no evaporation and thus no concentration of cooling water constituents in that kind of system.

2. Recirculating cooling water evaporative systems: it is the most common water cooling system. Cooling towers are widely used to absorb process heat of nuclear power plants by water evaporation. Cooling water recirculates into the system and some make-up water is added to replace the evaporated water. As cooling water evaporates, the concentration of dissolved solids constantly increases and may lead to some corrosion problems. Thus, cooling water has to be regularly removed from the system to avoid excessive concentrations of dissolved solids into the water.

Boiler make-up water

Reclaimed water may be used for boiler make-up water to produce steam. The quality of the water required increases with the boiler operational pressure. High pressure boilers require high purity water and additional treatments such as reverse osmosis or ion exchange. The hardness of the boiler feed water must be close to zero to prevent deposits, scaling, and/or equipment corrosion. The tremendous water treatment requirements and the small amounts of make-up water needed make water reuse trough boiler make-up water unsatisfactory for wastewater reuse.

Industrial process water

The use of reclaimed water as process water depends on specific requirements of industrial processes and on the desires and motivations of each industry. Water reuse should never negatively interfere with the product quality.

Potential concerns

The problems in Table 8-7 may affect process efficiency and product quality; they need to be under control for a sustainable water reuse.

TABLE 8-7
INDUSTRIAL WATER REUSE: CONCERNS, CAUSES, AND TREATMENT OPTIONS

Concerns	Causes	Treatment options
Scaling	inorganic compounds, salts	scaling inhibitor, carbon adsorption, filtration, ion exchange, extraction rate control

Corrosion	dissolved and suspended solids pH imbalance	corrosion inhibitor, reverse osmosis
Biological growth	residual organics, ammonia, phosphorous	biocides, dispersants, filtration
Fouling	microbial growth, phosphates, dissolved and suspended solids	control of scaling, corrosion, microbial growth, filtration chemical and physical dispersants

Source: Asano and Levine, 1998

8.3 Technical issues in planning water reuse system

Planning a water reuse system starts with a preliminary investigation followed by the identification of potential uses of reclaimed water and ends with a detailed evaluation.

8.3.1 Preliminary investigation

During this phase, examination of every single reuse possibility must permit to establish the real context of a project and avoid improper solutions. The questions that have to be answered during preliminary investigations are:

- What are the wastewater resources?
- What is the potential market of treated water?
- What are public health considerations linked with wastewater reuse and how to manage them?
- What is the potential environmental impact?
- How could wastewater reuse be combined with other water resources?
- What is the actual cost of clear water in the area?
- What are the actual standards about water reuse?
- Who must legally approve and follow up the project?
- What are the legal accountabilities of the supplier and of the treated water user?
- What are the available funds to support the project?

Potential users should be concerned with treated wastewater quality and the reliability of the delivery. They have to be aware of national (and/or local) wastewater reuse standards and of additional wastewater treatment costs that can affect their ability to use treated wastewater. Commonly, wastewater treatment costs concern only the local community (up to the outlet of the wastewater treatment plant). Farmers are usually asked to finance the irrigation network from the outlet of the wastewater treatment plant to their fields.

8.3.2 Identification

The identification phase is to identify potential uses (markets) of reclaimed water and compare clear water and treated wastewater costs. The value and the interests of reclaimed water uses depend on:

- Quality of the water needed by the farmers;

- Available quantities of water;
- National and/or local standards; and
- Actual cost or the future cost of water.

Exhaustive studies are required to detail and answer those inquiries.

8.3.3 Evaluation

Questions to be answered during the evaluation are:

- What are the specifications of water needed to satisfy each type of use and what are the accepted ranges and the quality limits?
- What are the risks linked to water quality and how to avoid them?
- Besides water, which other elements are brought by wastewater?
- Which safety measures should be taken to avoid any pollution risk?
- Is a storage system needed?
- Is storage or pumping the best way to satisfy demand fluctuations?
- If a complementary treatment is needed, who will finance it?
- Will the use of treated wastewater compel farmers to modify their irrigation practices?

Wastewater reuse can provide some really interesting agronomic results. Properly configured wastewater reuse systems can have a positive sanitary and environmental impact and increase crop yield. However, wastewater reuse in agriculture can also have a negative impact on environment and public health. This is why minimum guidelines and standards must be strictly respected.

8.3.4 Environmental impacts

Environmental advantages

Wastewater properly used for agricultural irrigation can improve environmental quality as follows:

- Avoiding waste discharge into surface water prevents unpleasant aesthetic situations, anaerobic conditions in any watercourses, and eutrophication of water in lakes or reservoirs;
- Preserving ground water resources in overexploited agricultural regions avoids dewatering and prevents saltwater from entering aquifers; and
- Can conserve or enhance soils and prevent soil drifting (erosion).

Potential environmental disadvantages

Wastewater reuse for irrigation may also have a negative impact on the receiving environment and on human health; for example, it may:

- Introduce chemical elements, sometimes at high concentrations, in sensitive ecosystems (mainly soils, water and plants); and
- Introduce and propagate pathogenic micro-organisms.

Effects on soils

Soils impacts are of a particular importance for farmers because they can decrease productivity, fertility, and crop yield due to:

- Salinisation;
- Alkalinity and a decrease in soil's permeability;
- Improper accumulation of potential toxic elements; and
- Accumulation of nutrients.

Effects on ground water

In certain conditions, effects on ground water are more important than effects on soils because wastewater constituents can pollute ground water. To reduce and/or to solve the problem, it is recommended to:

- Use a quantity of irrigation water based on crop water requirements with minimum lixiviation;
- Establish an irrigation management program based on crop water requirements, soil's water storage capacity, and wastewater quantities;
- Select crops that can absorb potentially toxic elements of wastewater;
- In case of saline water, select crops that can uptake the salt;
- Limit wastewater quantities to apply a precise nitrogen needed input and reduce the risk of NO_3-N contamination. If nitrogen exceeds crop requirements, you must :
    - Select high nitrogen requirements crops;
    - Select an irrigation system providing the best irrigation homogeneity;
    - Mix wastewater with clear freshwater; and
    - Maintain irrigation systems to an acceptable level.

It is highly recommended to establish a nitrogen balance to protect aquifers against nitrate contamination. A nitrogen balance allows keeping a nitric concentration in water under 50 mg/L or keeping the same nitrogen concentration if the actual concentration is already higher than 50 mg/L.

Effects on surface water

High concentrations of N and P in treated wastewater may result in eutrophication if it is mixed with irrigation water from reservoirs. Nitrogen is the limiting factor for the growth of algae in the sea; but N and P are the limiting factors in lakes, salt water basins, and retaining dams where wastewater is stored before irrigation.

Effects on crops

In addition to the global effect of some wastewater constituents such as salinity on irrigated crops, wastewater can be potentially toxic due to high concentrations of some elements such as boron and some heavy metals. Necroses appearing on sensitive crop leaves are the toxicity symptoms of boron.

8.4 Regulations and guidelines for reuse of wastewater

8.4.1 Microbiological quality guidelines

To protect public health, it is essential to minimise sanitary risks by implementing some microbiological guidelines and specific standards for each type of reuse conditions. WHO (1989) has established microbiological quality guidelines for treated wastewater used for irrigation (see Table 8-8) in “Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture”. Some more stringent reuse standards can be applied in regions or countries, such as the State of California that has regulated non-potable reuse under “Title 22” of the California Administrative Code since 1978. In countries where the existing standards are especially severe, a secondary treatment is necessary and a tertiary treatment may be needed.

WHO guidelines recommend for a non restrictive irrigation:

- a complete (or almost complete) removal of intestinal helminthes, with an average of 1egg/L; and
- an important removal of pathogen bacteria, with an average <1000FC/100mL.

For restrictive irrigation, WHO only insists on removing intestinal helminthes. The arithmetic mean of intestinal nematodes (<1egg/L) is debatable if it is assumed that a lot of water is needed to irrigate crops and nematodes eggs, which may live for months, can accumulate in soils and plants. A microbiological quality of 1000FC/100mL does not consider any climatic factor and its potential effect on the proliferation of pathogens. The epidemiological approach is thus different than the “zero risk” approach and depends on the accepted level of health risk and on economic and social standards. In countries where no more stringent guidelines exist, treated wastewater which comply with WHO guidelines for a non restrictive irrigation (category A) can be used for any crop cultures without additional health protection measures (WHO, 1989).

TABLE 8-8
MICROBIOLOGICAL QUALITY GUIDELINES FOR TREATED WASTEWATER USED FOR IRRIGATION

Category	Reuse conditions	Exposed Group	Intestinal nematodes[a] (arithmetic mean no. of eggs per litre)	Faecal coliforms (geometric mean[b] no. per 100 ml)	Wastewater treatment expected to achieve the required microbiological guidelines
A	Irrigation of crop likely to be eaten uncooked, sports fields, public parks[c]	Workers, consumers, public	≤ 1	≤ 1000	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops,	Workers	≤ 1	No standard recommended	Retention in stabilization ponds for 8-10 day or equivalent

	pasture, and trees[d]				helminth and faecal coliform removal
C	Drip irrigation of crops in category B if exposure to workers and the public does not occur	None	Not applicable	Not applicable	Pre-treatment as required by irrigation technology but not less than primary sedimentation

a/ *Ascaris lumbricoides*, *Trichuris trichiura* and the human hookworms
b/ during the irrigation period
c/ A more stringent guideline (≤ 200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.
d/ In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.
Source: WHO, 1989

8.4.2 Chemical quality guidelines for irrigation

Table 8-9 shows the general guidelines for the chemical and physical characteristics (total dissolved salts, sodium content and toxic ions) of irrigation water.

Salinity

Generally, municipal supply water is of the best quality available and is usually poor in salts. However, during water shortages, water salinity may increase, which may limit its use for irrigation. It is possible, within certain limits, to regulate irrigation according to salinity by adjusting applied quantities and irrigation systems. Domestic and urban uses slightly increase salinity of only a few dozens mg/L. Some potential irrigation problems are due to the total dissolved salt content, the type of salts or an excessive concentration of one or several elements (FAO, 1985).

Heavy metals and trace elements

Urban wastewater may sometimes contain some toxic organic or mineral elements (especially heavy metals) even without any industrial wastewater discharge. Industrial wastewater must undergo specific treatments before discharge into the water network. When heavy industrial activity is weak, it is not always essential to considerate heavy metals or trace elements as a serious problem.

TABLE 8-9
GUIDELINES FOR QUALITY OF WATER IRRIGATION[1]

Potential Irrigation Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Salinity *(affects crop water availability)*[2]				
EC_w	dS/m	< 0.7	0.7 – 3.0	> 3.0
(or)				
TDS	mg/l	< 450	450 – 2000	> 2000

Infiltration *(affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)*[3]				
SAR = 0 – 3 And EC_w =		> 0.7	0.7 – 0.2	< 0.2
3 - 6		> 1.2	1.2 – 0.3	< 0.3
6 - 12		> 1.9	1.9 – 0.5	< 0.5
12-20		> 2.9	2.9 – 1.3	< 1.3
20-40		> 5.0	5.0 – 2.9	< 2.9
Specific Ion Toxicity *(affects sensitive crops)*				
Sodium (Na)[4]		`		
surface irrigation	SAR	< 3	3 – 9	> 9
sprinkler irrigation	me/l	< 3	> 3	
Chloride (Cl)[4]				
surface irrigation	me/l	< 4	4 – 10	> 10
sprinkler irrigation	me/l	< 3	> 3	
Boron (B)	mg/l	< 0.7	0.7 – 3.0	> 3.0
Miscellaneous Effects *(affects susceptible crops)*				
Nitrogen (NO_3 - N)[5]	mg/l	< 5	5 – 30	> 30
Bicarbonate (HCO_3)				
(overhead sprinkling only)	me/l	< 1.5	1.5 – 8.5	> 8.5
pH		Normal Range 6.5 – 8.4		

[1] Adapted from University of California Committee of Consultants 1974 cited by FAO, 1985.

[2] ECw means electrical conductivity, a measure of the water salinity, reported in deciSiemens per metre at 25°C (dS/m) or in units millimhos per centimetre (mmho/cm). Both are equiva-lent. TDS means total dissolved solids, reported in milligrams per litre (mg/l).

[3] SAR means sodium adsorption ratio. SAR is sometimes reported by the symbol RNa. At a given SAR, infiltration rate increases as water salinity increases. Evaluate the potential infiltration problem by SAR as modified by ECw. Adapted from Rhoades 1977, and Oster and Schroer 1979 cited by FAO, 1985.

[4] For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use the values shown. Most annual crops are not sensitive. With overhead sprinkler irrigation and low humidity (< 30 percent), sodium and chloride may be absorbed through the leaves of sensitive crops.

[5] NO_3 -N means nitrate nitrogen reported in terms of elemental nitrogen (NH_4 -N and Organic-N should be included when wastewater is being tested).

Elements in the raw effluent remain in the sludge, which is a by-product of wastewater treatment plants. Table 8-10 shows an example wastewater composition before and after a WSP treatment. When wastewaters are of urban origin, a WSP treatment can generally meet the recommended guidelines for crop irrigation (see Table 8-11).

TABLE 8-10
CONCENTRATION OF TRACE ELEMENTS (IN MG/L) IN TREATED AND UNTREATED WASTEWATER

Trace element	Untreated wastewater	Treated wastewater
Al	2.3	0.48
As	0.0002	Not detected
Cd	0.0010	0.0001
Co	0.22.	0.077

Cr	0.012	0.0025
Fe	10.37	2.70
Mn	1.45	0.33
Ni	0.135	0.044
Pb	0.0090	0.001
Zn	2.26	0.96
Se	0.0025	0.001
B	0.10	0.01
Cu	1.28	0.24

Source: Xanthoulis, 1996

TABLE 8-11
GUIDELINES FOR TRACE ELEMENTS IN TREATED WASTEWATER USED FOR IRRIGATION

Constituent	Long-term [a] use (mg/L)	Short-term [b] use (mg/L)
Aluminum	5.0	20.0
Arsenic	0.10	2.0
Beryllium	0.10	0.5
Boron	0.75	2.0
Cadmium	0.01	0.05
Chromium	0.1	1.0
Cobalt	0.05	5.0
Cupper	0.2	5.0
Fluor	1.0	15.0
Iron	5.0	20.0
Lead	5.0	10.0
Lithium	2.5	2.5
Manganese	0.2	10.0
Molybdenum	0.01	0.05
Nickel	0.2	2.0
Selenium	0.02	0.02
Vanadium	0.1	1.0
Zinc	2.0	10.0

Source: adapted from National Academy of Engineering (1973)

[a] For irrigation with treated wastewater without interruption on any kind of soil.

[b] For irrigation with treated wastewater for 20 years maximum on fine, neutral or alkaline soils.

8.5 Examples of wastewater reuse in the world

Wastewater irrigation – Tunisia (FAO, 1992)

Wastewater use in agriculture has been practiced for several decades in Tunisia and is now an integral part of the national water resources strategy. In 1988, there were 26 wastewater treatment plants, mainly located on the coast to prevent sea pollution; by 1996, there should be 54 treatment plants. Of the existing sewage treatment plants, 16 are activated sludge, two trickling filters, five stabilization ponds, and three oxidation ditches.

Use of treated effluents is seasonal in Tunisia (spring and summer) and the effluent is often mixed with ground water before being applied to irrigate citrus and olive trees, forage crops, cotton, golf courses, and hotel lawns. Irrigation with wastewater of vegetables that might be consumed raw is prohibited by the National Water Law. A regional Department for Agricultural Development (CRDA) supervises all irrigation water distribution systems and enforces the Water Code. At the present time, an area of about 1,750 ha is irrigated with treated wastewater. Many new projects are now implemented or planned and the wastewater irrigated area will increase to 6,700 ha, so that 95% of the treated wastewater is used in agriculture. The most important developments will take place around Tunis, where 60% of the country's wastewater is produced and 68% of the effluent-irrigated area will occur.

Wastewater irrigation – Kuwait (FAO, 1992)

Untreated sewage has been used for many years to irrigate forestry projects far from the inhabited areas of Kuwait. After extensive studies by health and scientific committees and by international consultants and organisations (WHO and FAO), the government of Kuwait started a programme of sewage treatment and effluent use. In 1987, there were four sewage treatment plants: the 150,000 m^3/day Ardiyah sewage treatment plant (secondary stage) commissioned in 1971, the 96,000 m^3/day coastal villages and the 65,000 m^3/day Jahra sewage treatment plants commissioned in 1984, and a small (10,000 m^3/day) stabilization ponds treatment plant also installed on Failaka Island.

The effluent from the Ardiyah, coastal villages and Jahra, activated sludge treatment plants was upgraded in the mid-1980s with tertiary treatment, including chlorination, rapid gravity sand filtration, and final chlorination. Initially, the treated secondary effluent from the Ardiyah plant was distributed to the experimental farm of the Department of Agriculture at Omariyah. Trials were undertaken in the early 1970s to compare crop yields from irrigation with potable water, brackish water, and treated effluent. In 1975, the United Agricultural Production Company (UAPC) established an 850 ha farm under Government licence, especially to use treated wastewater. The directors of this close shareholding company represented the main private organisations involved in Kuwait agriculture, in particular the local dairy, poultry, and livestock farming organisations. In 1975, only part of the area was under cultivation; the main crop was forage (alfalfa) for the dairy industry, using side-roll sprinkler irrigation. However, aubergines, peppers, onions, and other crops were grown on an experimental basis, using semi-portable sprinklers and flood and furrow irrigation.

8.6 Reuse of treated wastewater for aquaculture

8.6.1 Introduction

Aquaculture and water resources

Concept of aquaculture

Aquaculture takes advantage of the growth, development, and propagation of aquatic organisms to gain economic interest; aquaculture includes growing aquatic plants and algae, breeding aquatic animals, processing aquatic products, and managing water environment.

Aquatic livestock and aquatic plant

The hydrobios refers to all of the organisms in water including aquatic plants, aquatic animals, algae, and some hydrophytes. Aquatic animals include all of the animals in water, such as fish, shrimp, shellfish, and amphibians. According to their relationship with water and substrates, hydrophytes can be classified as sunken, floating, and emerging plants.

Importance of water for aquaculture

Water is important for all living organisms as it takes part in their metabolism directly. The water content of plants is 60%~ 80% while its content in animals is much higher; for example, malacoderms have a water content of 80 to 92 %, fish 80 to 85 %, and birds 70 to 75 %. Water is also the medium of biochemical reaction. As a good solvent, water can hydrolyse and ionise many compounds, thus making them easy to be absorbed by and transported in aquatic organisms. Moreover, water plays a key role in photosynthesis. Furthermore, water is an essential element for the hydrobios, as it can adjust luminosity, heat, dissolved oxygen, nutrient substance, osmotic pressure, and other factors to maintain a normal living environment and physiological state.

Water resource limitation of regional aquaculture

The development of regional aquaculture is often decided by its water resources. Sometimes regional aquaculture is limited by water resource because it is not enough itself, unevenly distributed in space and time or polluted.

Treated wastewater —another water resource

Treated wastewater discharge

This is the amount of water used in city and industry and discharged into the environment after treatment; world water consumption keeps increasing (see Table 8-12).

TABLE 8-12
WORLD ANNUAL WATER USE (km^3)

Water usage	1900	1940	1950	1960	1970	1985	2000
City	20	40	60	80	120	350	440
Industry	30	120	190	310	510	1,100	1,900
Agriculture	350	660	860	1,500	1,900	2,400	3,400
Total	400	820	1,110	1,890	2,530	3,850	5,740

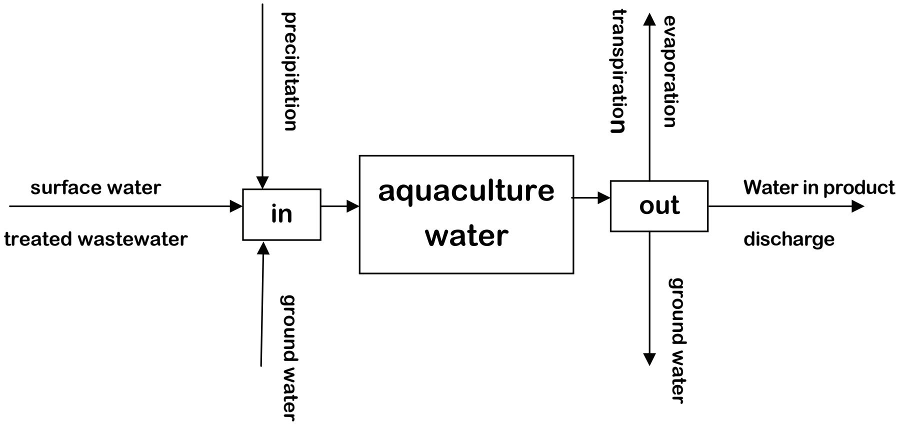
Source: Handbook of City Waste Water Recycling Usage (Cn) edited by Zhaofeng JIN and Jincheng XU and published by Chemical Industry Press (January 2004).

If we treat wastewater scientifically, the treated wastewater can become a source of water that can be used in industry, agriculture and landscape maintenance.

Water requirement in aquaculture

In aquaculture, the water budget, i.e., the difference between water input and output, must be balanced and the water quality constant. A water input less than the output will make the water body atrophic, i.e., unable to maintain normal environmental conditions for aquatic organisms; it will also weaken mass exchange in the water body and lead metabolites accumulate, dissolved oxygen fall, water quality deteriorate, which will end up restraining the growth, development, and propagation of aquatic organisms, thus creating fatal harm to the products. A water input greater than the output will waste water resources and affect production efficiency. So, water input and output must be balanced (see Figure 8-9).

FIGURE 8-9
WATER BALANCE FOR AQUACULTURE PRODUCTION



Treated wastewater reuse in aquaculture

Treatment standards for wastewater vary by region. In China, the main guidelines for wastewater treatment are not as stringent as the water quality standards for aquaculture. Introducing aquatic plant treatment can purify the water to the level required for aquaculture.

In summary, using treated wastewater to grow aquatic plants can remove pollutants from wastewater, produce valuable plants, and make the treated wastewater available for fishery.

8.6.2 Use and performance

Using treated wastewater for industry, agriculture, and landscape maintenance can save fresh water resources and yield material and economic returns.

Quality of treated wastewater

In the world, the water quality standards for aquaculture strictly limit toxic substances, heavy metals, bacillus, nitrogen, and phosphorus (see Table 8-13).

TABLE 8-13
WATER QUALITY STANDARDS FOR AQUACULTURE (WHO 2006)

Microbial quality targets for waste-fed aquaculture			
Media	Viable trematode eggs (including schistosome eggs where relevant) (number per 100 ml or per g total solids [a])	E. coli (arithmetic mean number per 100 ml or per g total solids [a,b])	Helminth eggs[c] (arithmetic mean number per liter or per g total solids [a, d])
Product consumers			
Pond water	Not detectable	$\leq 10^4$	≤1
wastewater	Not detectable	$\leq 10^5$	≤1
Treated excreta	Not detectable	$\leq 10^6$	≤1
Edible fish flesh or plants parts	Infective metacercariae (presence or absence per fish or plant) not detectable or non-infective	Codex Alimentarius Commission specifications [e]	Not detectable
Aquacultural workers and local communities			
Pond water	Not detectable [f]	$\leq 10^3$	≤1
wastewater	Not detectable [f]	$\leq 10^4$	≤1
Treated excreta	Not detectable [f]	$\leq 10^5$	≤1

Standards for chemical concentrations in fish and vegetables				
Chemical	Standard for fish and fish products $/\text{mg.kg}^{-1}$	Source of standard	Standard for vegetables $/\text{mg.kg}^{-1}$ [g]	Source of standard
Heavy metals				
Arsenic	NS		0.2	Codex (2003)
Cadmium	0.05—1.0	EC (2001)	0.2	Codex (2003)
Lead	0.2	Codex (2003)	0.2	Codex (2003)
Methyl mercury	0.5—1.0	Codex (2003)	NS	

Organics				
Dioxins [h]	0.000 004	EC (2001)	NS	
DDT, DDE	5.0	USFDA (1998)	NS	
PCBs	2.0	USFDA (1998)	NS	

[a] Excreta is measured in grams of total solids(i.e. dry weight); 100ml of wastewater/excreta contains approximately 1—4g of total solids.

[b] An arithmetic mean should be determined throughout the irrigation season. For pond water and product consumers, for example, the mean value of ≤10^4 *E. coli*. per 100 ml should be obtained for at least 90% of samples to allow for the occasional high-value sample (i.e. with 10^5 or 10^6 *E. coli.* per 100 ml).

[c] Applicable when emergent aquatic plants are grown and when there is high contact with wastewater, excreta, contaminated water or contaminated soils.

[d] An arithmetic mean should be determined throughout the irrigation season. The mean value of ≤1 egg per liter should be obtained for at least 90% of samples to allow for the occasional high-value sample (i.e. with > 10 eggs per liter).

[e] The Codex Alimentarius Commission does not specify microbial qualities for fish flesh or aquatic plants; rather, it recommends the adoption of hazard analysis and critical control point (HACCP) principles as applied from production to consumption.

[f] Viable schistosome eggs where relevant.

[g] General standard for leafy vegetables except for arsenic, which is fruit based.

[h] Includes dioxins and other polychlorinated, co-planar aromatic compounds with similar

NS, no standard

Source: WHO, 2006. *Guidelines for safe use wastewater, excreta and grey water*. Wastewater use in aquaculture vol.3, WHO, Geneva, 41-43 p.

Treated wastewater that does not meet the standards could reduce the output from aquaculture, damage the water environment, and even destroy the entire system. Water used in aquaculture must have useful aquatic organisms, meet required hygienic standards, and let fishery products up to requirements. Only water with adequate pH, temperature, concentration of dissolved oxygen, very low concentration of deleterious chemicals and pathogenic microbes can be used for aquaculture. The following properties are needed for aquaculture:

- pH; aquatic organisms have strict pH requirements; in the adaptative range of pH, they grow better with increased pH, and their growth slows down after the pH reaches the optimum range. The optimum pH depends on the species and age of hydrobios. The adaptative pH range for aquaculture is between 6.5 and 9.0, and the optimum pH range for fish is between 7.2 and 8.5. A low pH is unfavourable to fish; fish eggs and fish fries are more sensitive to pH than adult fish. Fish growth is affected at the 5.5-6.5 pH range. At the same time, a high pH is not good for fish; fish are seriously affected when pH reaches 10-10.5, and die when pH reaches 11. The optimum pH range for aquatic plants is between 6.5 and 10. It is costly to change the pH artificially; so it is necessary to monitor the pH of treated wastewater to avoid extra cost when using treated wastewater in aquaculture.

- Temperature directly affects the metabolic intensity, thus controlling the growth, development, distribution, and population size of the aquatic organisms; it also affects the abundance of food and the dynamics of the physical and chemical factors, thus indirectly controlling the life and existence of aquatic organisms. Organisms have strict temperature requirements; they grow better with high temperature. Once the temperature reaches an optimum value and continues to rise, the organisms' growth will slow down. Change in water temperature can affect the metabolism and decomposition of organic matter of aquatic animals, thus affecting the growth and development of the fish. Temperature requirements vary with species; for example, some fish start to gain weight when the temperature is above 10°C, gain the most weight above 15°C, and increase weight fastest between 20 and 30°C. But it is not suitable to raise rainbow trout at 15°C. Plants can grow, develop, and propagate only at the right temperature. Water temperature affects fish production directly and indirectly by affecting the decomposition rate and vital movements of aquatic organisms, forming favourable or harmful environmental conditions

- Dissolved oxygen is the most important index of water quality. Almost all aquatic organisms, except some anaerobes, depend on dissolved oxygen. There are two sources of oxygen in water: gas exchange with air and photosynthesis of aquatic plants and algae. Suspended substances, dissolved organic matters, and sludge at the bottom of the pond consume oxygen in addition to aquatic animals and plants. So, the amount of dissolved oxygen in treated wastewater directly affects the quality of fishery products. The theoretical dissolvability of oxygen in pure water is 8.32 mg/L; most fish require 5-12 mg/L of dissolved oxygen. The specific ventilating tissues of aquatic plants are an important source of oxygen.

- Chemical substances; suspended substances, oil, sulphides, cyanides, phenols, heavy metals, and pesticides affect the fish's physiology, make breathing for them difficult, and kill them. Some of these substances damage the blood circulation and kill aquatic organisms. Chemical substances must comply with the standards in Table 8-13.

Quantity of treated wastewater

It cannot be exactly the same as that of water used in aquaculture. Water discharged from the pond in greater quantity than treated wastewater creates an open system, which keeps water at a good quality level. Such a situation uses only treated wastewater in aquaculture, and the water budget takes only the treated water into account. A different situation creates a closed system that degrades water quality, which is not good for the aquatic organisms; in such a situation, it is necessary to add fresh water.

Regional environment

In order to ensure the application of treated wastewater in aquaculture scientifically, the regional environmental factors such as precipitation, evaporating capacity, temperature, land and ground water etc. must be considered cautiously.

Precipitation; in areas of high precipitations, rain can supply water for aquaculture and reduce the concentration of some pollutants. In areas of low precipitations, in case of low bio-purge, pollutants may accumulate and water quality can be deteriorated quite rapidly.

Evaporating capacity; when evaporation is greater than precipitation, the concentration of pollutants and nutrients will rise if extra water is not added, which can result in water eutrophication and worsen water quality. When evaporation is less than precipitation, water quality should be strictly monitored and a certain amount of natural fresh water should be introduced to adjust the quantity and quality of water.

Temperature; it can directly or indirectly affect the growth of aquatic organisms and microbes in water. High temperatures evaporate water, reduce concentrations of dissolved oxygen, and modify the biological activity of soluble matters.

Land; soil is the basic material for building fish ponds. Land conditions include the area of land and the structure and nature of soil. One of the main concerns is the water tightness of the floor area of the pond. Clay soils have strong caking properties, poor osmosis, good swell-shrink characteristics, and good adsorption; sand soils have poor caking property, good osmosis, poor swell-shrink characteristics, and poor adsorption. Factors such as the altitude of the pond and outlet of treated wastewater also affect the costs of water transportation and power consumption.

Ground water; given that areas with a high ground water level can be polluted more easily than areas with low ground water level, ponds should be built in areas with low ground water level to reduce the risk of ground water pollution. If the ground water level is high, water tightness measures must be taken into consideration to avoid ground water pollution.

Hydrobios

Selection of hydrobios depends on some aspects as Environmental adaptability, Productivity, Security of environment, etc.

Environmental adaptability of aquatic organisms; it depends on three aspects:

1. Ecological condition: selection of local species to reduce technique risks and production costs.
2. Treated water quality: selection of species with high pollution resistance and high nutrition tolerance;
3. Social consumer market: selection of aquatic organisms with large and stable social demand.

Productivity of aquatic organisms; it depends on the species, physiological function, fecundity, and living environment. Organisms with high production performance have a strong fecundity, high growth speed, and fast increase in population size, which can reduce the cost of the product and benefit the development of aquaculture.

Security of environmental organisms; the internal structure of species and its system function depend on the competitive use of environmental resources, the toxic action of interspecies organisms, and the predacious relation of organisms. The encroachment of alien species can damage the fabric of species and food chain, which can perturb the ecological function and even cause ecological damage. Choosing unsuitable species or introducing alien species can change the food chain of the system, which can affect the stability of the environmental ecosystem and produce serious ecological damage.

Choice of aquatic organisms; proper aquatic species should be chosen according to the adaptability and productivity of species and the security of aquatic organisms to improve the ability of transforming aquatic systems into environmental resources, making full use of the treated water, and obtaining the needed biological product.

Social factors

The social factors which affecting the usage of treated wastewater in aquaculture mainly include Ideology, Science and technology of wastewater treatment, Laws and regulations, Infrastructure, Market factor, etc.

Ideology; reusing treated water is on the rise worldwide. People are usually comfortable with the idea of using treated water provided it is not in direct contact with the human body, but they are concerned with the use of treated water in aquaculture. In some areas, reusing treated water in aquaculture may also be a religious issue. So it is still necessary to educate people so that they accept the fish produced with treated water.

Science and technology; the quality of treated water is constantly improving. In recent years, although the techniques of reusing treated water have improved, most treated water has been for agriculture and landscape irrigation, industrial production, and municipal usage. In China, treated water has trouble meeting the water quality standards in Table 8-13; therefore, treated water is less used in aquaculture than in other fields.

Laws and regulations; policies, laws, and regulations encouraging the reuse of treated water in aquaculture need to be developed.

Infrastructure; in most areas, aquaculture cannot directly use the treated water discharged by municipal wastewater plants because of the layout of the pipe network.

Market factor; the key factor for using treated water in aquaculture is the market demand for the product.

8.6.3 Design criteria and material

Principles of design

Project security relies on adequate selection of land and soil quality. Proper land will provide easy construction, convenient drainage and irrigation, low investment, and convenient management. Projects built on highlands are more expensive, but lowlands are prone to flooding. It is necessary to select a good land and set an irrigation and drainage system. A place that can be conveniently irrigated and drained freely will reduce energy consumption. The selected site should also be easily accessible to facilitate goods transportation. It is also important to have a stable ground base and good anti-seepage effect. To ensure project architecture security, building design and materials should meet construction quality standards and have adequate safety coefficients.

Operation security requires engineering system and staff security. There must be power for lights, water drainage, and oxygen supply. There must be enough fresh water and low quality water should be drained on time. It needs a special laboratory and experimental facilities and staff with specialised knowledge and skills. Other risks to minimise include fire, drought, flood, poisoning, sanitary problems and diseases.

Staff security requires strict production system and work flow measures. Staff should be trained in safety awareness. Training should cover how to use electricity and chemicals, provide first-aid to people drowning and poisoned by toxic gases, and control fire.

Product security*;* product storage and transportation facilities should be safe. Given that aquatic products will be used as food of people or other animals, they should not contain any toxic and harmful matters such as heavy metals, carcinogens, and any other toxic or harmful substances. Industrial raw materials should not have any components harmful to staff or affecting the end-product quality.

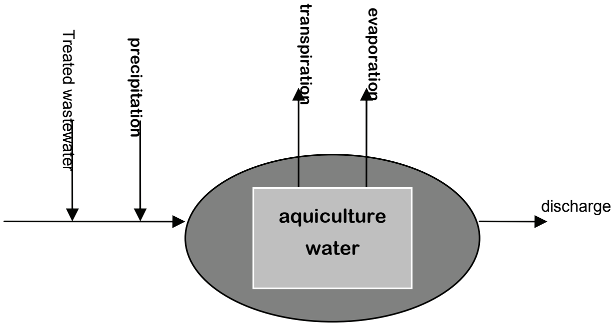
Environmental security*;* the project should not have any negative impacts on its surroundings. Potential impacts include flooding of downstream river due to dam rupture, pond leakage, and biological encroachment on the surrounding ecological system by the aquatic organisms due to engineering problems, and environment pollution caused by unsuitable use of the matter.

Water budget

Close system

In a close system, the only sources of water are treated water and precipitation (see Figure 8-10). The water discharge is limited and cannot be refreshed; such systems often occur in dry areas.

FIGURE 8-10
WATER BUDGET OF THE CLOSE SYSTEM



The water budget of a close system is:

$$Q_{TWW} + Q_{RF} = Q_{EVAP} + Q_{TRAN} + Q_{DISC} \quad \textbf{(E. 92)}$$

Where:

- Q = water flow
- TWW = treated water
- RF = received precipitation
- $EVAP$ = evaporating capacity
- $TRAN$ =transpiration
- $DISC$ = water discharge

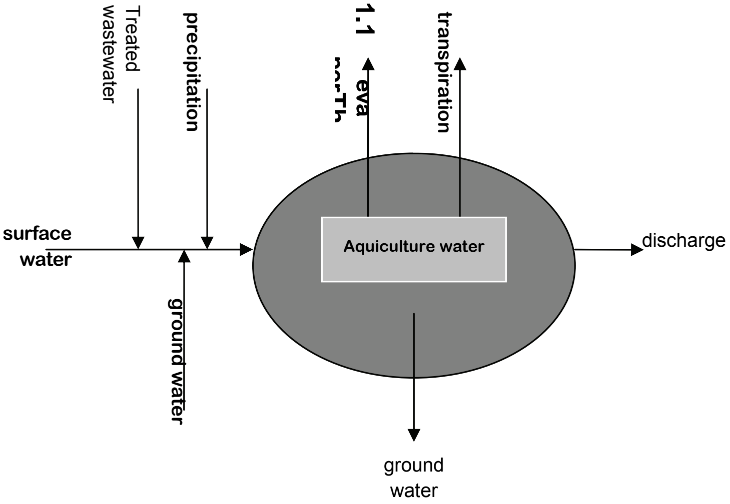
When treated water is the main source of water, there is no water discharge. The sum of treated water and precipitation is equal to or less than the sum of precipitation and evaporation:

$$Q_{TWW} + Q_{RF} \leq Q_{EVAP} + Q_{TRAN} + Q_{DISC} \quad \textbf{(E. 93)}$$

If the water in the weir is constant or decreases, the dissolved matter in the water will accumulate and the water quality will degrade. During design, measures should be taken to reduce water evaporation and transpiration or fresh water should be introduced.

<u>Open system</u>*;* an open system has sources of water other than treated water and rainfall (see Figure 8-11); its water discharge is high and its water turnover rate is high. Such systems are used in areas with abundant water.

FIGURE 8-11
WATER BUDGET OF THE OPEN SYSTEM



The water budget of an open system is:

$$Q_{TWW} + Q_{RF} + Q_{SF} + Q_{SW} = Q_{EVAP} + Q_{TRAN} + Q_{PW} + Q_{DIC} \quad \textbf{(E. 94)}$$

Where:

- SF = input of surface runoff, including artificially introduced water
- SW = seepage of ground water
- PW = leakage
- Other parameters are the same as with the close system.

In an open system, the sum of treated wastewater, precipitation, surface water, and seepage of ground water is often greater than the sum of water evaporation, transpiration, leakage, and discharge:

$$Q_{TWW} + Q_{RF} + Q_{SF} + Q_{SW} > Q_{EVAP} + Q_{TRAN} + Q_{PW} + Q_{DIC} \quad \textbf{(E. 95)}$$

Such as system has a positive water discharge. The continuous addition of fresh water and the water discharge from the pond prevent the accumulation of dissolved matter in water, thus keeping the water's good quality. During design, if surface runoff is artificially introduced, the retention period of water in aquaculture should be determined to ensure water quality, making full use of treated wastewater, and saving fresh water to preserve water resources.

Water quality control

Pollutant input control

Pollutants in aquaculture mainly come from treated wastewater, substances added during production, and the ecosystem. Precipitation can also bring some pollutants (such as dust); high precipitations may introduce dead plants and soil.

So drainage channels should be built to reduce the input of pollutants. The effective method to control pollutants is to exchange and refresh water.

Pollutant output control

Polluted input water and the metabolism of aquatic organisms can accumulate pollutants or create new pollutants. Discharging these pollutants into natural water bodies will pollute them. Many engineering processes can reduce pollution from aquaculture, but they are expensive. The most effective method is to use animals, plants, and microbes in water to remove input pollutants and reduce pollutants produced during production.

Self-purification

Any water body has a self-purification capacity due to physical chemistry and biochemistry processes; it varies depending on pollutants. The self-purification capacity of a close system is smaller than that of an open system because there is no exchange or refreshment; pollutants accumulate in ponds because there is no water output. In an open system, pollutants are less likely to accumulate. Whether the system is close or open, the input of pollutants must not exceed its self-purification capacity, otherwise pollutants will accumulate in aquatic organisms and the water quality will be bad, thus affecting the growth and survival of aquatic organisms.

Energy Budget

Up-flow design

Treated wastewater is pumped, which uses energy when outlets of wastewater treatment plants are lower than inlets of aquaculture units (up-flow). If adding fresh surface water requires pumps, then the energy needed will depend on the difference in height. Daily operation and maintenance of system (such as lighting and oxygen supply) also consume energy.

Down-flow design

When outlets of wastewater treatment plants are higher than inlets of aquaculture units, treated wastewater flows naturally, which does not use any energy (down-flow); in this case, energy consumption is just that of daily operation, which is lower than up-flow.

Materials

Construction

Materials for building ponds include cement, rolled products, metals, plastic plumbing, plastic anti-seepage film, brick, sand, lignum, glass, and power supply.

Operation and maintenance

Materials for operation and maintenance include chemicals used for monitoring, water, raw materials, and insecticides used during production.

8.6.4 Operation and maintenance

Inflow operation and maintenance include qualitative and quantitative adjustment of water inflow. Depending on the quality of water inflow, water quality requirements in the production, self-purification capacity of water, and requirements of water discharge, water sources of different quality are mixed and introduced into the ponds. If aquatic organisms need high quality water, the requirement for output water quality is strict, and the water has low self-purification capacity, the proportion of introduced treated wastewater should be low; otherwise, the proportion of treated wastewater can be increased.

Outflow; if the water inflow meets quality requirements and the operation process is normal, then the water outflow will meet the requirements. If the system has defects, supervision is poor, or operation does not work properly, then the water outflow must be treated further before discharge into the natural water body. If the primary production system has the potential of self-purification, then some of the output water can be recycled. If not, then a multi-system treatment unit may be needed to reach the purification objective. Such a unit could combine aquaculture and artificial swamp land.

Water body quality management and pollution control

Water quality monitoring and pollution control

Water quality monitoring is very important to control and maintain water quality in aquaculture. To monitor water quality parameters such as COD, BOD, SS, TP, TN, NH_4^+-N, and DO, there should be optimal monitoring points in the water inlet and outlet cross-sections and each water cross-section selected in different zones but also during planting and breeding. Thus real-time and on-line automatic monitoring systems can provide accurate data that can be compared to monitoring data in other countries. Pollution control is mainly to exchange water and refresh water; using products such as fish bait and pesticides rationally will prevent pollution and reduce the cost of aquaculture.

Substrate quality monitoring and pollution control

The water body, substrate, and hydrobios make a whole system. The characteristics of the substrate have a direct impact on the quality of the water body and hydrobios. The substrate can absorb the accumulated pollutants and degrade and transform organic matters in sediments to improve the water self-purification. Accumulated pollutants in the substrate can also cause secondary pollution, so the substrate needs to be monitored; substrate monitoring cross-sections should coincide with water monitoring cross-sections. Given that the substrate is stable and not much affected by hydrological and climatic conditions, its sampling should be less frequent than for water. The substrate should be treated when it has a negative impact on water quality. The method to treat substrate is to desalt it; given the large quantities of substrate and the necessity to stop production, desalting should be done only when pollution is important.

Production process management

Growth season management

Every species has its own ecological adaptability, growth and development law, and phonological phase. Aquatic species with different phonological phases should be selected to use environmental resources optimally all year round. Depending on the season, aquatic species have different physiological features and different endurance to various harmful environmental factors. For example, during the fish fry period, environmental requirements are stricter, food consumption is little, the ratio of treated wastewater to water inflow must be reduced, and bait supply must be controlled. The pollution purification of plants is also limited, but gets strong in the middle of growth and weak in the anaphase; therefore, the proportion of treated wastewater used should be little initially, then increased, and reduced in the anaphase to meet production requirements and the quality of water outflow.

In summer, the temperature and air humidity are high, the concentration of dissolved oxygen is low, while the vital movement of aquatic organisms is vigorous; so the concentration of dissolved oxygen must be increased. In seasons of high temperature and humidity, it is also important to prevent and control worms and diseases. The quantity of treated wastewater can be increased in rainy periods because of high precipitation; conversely, the quantity of fresh water should be increased during the dry season.

Pest control

Pests always occur during the growing season of aquatic animals or plants, which can affect the quality and quantity of aquatic production. The best is to control pest beforehand with environmental control and bio-control. When pesticides are needed, they should have low toxicity, low residue, and good environmental compatibility and be used efficiently to ensure environmental and product safety.

Harvesting

Harvest seasons vary with different growth cycles and production goals of different aquatic animals and plants. Harvesting one species should not have a negative impact on another's growth and development and harvesting in a season should not affect harvesting in the next season.

8.6.5 Unit cost assessment

Key cost items include the cost of land, construction, and operation.

Land; the cost of land depends on the surface area and the area unit cost, which depends on the location and the use of land. In general, the more advanced the regional economy, the higher the use of land and then the higher the land cost.

Construction; the cost of construction depends on the equipments and tools, and construction and engineering. Construction and engineering costs include the cost of labour, materials, machines, and management.

Operation; operation costs include the depreciation of fixed assets, consumables, equipment maintenance and repair, staff salaries, marketing, and training.

8.6.6 Human resources

In general, the staff includes the General Manager, Operation Manager, Environment and Security Project Manager, and operating staff.

8.6.7 Environmental impact

Positive

Reduce consumption of natural water resources; to some extent, reusing wastewater can reduce fresh water consumption and save fresh water resources.

Negative

Sanitation*;* pathogenic microbes and eggs of parasites from the treated wastewater can propagate diseases. There must be a strict hygienic control to prevent the spread of diseases and protect human population.

Pollutant accumulation in water body*;* pollutants can accumulate in the bottom with suspended solids, especially in a close system.

Pollutant accumulation in aquatic products*;* pollutants can accumulate in aquatic products and exceed the standards.

Ground water safety; the water discharged from aquaculture can seep into and pollute ground water.

Surface water safety; spills can also pollute surface water.

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9. SLUDGE FOR AGRICULTURAL REUSE

9.1 Introduction

The excess sludge from wastewater treatment plants (WWTP) contains significant amounts of nutrients that agricultural crops can use. Several countries in the world apply sludge in agriculture; it is convenient for the WWTP operator because it is an easy and relatively inexpensive way of disposing of sludge. It is also attractive for the farmers as they can reduce their use of expensive commercial fertilisers by replacing them with low-price sludge. The sludge's nutrient content provides nitrogen, phosphorus, and microelements for plant growth. Furthermore, the sludge's organic content increases the soil organic content. However, using sludge in agriculture also has its drawbacks, such as investment in sludge storage facilities, administration expenses, monitoring and compliance control.

Where agricultural reuse of sludge is permitted, the reuse is controlled by local regulations. In most cases, the factors limiting the agricultural reuse are heavy metal concentrations, pathogens, vector attraction, and contents of toxic organic compounds in the sludge. The legislation may also restrict other specific substances. Theoretically, any sludge can be used for agricultural purposes, but actual practices in the developed world tend to minimise the use of sludge that is not stabilised by long-term storage and/or addition of lime. The stabilisation ensures that the sludge has low or no pathogens and that the sludge is chemically stable.

9.2 Sludge characteristics and agricultural use

Sludge is the semisolid by-product of wastewater treatment that contains all of the compounds removed from wastewater and those added during the process. Sludge characteristics are affected by the wastewater treatment and can be classified by the place of origin during the treatment process (for more details, see Chapter 4 on sludge treatment).

The sludge composition depends mainly on the characteristics of the wastewater and the treatment process. If wastewater is exclusively domestic, the resulting sludge should have very low contents of heavy metals and toxic organic compounds and its potential for reuse in agriculture should be high. The decision of whether to use sludge depends on sludge characteristics such as total solids content, volatile solids content, pH, organic matter, pathogens, metals, and organic hazardous pollutants.

The quantity of sludge provides information on the total volume of sludge available for application. The total solids content of sludge indicates transportation and storage needs and possible application methods. Volatile solids describe the sludge's organic content and can help predict potential odour problems. The pH measures the acidity of the sludge and describes its potential to modify the soil's pH and all the associated effects in agriculture. Pathogens describe the potential of the sludge to cause diseases when used in agriculture; before agricultural use, however, the sludge is generally stabilised and very low pathogen counts should be expected. If domestic sludge is not stabilised, significantly higher number of pathogens are to be expected and sludge handling can be hazardous. The nutrients in the sludge are one of the main reasons for using sludge for agricultural purposes as fertiliser. The nutrients include nitrogen (in all species), phosphorous, potassium, and some microelements; their actual concentration depends on the nature of the wastewater and the treatment process. Metals are of concern and most of the legal restrictions relate to the contents of heavy metals. Organic chemicals are present in most wastewaters and therefore also in the sludge. Hazardous organic pollutants can harm humans and nature by their toxicity and reactivity.

9.3 General requirements for reusing sludge in agriculture

Local legislation controls sludge reuse in agriculture; therefore, it differs from country to country. In general, however, the potential reuse and application rate are based on the concentrations of nutrients, heavy metals, and organic pollutants. In some countries, the regulations for sludge use in agriculture are so strict that it is almost unviable. In the United States of America, the Clean Water Act (40 CFR part 503) regulates the reuse of sludge (EPA 1994). In Europe, Directive 86/278/EEC regulates the reuse of sludge; this directive is a minimum requirement and member states might have stricter regulations, depending on their needs or environmental goals.

The most common requirements for sludge reuse involve the level of sludge treatment (dewatering, stabilisation or specific treatments), restrictions on the content of heavy metals, dry solids, and nutrients, and limitations on soil pH, type of crop that can receive the sludge, and human access to the field and follow up.

9.3.1 Physical, chemical, and biological characterisation

The sludge characteristics vary depending on the origin of the sludge and the wastewater treatment. Before approving any use of sludge for agriculture, a thorough characterisation of the sludge must be performed. The characterization gives information that is useful for managing and assessing the suitability of the sludge. The physical characteristics describe the sludge in terms of how easy it is to process and handle (EEA, 1998). The chemical parameters indicate the presence of useful substances such as nutrients or toxic and/or dangerous compounds that will make the sludge unusable. The biological characterisation provides information on the micro-organisms and organic matter in the sludge.

The US regulation on sludge use for agriculture refers to sludge as bio-solids because it assumes that the sludge is stabilised; it sets four groups of limits for metals: ceiling concentration, pollutant concentration, cumulative pollutant loading rates, and annual pollutant loading rates. The ceiling concentration limit (in mg/l) is the maximum allowable concentration of a pollutant in the sludge for land application. Pollutant concentration limits for EQ (exceptional quality) (in mg/l) are the most restrictive concentrations for pollutants, generally found in commercial pre-packed sludge. Cumulative pollutant loading rates (in kg/ha) are the maximum amounts of pollutant that can be applied to a site or a field. The annual pollutant-loading rate (in kg/ha per 365 days) is the maximum amount of pollutant that can be applied to a site or field within a 12 month-period (Table 9-1). The EU directive limits metal concentrations in the sludge and restricts the use of sludge for agricultural purposes depending on heavy metal concentrations in the receiving soils (Table 9-2).

TABLE 9-1
US POLLUTANT LIMITS FOR SLUDGE REUSE

Pollutant	Ceiling concentration limits for all bio-solids applied to land (mg/kg)[a]	Pollutant concentration limits for EQ bio-solids (mg/kg)[a]	Cumulative pollutant loading rate limits for bio-solids (kg/ha)	Annual pollutant loading rate for bio-solids (kg/ha/365 day)
Arsenic	75	41	41	2,0
Cadmium	85	39	39	1.9
Chromium	3,000	1,200	3,000	150
Copper	4,300	1,500	1,500	75
Lead	840	300	300	15
Mercury	57	17	17	0,85
Nickel	420	420	420	21
Selenium	100	36	100	5.0
Zinc	7,500	2,800	2,800	140

[a] Dry weight

Source: modified from Part 503, 1994

TABLE 9-2
EU LIMIT VALUES FOR SLUDGE REUSE

Pollutant	Limit values for heavy-metal concentrations in sludge for use in agriculture land (mg/kg)[a]	Limit values for concentrations of heavy metals in soil (mg/kg)[a]	Limit values which may be applied to land based on a 10 year average (kg/ha/365 days)
Cadmium	20 to 40	1 to 3	0.15
Copper	1,000 to 1,750	50 to 140	12
Nickel	300 to 400	30 to 75	3
Lead	750 1,200	50 to 300	15
Zinc	2,500 to 4,000	150 to 300	30
Mercury	16 to 25	1 to 1.5	0.1
Chromium	-	-	-

[a] Dry weight

Source: modified from 86/278/EEC, 1986

Danish limit values for some of the metals are even stricter than in the EU directive (Table 9-3). The Danish law also limits the content of some of the metals in relation to the contents of nutrients (phosphorus) in the sludge.

Biological recommendations deal mainly with pathogen reduction and vector attraction to minimise health risks at the site of application. According to Jiménez and Wang (2006), the highest risk comes from salmonella and helminths.

TABLE 9-3
DANISH LIMIT VALUES FOR SLUDGE REUSE

Pollutant	Limit values for concentrations (mg/kg)[a]	mg/kg of total phosphorous
Cadmium	0,8	100
Copper	1,000	
Nickel	30	2,500
Lead	120	10,000
Zinc	4,000	
Mercury	0,8	200
Chromium	100	-

[a] Dry weight

Source: modified from Ministry of Environment and Energy, 2003

9.3.2 Sampling and analysis

The EU directive 86/278/EEC recommends that sludge be analysed at least once every six months if the sludge production and quality are stable. If there are changes in the operation of the wastewater treatment system and sludge production, there should be more frequent sampling and analysis. The analysis should cover the following parameters:

- Dry matter;
- Organic matter;
- pH;
- Nitrogen and phosphorous; and
- Cadmium, copper, nickel, lead, zinc, mercury, chromium, and arsenic.

Since restrictions also apply to the receiving soils, soils should also be analysed, but only for pH and metals. The USA requires similar analyses (EPA, part 503, 1994).

The Danish environmental authority requires a minimum of sampling according to a fixed volume of dry sludge produced per year (every 2000 m^3). Denmark also requires analysing other environmentally noxious substances, i.e., linear alkylbenzene sulfonates (LAS), polycyclic hydrocarbons (Σ PAH), nonylphenols (NPE), and phthalates (DEHP) (Ministry of Environment and Energy, 2003).

TABLE 9-4
DANISH LIMITS FOR ENVIRONMENTALLY NOXIOUS SUBSTANCES

Pollutant	mg/kg as dry weight
Alkylbenzene sulfonates (LAS)	1,300
Polycyclic hydrocarbons (Σ PAH)	3
Nonylphenols (NPE)	10
Phthalates (DEHP)	50

Source: modified from Ministry of Environment and Energy, 2003

9.3.3 Risk assessment

The risk assessment should take into account the sludge characteristics, application site conditions, local environmental characteristics and restrictions, and the possibility of human and animal exposure to the sludge.

9.4 Factors affecting sludge reuse

9.4.1 Geographical factors

The local climate and agricultural practices can affect the potential for sludge reuse in agriculture. The nutrient demands of the agricultural crops depend on the climate and the type of crop. The sludge application rate should meet the crops demand, which will affect the reuse potential of the sludge. In Denmark, the maximum allowable sludge application rate is 170 kg N/ha.year and 30 kg P/ha.year.

Transportation costs depend on the distance between the sludge production site and the application place. Generally, farmers cover these expenses; the use of the sludge for agriculture depends on the potential economic benefits for the farmers.

9.4.2 Socio-Economic factors

Although using sludge as a source of nutrients for the plants is a natural and environmental friendly way to handle a waste product, the general population may resist because they perceive sludge as hazardous. For the farmers, sludge is a resource, due to its fertilising potential and the associated benefits of its organic material. Local legislation should control the balance between perceptions and benefits and reassure the public by minimising threats to health and the environment. Once proper legislation and control are in place, farmers will decide on using sludge in agriculture depending on the expected benefits. Using sludge for agriculture requires some investments and operation costs to transport the sludge from the production site to the farms (costs vary depending on the type of sludge), store, spread, and plough the sludge, sample and analyse the sludge and soils, and bureaucratic and administrative expenses.

FIGURE 9-1
DEWATERED SLUDGE READY FOR TRANSPORT

08/02/2005

9.4.3 Environmental factors

The local legislation addresses environmental issues associated with the use of sludge in agriculture. The most common restrictions for using sludge in agriculture are the level of sludge pre-treatment, concentrations of heavy metals in the sludge and in the receiving soils, the application rates according to metal content, and the contents of toxic organic contaminants. Additional restrictions might include the amount of nutrients applied, distances to watercourses, the type of crop, and a restricted accessibility of farms where sludge is applied. Other environmental factors that may be considered include gas emissions (odours), surface and ground water conditions, noise, safety (risk of exposure to pathogens), and energy needs.

9.5 Conservation and usage of sludge

Sludge for agricultural use is usually stored at the production place or in some instances at the site of application (see Figure 9-2). The decision depends on the state of the sludge; in both cases, storage facilities are needed. When liquid sludge is used, the possible storing alternatives include digesters, holding tanks or lagoons. If the sludge is already dewatered, the most common storage alternative is at the application site; in any case, the weathering effects on the sludge should be avoided as well as possible nuisances due to odours and vector attraction. The design of a storage facility should take into account factors such as solid concentration, stability of the sludge nutrient, and organic matter and pathogen concentration.

FIGURE 9-2
STABILISED SLUDGE IN A STORAGE FACILITY

Source: www.cambi.no, 2006

9.6 Management practices

Sludge application for agriculture requires management practices to be economically viable and environmentally safe. The application scheduling depends on the climate, soil properties, growing seasons, and plant requirements. Sludge should not be applied when the soils are frozen, covered by snow, or flooded. Sludge should not be applied during heavy rainfalls that can wash off the surface. In very hot weather, sludge application might volatilise nutrients. Sludge application must meet plant needs and comply with the agronomical rates (depend on the crop, soils, and climate). Sludge application on soils should not affect surface water quality or threaten natural plant and animals.

FIGURE 9-3
SLUDGE SPREADING ON THE FIELD

Source: www.cambi.no, 2006

When applying sludge where forage and crops for human consumption are grown, some restrictions apply depending on the crop and the possibility of exposure to the sludge. The EU directive prohibits the use of sludge for grassland or forage crops before a minimum elapsed time (recommends at least 10 months, but leaves member states free of shortening the period). The directive also prohibits using sludge for crops such as fruits and vegetables and restricts the time for using sludge where fruits and vegetables are grown (86/278/EEC, 1986).

The USA restricts the time of crop harvesting on soils fertilised by sludge (EPA, 1994). For crops growing above the soil surface, harvesting should start only 14 months after application. For crops growing under ground, the harvesting restriction period extends to 20 months. Harvesting time restrictions also apply to crops for forage, grasslands, and for the use of sludge in places of possible public access (parks, fields, and forests).

9.7 Crop and soil vigilance

Sludge use can affect crops depending on where they grow and whether there can be exposure to the sludge. Consequently, crops can be divided into three groups:

1. Without any contact with the soil (oranges, apples, corn, etc.);
2. In contact with the soil (tomatoes, cucumbers, lettuce, etc.); and
3. Below ground level (potatoes, onions, beets, etc,).

In all cases, the local sludge directives limit the time of sludge use before harvesting, consumption, or exposure.

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www.cambi.no/References/**sludge**/default.htm

10. FINANCIAL AND ECONOMIC ASPECTS

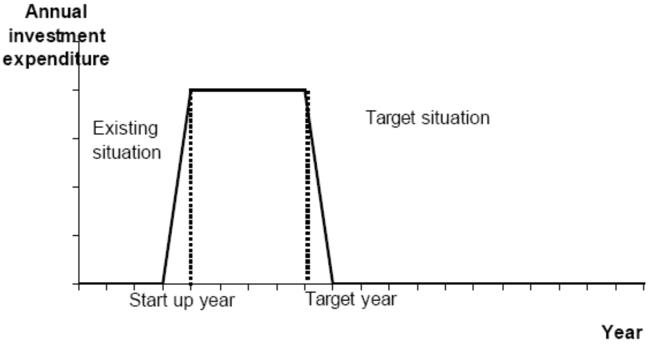
10.1 Economic Basic Concepts for WWTS Evaluation

This chapter provides engineers with the basic principles and practices of engineering economics to assess and compare the costs of various WWTS and assess financially and economically the cost efficiency of the "Low Cost" WWTS solutions described in the preceding chapters, especially when compared with more conventional treatment processes. This chapter also explains how to conduct a basic engineering economic analysis of alternative WWTS for effective decision-making.

10.1.1 Investment expenses

Investment cost or capital expenses (or CAPEX) are the total investment expenses resulting from the construction of new infrastructure or facilities. Figure 10-1 shows a standard time profile for implementing an investment; this profile assumes an implementation in equal shares over the implementation period.

FIGURE 10-1
TIME PROFILE OF AN INVESTMENT



In the case of natural low cost WWTS, the investment cost can vary widely depending on the siting and characteristics of the plant to be built. In general, the following main investment elements may be included:

- Cost of the land;
- Site investigation;
- Site clearing;
- Earthwork and excavation;
- Basin construction when required;
- Pipes drains when necessary;
- Berm construction and grading of slopes;
- Gravel media where necessary;
- Rooting media when adequate;
- Inlet and outlet structures;
- Transmission line to the site;
- Pumping station where necessary;

- Liner (if the soil is permeable, an additional cost for lining of the lagoons may be necessary to consider);
- Fencing;
- Miscellaneous piping; and
- Engineering, legal, contingencies, and contractor's overhead and profit.

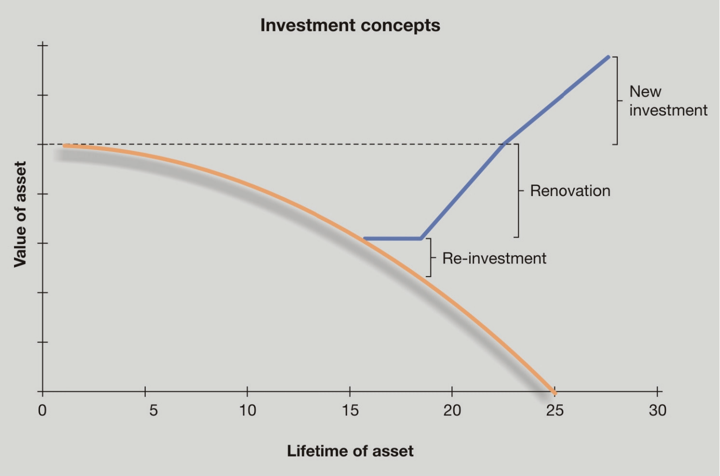
Other investment related costs may include buildings, roads, relocation of residents, and purchase of water rights.

When necessary, the liner and the gravel media are often the most expensive items. For example, a plastic liner can cost 40 percent of the total cost of construction. In many cases, however, compacting in-situ native soils provides a sufficient barrier against ground water contamination.

Service extensions, renovation, and re-investment

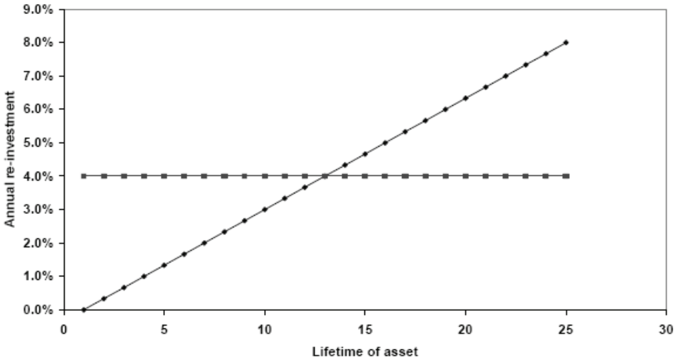
Service extensions, renovation, and re-investment can also result in expenses of the same size and with the same time profile as investment cost. Figure 10-2 shows how the relationship between maintenance costs, renovation, and new investments and the asset value of the infrastructure develops over time.

FIGURE 10-2
RELATIONSHIP BETWEEN SERVICE EXTENSIONS, RENOVATION, AND REINVESTMENT AND THE ASSET VALUE OF THE INFRASTRUCTURE



Re-investment costs are estimated as the annual depreciation of the infrastructure and assumed to increase over the lifetime of the asset. In the first year, there is no re-investment; then, there is a constant increase during the life time of the infrastructure (see Figure 10-3 where the horizontal line assumes a constant yearly real reinvestment over the lifetime of the invested asset considered to be 25 years. The slant line assumes an incremental linear real increase of the re-investment costs over the lifetime of the assets. Both profiles yield a complete reinvestment of the assets after 25 years).

FIGURE 10-3
TYPICAL RE-INVESTMENT PROFILES



Renovation costs are the investments that will increase the value of the system reaching partially or fully the originally designed level, while re-investment just keeps the value constant. There is a close link between reinvestment and renovations/rehabilitation. If there is no reinvestment over a period, then there should be renovation at the same amount as the accumulated re-investment to restore the value of the system. The cumulated value of reinvestment not carried out is called “backlog of maintenance”. This is a key indicator of the value of the infrastructure and its operational effectiveness. Operational costs will increase if there is no necessary reinvestment; after some time, operations will even stop.

Service extensions are extensions or improvement of the infrastructure. Investments in service extensions will increase the annual depreciation and thus the annual re-investment costs.

10.1.2 Operation and maintenance costs

O&M costs for natural WWTS are usually very low, compared to conventional treatment systems, hence the “low cost” character of such treatment processes.

Operational expenses (or OPEX) include expenses for the daily operation and maintenance of the infrastructure or equipment. These costs occur periodically throughout the life of a project. They vary depending on the design and process of the WWTP systems. For low cost WWTS and depending on the type of system, they may include:

- Hydraulic and water depth control;
- Pumps and valves lubrication;
- Inlet/outlet structure cleaning;
- Grass mowing on berms;
- Vegetation management;
- Mosquito and vector control (if necessary); and
- Routine monitoring.

Because most natural WWTS operate by gravity flow (i.e., pumps and other electrical devices are not required), they do not require intensive maintenance and power costs are minimal. In general, labour requirements for natural WWTS are less than for conventional wastewater systems. For harvesting crops, more labour is required. Vegetation grown on natural WWTS may have to be harvested routinely. In a constructed wetland, the plant uptake of pollutants represents a relatively minor pathway, so harvest and removal on a routine basis does not provide a significant treatment benefit. Removing accumulated litter may become necessary if there are severe restrictions to flow. Generally, this occurs only if the lagoons or wetland inlet and outlet channels are relatively narrow or when channels banks have relatively steep slope.

Vegetation management may also include wildlife management, depending on the type of vegetation selected for the system. Animals such as nutria and muskrats are known to consume all emergent vegetation in constructed wetlands.

Systems using sprinklers should have a regular inspection and cleaning schedule, including regular draining of lines and pipes in seasonal operation to avoid corrosion. Pumps, valves, and other mechanical elements require routine maintenance, including lubrication.

The water depth in a natural WWTS may need adjustment on a seasonal basis or in response to increased resistance from the accumulating plant litter in the wetland channel. Mosquitoes may require control, depending on local conditions and requirements. The mosquito population in the treatment wetland should be no greater than in adjacent natural wetlands. In some systems, recycling the secondary effluent will allow a higher hydraulic loading rate and therefore a smaller basin system. Basins receiving influent at high application rates from algal laden facultative lagoons and polishing ponds often experience rapid clogging. In certain types of land systems, the operator has to periodically preserve the design infiltration capacity of the basins. The operator should inspect the basins daily and record drainage time to track the infiltration rate.

Routine monitoring is important. Although some analytical work is essential to ensure proper operation of any natural WWTS, an all-embracing sampling and monitoring program is usually not necessary. Routine water quality monitoring is also required for all WWTS systems with a discharge permit into receiving water. The permit specifies the monitoring requirements and frequency of monitoring.

Sampling for permit monitoring is usually limited to untreated wastewater and the final system effluent. Since a natural WWTS is usually preceded by some form of preliminary treatment, the routine monitoring program does not document wetland influent characteristics. Periodic samples of the system influent and effluent beyond permit requirement may also be desirable for all but the smallest systems to provide the operator with an understanding of system performance and a basis for adjustments, if necessary.

O&M of individual systems

O&M of onsite treatment systems essentially include regular monitoring of the sludge and scum layers in all chambers of the septic tank or comparable chambers. Septic tank should be pumped when the thickness of the sludge layer and the scum layer exceeds 1/3 of the septic tank's total height. Failure to pump a septic system will result in solids flowing out to the drainfield, which will clog the soil pores and cause drainfield failure. The cost of pumping a septic tank regularly is small relative to the cost of replacing a drainfield.

Monitoring the condition of the drainfield periodically is also desirable. It includes the control for standing water on the soil surface, observation ports, and areas of massive plant growth. Massive plant growth can indicate: 1) leaks (if massive plant growth is only in one small area of the drainfield) and/or 2) subsurface mounding of septic tank effluent resulting from an undersised or clogged drainfield (if the massive plant growth is throughout the drainfield or in the area of lowest elevation).

Maintenance expenses

Maintenance is needed to upkeep and replace the infrastructure to maintain the lifetime expectancy of the system. For many natural WWTS, this includes essentially inspecting berms integrity and monitoring dikes for signs of erosion. In some cases, earthen structures used as impoundments must also be inspected for rodent damage. Dikes and berms for ponds require regular investigation to check for burrowing animals or decay/destruction of the structure and liner material.

In some land systems, restoring the infiltrative surface may be necessary when the infiltration rate decreases. Accumulated organic deposits are typically removed at least annually, and the infiltration surface is raked, disked or tilled to restore infiltration capacity. On a more extended interval, it may be necessary to remove the top few inches of soil to expose clean material. Repairing dikes, fences, and road every 10 years may also be desirable.

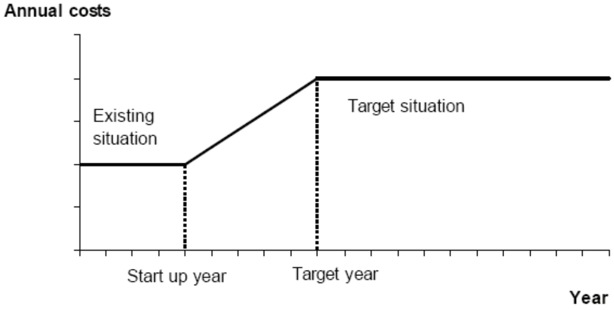
Replacement of equipment

In low cost WWTS, replacing equipment is often part of the maintenance if the replacement extends the lifetime of the system. Maintenance necessary to operate the infrastructure, but not extending the lifetime of the infrastructure as such, is included in the operational expenses.

In practice, however, it may not be possible to separate all minor replacements from operational procedures. The operational expense of existing infrastructure or equipment is based on the operational expense of new equipment. Using a standard breakdown of expenses on items like energy, chemicals and labour, and price indicators that incorporate the local price level for each item, local prices can be corrected. A scaling factor can also be included to take into account specific local conditions, which otherwise cannot be included.

Figure 10-4 shows a typical time profile for operational and maintenance costs. Input data on the existing situation determine the level of costs in the first period, while data on the target situation determine the last period. Between these points in time, the investment and/or changes in the mode of operation to achieve the target take place. Such a time profile shows that the target implies extending the infrastructure, which causes a gradual increase of annual operational costs as the new infrastructure is being built.

FIGURE 10-4
TYPICAL O&M COST PROFILE



10.1.3 Fixed and variable costs

Fixed and variable costs refer to various elements of O&M costs

Fixed costs: remain fixed whatever the level of activity of the WWTS; they may include land lease, monitoring costs, vegetation management costs, administrative staff, insurance, permits, etc.

Variable costs: change with the level of activity of the WWTS; they may include direct material and consumables, energy supply and lubricants, seasonal or part time direct labour costs, etc.

10.1.4 Inflation

The inflation is the rise in the general level of prices, as measured against some baseline of purchasing power. In project analysis, it is customary to use constant prices, i.e., prices initially adjusted for inflation but then fixed at a base-year. However, in the analysis of financial flows, current prices may be more appropriate; these are nominal prices effectively observed year by year. The effect of inflation, or rather the general increase in the price index, or oscillations in relative prices, may affect the calculation of the financial return on the investment. Therefore, using current prices is in general recommended.

Nominal numbers --such as nominal wages, nominal interest rates or nominal investment value-- refer to amounts that are paid or earned in money terms of the day. A pay check shows money wage and a loan agreement for a wastewater treatment plant indicates the nominal interest rate.

NOMINAL AND REAL COSTS

A nominal (or current) cost is the cost of anything expressed in money of the day, which means taking into account the impact of inflation. A real (or constant) cost does not take inflation into account.

Real numbers --such as real wages, real interest rates, or real gross domestic product-- are corrected for the effects of inflation. They indicate the value of these numbers in terms of the purchasing power of wages, interest, or production. That is, they calculate how many goods and services a wage, an interest payment, or an income will really buy.

The relationship between a real rate and a nominal rate for a specific inflation rate is:

$$R_n = (1 + R_r)(1 + R_i) - 1 = R_r + R_i + R_r R_i \quad \textbf{(E. 96)}$$

Where:

- R_n = nominal rate
- R_r = real rated
- R_i = inflation rate.

For example, a real rate R_r of 8 % and an inflation R_i of 4 % yield a nominal rate R_n of 12.32 %.

10.1.5 Discount rate

To compare investments over time, a decision maker needs to use a discount rate to reduce the flows of benefits and costs to a present value. The basic idea is that there is a time value of money. Table 10-1 shows a simple example based on a discount rate of 10 %. As an alternative of consuming €100, the money can be invested at say 10 % per year for 4 years. Then, today, the backward discounted value of €146 in year 4 is €100.

TABLE 10-1
TIME VALUE OF MONEY

Choice	Time/consumption				
	Now	Year 1	Year 2	Year 3	Year 4
Consume Today	€100	0	0	0	0
Invest	€100	0	0	0	€146

Three main concepts can help explain the choice of discount rates:

1. Social time preference;
2. Cost of funds; and
3. Opportunity cost of capital.

The social time-preference or social discount rate is completely free of all risk and uncertainty; it is appropriate in an economy of stable prices and economic conditions where the value of goods and services does not experience unexpected changes. The best approximation of social discount rate is the interest rate on long-term government bonds of small denominations sold directly to savers.

The cost of funds, or market rate of interest, reflects the price instability, risk, and uncertainty that the market assigns to a project over time. This should also include the inflation risk that the market assigns over time. Often used to reflect this discount rate is the government long-term bond rate for government projects, which is usually higher than the social rate of discount.

The opportunity cost of capital is what the rate funds would yield if invested in projects at the highest available yields. This is normally the highest discount rate. Using this discount rate infers that the wastewater treatment project is equal to any other investment that the public agency can make.

10.1.6 Present Value: discounting

The concept of time preference of money leads to calculating the present value of an investment by discounting the future backward to the present. The basic discounting formula is $1/(1+r)^t$ where r is the discount rate and t is the number of years in the investment. The present value of a cash flow reflects in today's terms, the value of future cash flows adjusted for the cost of capital. The calculation formula is:

$$\sum_{t=0}^{t=n} \frac{B_t}{(1+r)^t} \quad \textbf{(E. 97)}$$

Where:

- B = net cash flow (revenues minus costs) of the project each year
- r = discount rate
- t = number of years

Exercise: *calculate the present value of the yearly operation cost of a WWTP (750 m^3/d) in real and nominal terms over 25 years assuming that the operational cost is today €0.1/m^3 and grows at 3% per year, with an inflation of 4%. Assume a real discount rate of 6%.*

Cost	*Year 0*	*Year 1*	*Year 2*	*Year 15*	*Year 25*
Real Cost (annual growth of 3%)	*27,375*	*28,196*	*29,042*	*42,649*	*57,317*
Nominal Cost (inflation of 4%)	*27,375*	*29,324*	*31,412*	*76,809*	*152,798*
Discounted real cost (6% real discount rate)	*27,375*	*26,600*	*25,847*	*17,796*	*13,355*
Discounted nominal cost (10.24% nominal discount rate)	*27,375*	*26,600*	*25,847*	*17,796*	*13,355*

The present value of the cost using real or nominal value remains the same (€481,359). The calculated present value does not take into account the cost for year 0 because the WWTP was under construction in year 0 and did not incur operation costs.

10.1.7 Net Present Value (NPV)

The Net Present Value (NPV) is the sum of the present value of the stream of discounted benefits and future costs minus the capital cost of the project. The criterion for an investment is to invest only if NPV is positive. Table 10-2 shows the PV calculations for two projects, one with an initial investment of $100 and the other with an initial investment of $200. Numerous standard spreadsheet programmes have financial functions including a PV function and a NPV function, which allow the easy calculation of the present value and net present value of series of cost and revenues streams for a given discount rate.

TABLE 10-2
EXAMPLE OF DISCOUNTING DIFFERENT SIZE PROJECTS

	Capital K	Benefits (year 1)	$\frac{B}{(1+r)^n}$ PV 3%	$\frac{B-OC}{K}$ at 3%
1st project	\$100	\$110	107	1.07
2nd project	\$200	\$218	211	1.06
OC = operating cost (equal 0 here) At 3% Project 1 PV = 110/1.03 = \$107 NPV = \$7 Project 2 PV = 218/1.03 = \$211 NPV = \$11				

Exercise: *calculate the Net Present Value of the WWTP Project in the preceding exercise with the following assumptions: investment of €470,000, construction in year 0, beneficiaries of WWTP paying a wastewater tariff of €0.12/m^3 increasing at 2% per year, and sale of treated wastewater for agriculture generating a constant real revenue of €0.14/m^3. The calculation is in real terms.*

Operation cost and revenues in year 0 are not considered because the WWTP is under construction in year 0; no tariff is collected in year 0 either (no service to user); there is only the investment cost. The Net Present Value is positive, which shows that the project is financially viable.

Item	*Present Value*	*Year 0*	*Year 1*	*Year 2*	*Year 15*	*Year 25*
Investment Cost	***-470,000***	***-470,000***				
Discounted O&M Cost (6% real discount rate)	***-481,359***	*-(27,375)*	***-26,600***	***-25,847***	***-17,796***	***-13,355***
Revenue from tariff (annual growth of 2%)		*(32,850)*	*33,507*	*34,177*	*44,212*	*53,894*
Discounted revenue from tariff (6% real discount rate)	***+517,466***	*(32,850)*	***31,610***	***30,418***	***18,448***	***12,557***
Revenue from water sale		*(38,325)*	*38,325*	*38,325*	*38,325*	*38,325*
Discounted revenue from sale (6% real discount rate)	***+489,922***	*(38,325)*	***36,156***	***34,109***	***15,992***	***8,930***
Total	***+56,029***					

10.1.8 Internal Rate of Return (IRR)

The IRR is the rate of discount that reduces the cash flow of a project to a zero NPV. The IRR is the statement of expected yields over the life of the project---or the average annual yield of the investment. The investment criterion is to invest only if the IRR is greater than the opportunity cost of capital. The IRR is the *r* (rate of discount) for which:

$$\sum_{t=0}^{t=n} \frac{B_t}{(1+r)^t} = 0 \quad \textbf{(E. 98)}$$

Unfortunately, there is no easy method for determining the correct *r,* except trial and error. Numerous standard spreadsheet programmes have under their financial functions an IRR function, which provides an easy iterative calculation of the IRR for series of cost and revenues streams.

Exercise: *for the WWTP project of the preceding exercise and using the same assumptions about costs and revenues, calculate the IRR of the project. The trial and error process shows that the IRR is between 7 and 7.274%; it is actually 7.27%.*

Real rate of discount (%)	*Net Present Value*
6.00 %	***+56.029***
8.00 %	***-27.737***
7.00 %	***+11.224***
7.274%	***+10***

10.1.9 Project Financial Viability Indicators

The two criteria best suited for determining whether to undertake a wastewater project are the NPV and IRR:

1. If the NPV of the stream of benefits and costs of a project is greater than zero, the project is economically feasible; and

2. If the IRR of the project is above the cost of capital used to finance the project, the project is economically feasible.

When evaluating a project, benefits and costs clearly accrue over many years. Thus, it is necessary to estimate the project's present value, which is the sum of the discounted cash flows produced by the project over time.

10.2 Treatment Options Comparison Techniques

Deciding on a centralised or decentralised WWTS is a complex process, often beyond the understanding of beneficiary communities, especially smaller townships and villages where natural WWTS may be the most desirable alternatives. There are many strategies and technologies available within the centralised and decentralised wastewater treatment sectors. This section presents a brief overview of the analytical tools and methods to assess the impacts of such wastewater treatment alternatives during the decision making process. Balkema *et al.* (1998) reviewed 15 publications and identified 35 parameters --economic, environmental, technical, and socio-cultural criteria-- to assess the suitability of wastewater treatment systems. Table 10-3 presents an overview of the parameters and shows the complexity of the issues to be considered. The table shows the variety of questions that can be asked to understand the sustainability of a technology; there are 21 parameters to assess only environmental sustainability.

When the community is smaller and the alternative is between a conventional or natural wastewater treatment system, there are simpler assessment techniques such as:

- Life-cycle assessment (LCA);
- Environmental impact assessment (EIA); and
- Open wastewater planning (OWP).

TABLE 10-3
OVERVIEW OF PARAMETERS USED TO COMPARE WASTEWATER TREATMENT

Source:
Aa = Aalbers 1997
Az = Azar 1996
Be = Bengtsson 1997
Bu = Butler 1997
D = DTO 1994
Em = Emmerson 1995
E = ETC 1996,
F = Finnson 1996
I = Icke 1997
J = Jacobs 1996
L = Langeveld 1997
N = Niemcynowicz 1994
O = Otterpolh 1997
S = STOWA 1996
Ø = Ødegaard 1995

Note: The numbers in the table indicate the used weighting factors, the abbreviations refer to the terms used in the publications; C = costs, Cn = concerns, E = environmental efficiency, P = principles for sustainability, S = sustainability factors, St = steering variables, T = target, Te = technical paradigm, V = variables in the LCA input-output table, * = LCA study.

	Aa	**Az**	**Be***	**Bu**	**D**	**Em***	**E**	**F**	**I**	**J**	**L***	**N**	**O**	**S***	**Ø***
Economical criteria:															
Costs	2				C		S	P		E	C				E
Environmental criteria:															
Accumulation		P							T						
Biodiversity / land fertility		P			100		S	P					P		
Dissication													Cn		
Export of problems in time & space									T	S			P		
Extraction		P													
Integration in natural cycles							S						P		
Land area required / space	2				1										
Odour/ noise / insects/ visual	0.5														
Optimal resource utilisation / reuse:		P		S			S	P	St	S		P	P		
Water	2			S	1000		S	P	St		V		Cn		
Nutrients	2		V	S			S	P	St				Cn		
Energy	2		V		100	V	S	P			V		Cn	V	V
Raw materials			V		10	V	S	P			V		Cn	V	
Pathogen removal / health	1			S	1000		S	P			V				
Pollution prevention				S			S	P				P	P		
Emissions:															
BOD / COD	1		V		1000	V	S				V			V	V
Nutrients	1		V		100		S				V			V	V
Heavy metals	1				1000	V	S				V			V	
Others	1		V			V	S				V			V	
Sludge / waste production			V		1000	V	S				V			V	V
Use of chemicals			V		10		S								
Technical criteria:															
Durability				S			S								
Ease of construction / low tech	1											P			
Endure shock loads / seasonal effects	1												Cn		
Flexible / adaptable				S			S								
Maintenance	2												Cn		
Reliability / security	1						S	P							
Small scale / onsite / local solution				S						Te	V	P			
Social-cultural criteria:															
Awareness / participation							S			S					
Competence / information requirements	1						S	P							
Culturally accepted							S								
Institutional requirements	1						S	P							
Local development				S											
Responsibility								P							

Source: Balkema *et al.* (1998)

The LCA estimates the environmental impacts of a product, service, or process over the course of its life cycle from extraction of materials to disposal or reuse of the final product. The EIA (see Chapter 11) is a framework for identifying, predicting, evaluating, and mitigating the biophysical, social, and other effects of proposed projects or plans and physical activities. The OWP is an approach to wastewater decision making that broadens the boundaries of options considered and expands typical evaluation criteria to include indirect environment impacts.

Both the LCA and EIA methodologies evaluate the environmental impacts of human actions. The OWP evaluates wastewater treatment alternatives using a wider framework for consideration. The main difference between LCA and EIA is that the LCA attempts to provide a systematic method for estimating environmental impacts, while the EIA provides more of an interpretive process. Through comprehensive analysis and aggregation, the LCA identifies mere changes or displacements of environmental problems in space or time. The EIA is much less standardised in its quantification of impacts and instead changes its analyses in response to the uniqueness of place and process. The OWP tends to be less formalised and may be adapted to either the LCA degree of analysis or EIA style of interpretation.

The paragraphs below describe the three methodologies.

10.2.1 Life-Cycle Assessment (LCA)

The environmental life-cycle assessment (ELCA), commonly referred to as life-cycle assessment or life-cycle analysis (LCA), estimates the environmental impacts of a product, service, or process over the course of its life cycle. In its broadest definition, the LCA sums up all environmental burdens that occur from “cradle to grave” during a product’s or service’s life cycle:

- Extraction of raw materials;
- Transportation;
- Manufacturing;
- Operation;
- Maintenance;
- Reuse; and
- Disposal.

The environmental burdens generally include use of land, energy, water, and other materials and the release of substances (harmful and beneficial) to the air, water, and soil. In the case of a low cost WWTS, an important aspect to consider may well be the ability of the project to remove pathogens.

A typical environmental LCA proceeds as follows:

1. **Goal and scope definition:** includes the purpose of the study, the system boundaries, and the functional unit. A material and energy flow chart is also mapped.

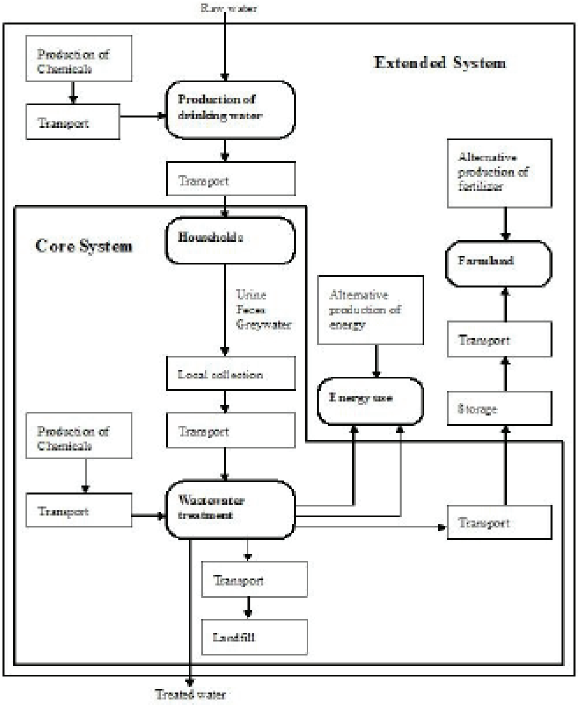
2. **Life-cycle inventory (LCI):** all information on emissions and the resource consumption of the activities in the system under study are catalogued.

3. **Life-cycle impact assessment (LCIA):** the environmental consequences of the inventory are assessed and sensitivity analyses are developed. This typically includes aggregating the inventory into impact categories.

4. **Interpretation:** this fourth but controversial step occasionally included by some LCA methods is the interpretation of the results, which may include normalisation, weighting, and/or additional aggregation.

Figure 10-5 shows the typical LCA boundary for a wastewater treatment plant.

FIGURE 10-5
FLOW-CHART OF LCA BOUNDARY FOR A WASTEWATER TREATMENT PLANT



Source: Adapted from Tillman *et al.* (1998)

The concept of life-cycle assessment first emerged in the late 1960s, but did not receive much attention until the mid-1980s (Ecobilan undated). In 1989, the Society of Environmental Toxicology and Chemistry (SETAC) became the first international organisation to oversee the advancement of LCA. In 1994, the International Standards Organization (ISO) began developing standards for the LCA as part of its 14000 series standards on environmental management. The standards address both the technical details and conceptual organisation of the LCA:

- ISO 14040—A standard on principles and framework;
- ISO 14041—A standard on goal and scope definition and inventory analysis;
- ISO 14042—A standard on life-cycle impact assessment; and
- ISO 14043—A standard on life-cycle interpretation.

Several of the methods described as LCA methods follow the LCA framework defined in ISO 14040, involving an inventory similar to that described in ISO 14041, and assessment of impacts to some degree as described in ISO 14042, while a smaller number take on the normalisation and weighting also discussed in ISO 14042. Still, methods based on the ISO standards may differ greatly, given that the ISO standards allow flexibility to customise characterisation and normalisation factors and weighting methods to suit the values and conditions of a particular location or sector.

10.2.2 Environmental Impact Assessment (EIA)

The EIA is the process of identifying, predicting, evaluating, and mitigating the biophysical, social, and other relevant effects of proposed projects or plans and physical activities prior to making major decisions and commitments. The EIA as a procedural concept was introduced in Europe after the EIA Directive (Directive 85/337/EEC amended by 97/11/EC and 2003/35/EC), which mandates that all planning agencies systematically integrate environmental concerns into the planning and decision making for all projects, plans, and activities. The general procedure for EIAs includes the following steps:

1. **Scoping:** identify key issues and concerns.

2. **Screening:** decide whether an EIA is needed (for example, is there a significant environmental impact?).

3. **Identify Alternatives:** list the alternatives, sites, and techniques; and describe the affected environment.

4. **Assess Impacts:** assess the social and environmental impacts of each alternative.

5. **Mitigation Measures:** develop mitigating actions to prevent or reduce potential impacts.

6. **Issue Environmental Statement:** produce a non-technical report on findings of the EIA. Steps 2, 5, and 6 are unique to EIAs when compared to LCA. Step 3 is similar to the LCI step of LCA, but in practice it has been much less comprehensive.

10.2.3 Open Wastewater Planning (OWP)

Open wastewater planning is a newer, less well known, and less formalised method than LCA or EIA, which has been developed especially for wastewater treatment decisions. OWP begins by setting goals for the wastewater treatment process. The decision-makers may be guided in their goal setting by a third party (for example, a consultant and/or local or national regulator), but it is crucial that the decision-makers take ownership of the goals. When the goals are set, a third party generates a diverse set of design alternatives that meet most or all of those goals and presents them simply, at the level of a feasibility study. The ways in which the alternatives affect the goals set up in the beginning are described briefly, and decision-makers use the material as a decision aid. OWP has been used on a limited basis in Sweden, and a document describing the process in English has been distributed to promote OWP as a model throughout the Baltic Sea region.

Swedish Case Study on Applying OWP

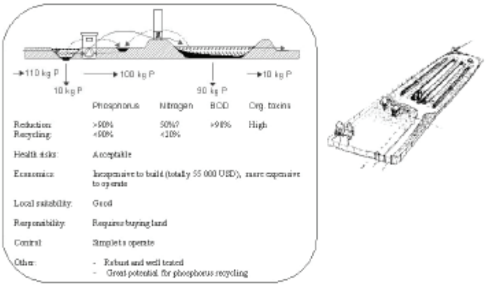
OWP has worked well in Vadsbro, Sweden, a village of 40 households, in the same region as Stockholm. The village renovated the sewer system, connecting it to a wastewater treatment plant. Their next step was to upgrade the treatment plant. The regulatory authority, the municipality's Environmental and Public Health Committee, believed that a package treatment plant was the appropriate solution, but they wanted to work with someone to confirm that choice. They embarked on a two-month process of OWP under the guidance of Prof. Ridderstolpe, an external consultant.

Ridderstolpe began by asking the committee what their goals for the wastewater treatment plant were. They identified measurable goals in the areas of cost, nutrient and BOD removal, potential for recycling nutrients, energy use, chemical use, and public health, as well as qualitative goals that the solution fit in with local conditions and that responsibility and maintenance requirements be clear. Ridderstolpe then developed six alternatives, including the package treatment plant, which more or less met the criteria:

- Land application of wastewater: energy forest irrigation;
- Stabilisation pond with calcium hydroxide precipitation;
- Packed media filter plus biofilter ditch (a long, narrow wetland);
- Land application of wastewater: crop-wetland rotation; and
- Sand filter.

The committee was surprised that such widely varying options could fulfil the criteria. A report with two-page spreads on each alternative helped them decide among the options. The first page was a textual description of the alternative with information on how it fulfilled the criteria. The second page contained a sketch of the system and a short summary of how the system performed on the criteria (see Figure 10-6).

FIGURE 10-6
SUMMARY SKETCH OF VADSBRO'S ALTERNATIVE 2: STABILIZATION PONDS WITH CHEMICAL PRECIPITATION



	Phosphorus	Nitrogen	BOD	Org. toxins
Reduction:	>90%	50%?	>98%	High
Recycling:	<90%	<10%		

Health risks: Acceptable

Economics: Inexpensive to build (totally 55 000 USD), more expensive to operate

Local suitability: Good

Responsibility: Requires buying land

Control: Simple to operate

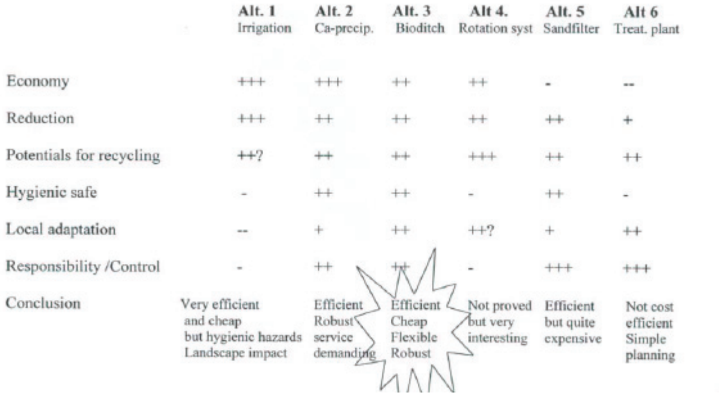
Other:
- Robust and well tested
- Great potential for phosphorus recycling

Source: Ridderstolpe (1999)

A single chart compared the relative strengths and weaknesses of the alternatives (see Figure 10-7). The chart is not a formal decision-making tool; there are no specific definitions for the differences between two plusses and three plusses, for example, and there is no method for adding the plusses and minuses together.

Rather, the chart is a mnemonic tool. The descriptions of each treatment alternative provide details on how the alternative performs according to each criterion; the chart merely provides an overview for deliberations. The Committee used all of these aids to decide on a filter bed followed by a biofilter ditch—a type of long, thin wetland.

FIGURE 10-7
COMPARISON OF ALTERNATIVES IN VADSBRO, SWEDEN, USING OWP



	Alt. 1 Irrigation	**Alt. 2** Ca-precip.	**Alt. 3** Bioditch	**Alt 4.** Rotation syst	**Alt. 5** Sandfilter	**Alt 6** Treat. plant
Economy	+++	+++	++	++	-	--
Reduction	+++	++	++	++	++	+
Potentials for recycling	++?	++	++	+++	++	++
Hygienic safe	-	++	++	-	++	-
Local adaptation	--	+	++	++?	+	++
Responsibility /Control	-	++	++	-	+++	+++
Conclusion	Very efficient and cheap but hygienic hazards Landscape impact	Efficient Robust service demanding	Efficient Cheap Flexible Robust	Not proved but very interesting	Efficient but quite expensive	Not cost efficient Simple planning

Source: Riddlestolpe (1999)

OWP is more than a formal analytical model like LCA or EIA. It is a decision-making method, from framing the problem to choosing among alternatives. OWP is simple and can adapt to local conditions; it is also flexible in identifying various non-economic criteria to compare wastewater treatment alternatives. By helping the decision-makers identify which criteria are most important to them, it is possible to concentrate data gathering on information that will make a difference for the decision. It is also possible to gauge the level of sophistication needed to provide useful information. The analysis can then use any of the other methods such as EIA and streamline any LCA component as appropriate. Ridderstolpe (2004) reports that he has used OWP for communities of up to 500 persons. The larger the project and the larger the constellation of interest groups, the greater the demand is likely to be for a more formally documented process. As the formal documentation increases, OWP starts to be more like an EIA.

10.2.4 Comparison of methods

This section briefly compares the three methodologies presented earlier. The EIA is a framework for conducting assessments (Kärrman 2000). For most practical purposes, the LCA is associated with specific methods of analysis. With an EIA, there are no assigned or standardised categories or methods of analysis for those categories.

The EIA generally addresses localised impacts and allows for the most appropriate methods for the uniqueness of the site and significant impacts. However, in practice, this flexibility, combined with less attention to system boundaries, allows some indirect and cumulative impacts to be skipped, particularly those that affect other locations or that are regional or global in scale.

The standard LCA methods, on the other hand, are virtually unable of detailing most local impacts. These distinct differences could lead to an easy choice between the two; however, the environmental impacts of wastewater treatment occur at both local and global scales and environmental sustainability generally requires considering both.

The OWP may adopt characteristics of both LCA and EIA, but is most similar to an EIA. The OWP may adopt the extended system boundaries global or regional impact characterisation of the LCA, but its flexibility to adapt to the decision-making needs and context mimics the framework of the EIA. OWP's unique aspect is that it is specific to wastewater treatment and practical for smaller communities, particularly those with less monetary and human resources. The OWP, however, is more vulnerable to allowing decision-makers to ignore externalities.

10.3 Economic and Financial Evaluation of WWTS

The main principles, concepts, and procedures used for the economic and financial analysis of WWTS provide a general methodological framework to understand the basic concepts and methodology. The economic analysis generally aims to improve the social well being of the society in terms of income or consumption by encouraging the efficient use of resources. Financial viability and project risks are assessed to test the financial sustainability of the service delivery and economic benefits. These analyses are done in conjunction with social, technical, institutional, and environmental analyses prior to appraising a WWTS and, when necessary, throughout the project cycle.

10.3.1 Least-Cost Analysis

After defining the project's objectives and forecasting wastewater management needs, the next step is to identify the least-cost alternative to achieve the project's objectives. Economic costs are used to examine the scale, location, technology, and timing of alternative project designs. The analysis aims to identify the least-cost option for collecting and treating the wastewater to meet forecast demand. If the benefits are the same, the least-cost analysis compares the economic costs of mutually exclusive, technically feasible options, and identifies the one with the lowest present value. If the economic benefits of the project alternatives differ, a net present value analysis is carried out.

If the least-cost option for increasing wastewater treatment is through more efficient management and rehabilitation of the existing system rather than through a capacity increase, this option should be a priority project component. Capacity increase is the next step and should be considered in the project design, if clearly indicated by the demand forecasts.

The average incremental cost (AIC) of water for each project (or long-term expansion plan) alternative is a good proxy of the full cost of providing the services. It reflects the financial cost by unit of environmental resources consumed to be recovered by the system operator for a given investment stream to reach full cost recovery. The AIC is the discounted cash flow of the system during the forecast period divided by the flow of environmental resources consumed or treated during the period; it is expressed as follows:

$$AIC = \frac{\sum \left[\frac{(KKR_n + OMR_n)}{(1+r)^t} \right]}{\sum [QW_n]} \qquad \textbf{(E. 99)}$$

Where:

- AIC = Average Incremental Cost in currency per unit of resources consumed.
- KKR_n = Total capital cost of project in year n.
- QW_n = Projected environmental resource consumption in year n.
- OMR_n = Total cost of operations and maintenance in year n.
- r = Discount rate.
- t = time [years]

The AIC is often a useful indicator to establish tariffs for the required services. In the AIC calculation, grants are counted as additional revenues, thus lowering the AIC and the resulting tariff required to cover the cost of the services considered.

Exercise: *calculate the AIC of the WWTP project described in the paragraphs 10.1 above.*

Item	*Present Value*	*Year 0*	*Year 1*	*Year 2*	*Year 15*	*Year 25*
Investment Cost (€)	***470,000***	***470,000***				
Discounted O&M Cost (€)	***481,359***	*(27,375)*	***26,600***	***25,847***	***17,796***	***13,355***
Quantity of wastewater treated (m^3)	***6,750,000***		***270,000***	***270,000***	***270,000***	***270,000***
AIC (€/m^3)	***0.14***					

10.3.2 Economic and financial analyses

Economic and financial analyses represent complementary, yet distinct ways to estimate the net benefits of an investment project. Both are based on the difference between the situations with project and without project. The net financial benefit, however, differs from the net economic benefit. Whereas the financial analysis estimates the financial impact of the project on the project operating entity, the economic analysis estimates the economic impact on the country's economy. They are complementary because a project must be financially sustainable to benefit the economy. If a project is not financially sustainable, there will not be enough funds to properly operate, maintain, and replace assets, and the quality of the water service will deteriorate, eventually affecting demand and the realisation of financial revenues and economic benefits.

To demonstrate the project’s financial viability and sustainability, the financial analysis should be done at the water utility and project levels. The financial analysis at the project level may assess economies of scale associated with the use of one or several treatment sites. One single larger treatment plant may be less expensive than several smaller ones, but the cost of conveying wastewater to one single larger treatment plant (larger collector) may lower this cost advantage. This assessment is very much project, site, and geography specific.

The financial analysis at the water utility level involves preparing balance sheets, income statements, and sources and uses of funds statements, all at current prices. The analysis should cover the financial liquidity aspect of the project at both levels.

Assessing sustainability includes estimating the role of cost recovery through wastewater service pricing, estimating the direct effect on public finances of the project's net cash flows, and assessing the community's capacity to provide subsidies. This is done by calculating the AIC of water treated and comparing it with the average current price charged for system connection and wastewater treatment.

The financial cost-benefit analysis of the project involves estimating the financial internal rate of return (IRR) in constant prices. As explained earlier, the IRR is the rate of return at which the present value of the stream of incremental net cash flows in financial prices is zero. If the IRR is equal to or greater than the financial opportunity cost of capital, the project is financially viable. Thus, the financial cost-benefit analysis covers the profitability aspect of the project at the utility level.

The basic difference between the financial and economic cost-benefit analyses of a project is that the former compares benefits and costs to the utility, in constant financial prices, while the latter compares benefits and costs to the whole economy measured in constant economic prices. Financial prices are market prices of goods and services that include the effects of government intervention and distortions in the market structure. Economic prices reflect the true cost and value of the economy of goods and services after adjusting for the effects of government intervention and distortions in the market structure through shadow pricing of the financial prices. Therefore, financial and economic analyses should not include depreciation charges, sunk costs, and expected changes in the general price level. Depreciation should not be included as the investments already figure in the cash flows; sunk costs are expenditure for fixed assets in place prior to the investment decision; and in the analyses, the benefits and costs are to be valued at constant prices (of the appraisal year). The expected changes in relative prices (as distinct from the changes in the general price level), however, should be incorporated.

The financial and economic cost-benefit analyses also differ in relation to the external effects (costs and benefits) of a project. There are many examples of such externalities that market transactions do not account for and are, therefore, not directly reflected in the financial cash flow of a project. The environmental impact of a project is a typical example of such an externality. Other examples in the case of wastewater management projects are depletable water resources, especially in the case of projects using ground water, and water supply projects using scarce raw water resources in the case of competition among users of raw water. The economic analysis attempts to value such externalities and internalise them into project benefits and costs to improve the efficiency of the use of the limited resource and to contribute to enhancing environmental sustainability.

An important objective of a wastewater management project is to improve health by reducing and ultimately eliminating water-borne diseases. Although environmental and health economists advocate some techniques for monetising health benefits from safe water, it remains difficult to appraise wastewater management projects. For example, financial revenues collected from the users of a WWTS can determine the monetary benefits from the project; the financial revenues do not capture, however, all the external effects of better community health stemming from access to a cleaner environment and possibly safe water supply. When public health benefits are expected to be significant and sustainable, they can be estimated either in terms of avoided private and public medical expenses, productivity and income gains due to reduced morbidity or alternative cost of achieving those health benefits, e.g., boiling and filtering water plus public awareness campaigns.

Financial analysis

The outflow should consider the purchasing price of the investment and the expenditures necessary for operation and maintenance. The inflow usually comes from tariffs or fees applied to users of wastewater treatment services. The inflow should also take into account the sale price of any additional service that the manager may offer to the user (for example, sale of treated water, periodic maintenance of household facilities, etc.).

Since water infrastructure is usually characterised by a long useful life, the financial analysis should consider the residual value of the investment. A time horizon of 30 years is often advisable.

Economic analysis

The main social benefits to be introduced in the economic analysis may be usefully evaluated according to estimates of expected demand for water resources that the WWTP investment will satisfy. The basis for estimating a price for water may be the user's willingness to pay for the service, which can be quantified by applying the market prices of alternative services (household small wastewater treatment system, in situ treatment of receiving waters, etc.).

For a water pollution control project, the benefit may also be directly estimated by valuing the deaths and illnesses avoided thanks to efficient wastewater treatment. To make an economic valuation, it is necessary to estimate the total cost of hospital or outpatient treatments and the income loss due to a possible absence from work and the human life value based on the average income and residual life expectancy.

A direct valorisation of the benefits of a WWTP may also consider the following aspects:

- The damage avoided to land, real estate and other structures due to potential flooding or unregulated rainwater (for “white” or mixed drains), based on the costs for recovery and maintenance;
- The value of water resources in non-polluted receiving waters.

In any case, if no standard economic appraisal method is applicable for the specific project, it is possible to resort to any similar project, which may have been developed in a context as close as possible to the one of the affected area. Efforts should be made to quantify environmental externalities such as:

- The possible value of the served area, quantifiable, for example, by the cost of real estate and building or agricultural area prices;
- The increased income due to collateral activities (tourism, fishing, coastal agriculture, etc.) that the natural WWTS may help settle or maintain;
- Potential impacts on the environment (spoiling of scenery, impact on nature) and on any other infrastructure (e.g., roads and/or railways); and
- Negative impacts during construction (loss of mobility, historical and cultural heritage, impact on agriculture or nearby infrastructure, etc.).

10.3.3 Private Sector Participation (PSP)

The role of the private sector for developing environmental public utilities is often misunderstood. The private sector is often presented as the source of finance of last resort to be tapped to fill a financing gap when all other sources of finance have been exhausted. This is misleading. The private sector is unlikely to contribute capital to a project whose overall financial viability is unsecured and which cannot generate an adequate additional financial return.

Involving the private sector should create efficiency gains in productivity and cost management that can extract enough savings to close the financial gap. Clearly, private involvement has an additional cost equal to the financial return on the capital contributed by the private sector as private equity or debt.

Benefits from PSP include:

- Improving service quality;
- Providing cost transparency;
- Contributing cost efficiency;
- Stimulating well motivated and trained personnel;
- Promoting inflow of technology and know-how;
- Developing competitive capability; and
- Fostering entrepreneurial capability.

If it can be demonstrated that PSP can generate enough savings to fill in the financial gap and provide an adequate return on the contributed private capital, then the private sector could be a viable option for project financing. Mobilising the private sector for public environmental investment is often challenging.

Water (and to a lesser extent) waste management have significant natural monopoly elements difficult to regulate for competitive supply. Also water is in part a public good service, the delivery of which if allowed to be run under private management, has important political implications that can preclude full private/foreign ownership. To be efficiently managed and regulated, water services require mature, transparent, and socially responsible legal and regulatory frameworks capable of balancing tensions between public and private interest.

The Return on Investment (ROI), a standard measure of a corporation's profitability, equal to the net income divided by the equity plus the long-term debt contributed by the private sector, can demonstrate the financal viability of involving the private sector. As the private sector is expected to contribute only part of the capital, only the percentage of the income that can be linked to the investment provided by the private sector (as percentage of the total investment) should be taken into account.

10.3.4 Tariff setting consideration

Cost recovery mechanisms allow to recover from wastewater generators all or some of the costs of wastewater collection, treatment, and disposal, and the associated financial, environmental, and social costs of wastewater generation. Systems relying entirely or largely on fees collected from users to meet the costs of service are those most likely to operate sustainably over the entire economic life of the system. The cost recovery mechanisms most likely to provide long-term sustainability are based on their ability to meet economic, financial, social, and administrative objectives such as:

- Financial sustainability and full cost recovery;
- Economic efficiency and marginal costs;
- Price equity and polluter pays principle;
- Administrative efficiency and good governance; and
- Ability to pay by customers.

These are briefly discussed below. Note that if the charge for wastewater comes on top of the water charge, consumers cannot distinguish between them economically. Therefore, it is often desirable to consider objectives for the combined water and wastewater charge.

Financial sustainability and full cost recovery

Financial sustainability is one of the most important objectives in tariff setting. It may differ for a utility setting its own particular tariff from that required according to the long-term guidelines set by the State. It also differs for a city that has not developed a system and wishes to raise funds from users/polluters.

If all future investments (for expansion and rehabilitation) are covered by loans, then a utility has to cover its cash flows, plus any requirements such as debt coverage ratios. The utility should forecast its cash-flow needs over the medium term so that tariff levels and necessary increases can be planned in a stable manner.

The government may ask for a return on past government equity (grant to fund investment) through a dividend (a % on equity invested). This is not a necessity and, unless the government actually requires the payment of a dividend, it would provide the utility with surplus cash flow. Different countries hold different positions on this account. In China, the government believes that the utility should raise and keep the money. Other countries, such as Indonesia, believe that asking right away for a return on past investment would yield too rapid tariff increases and so they ask only that tariffs be high enough to cover loans for all future investments.

Economic efficiency and marginal costs

Economic efficiency promotes the efficient use of national resources. At its most basic level, economic efficiency occurs when no change in tariffs would benefit someone without making someone else worse off. According to equilibrium-based economic theory, this happens when the marginal tariff equals the enterprise's marginal cost. While this will maximise welfare only if it is applied throughout the economy, benefits can be expected even when applied only at an industry wide level. When there is excess capacity, average costs will decrease when consumption increases. When there is no spare capacity, however, the pricing system should constrain demand to meet capacity since pricing mechanisms are nearly always the most efficient way of rationing.

The change from a tariff to promote consumption to one designed to constrain it, may seem to imply that the marginal cost rule is not generally applicable. This is not the case, however, since marginal costs are not the same as variable costs. To understand this, it is useful to define the full range of variable costs. In the short term, increased production will increase only the costs of consumables, such as power and chemicals. In the medium term, increased production will require additional employees, etc. In the long run, everything can be variable. Marginal costs are the increase in costs arising from a production increase. So, when there is significant spare capacity, marginal costs equal short run variable costs. As the utility moves towards capacity, marginal costs move to medium run variable costs. When capacity is reached and capital investments are required, marginal costs equal long-run variable costs including capital elements. The latter is in fact equal to the average incremental cost (AIC) discussed above.

The usage charge should never be less than short-run variable costs. Users should be charged for the costs and also to avoid waste.

Price equity

Price equity bases tariffs on “fair” criteria; this is best done when the charge is based on costs traced to or caused by each customer. When possible, however, separate tariffs should be levied. Otherwise, the only variation for water supply is in the costs of making the connection, which can be covered by separate and specific connection charges.

There is a possible conflict between economic efficiency and price equity if the former implies the need for a fixed charge separate from a usage charge. For the fixed charge not to affect demand, it must be based on some objective criteria other than sales. Whatever these criteria are, they will by definition not align exactly with the costs. Therefore, while there need be no inequity between consumer classes, there will always be some price inequity within each class of customers, since each user will have a different use but the same fixed charge.

This price inequity may be minimised by using several or many consumer classes, each designed to include consumers with about the same consumption; however, it will never be zero.

Polluter Pays Principle

The polluter pays principle (PPP) is an extension of price equity. As outlined by the OECD in 1972, "the polluter should bear the expenses of carrying out the (pollution prevention and control) measures decided by public authorities to ensure that the environment is in an acceptable state." This is a simple reformulation of the price equity principle, i.e., people should pay the costs of the Wastewater Treatment Plant (WWTP).

The Mogden Formula, applied by Thames Water in the UK, defines a charge that is the sum of a uniform flow cost and treatment costs that vary based on the level of COD and SS relative to domestic strength effluent characteristics:

$$Charge = V + B \,.\, Or + S \,.\, Sr \quad \textbf{(E. 100)}$$

Where:

- V = charge for collection and flow element [€/m^3]
- B = charge for treatment [€/m^3]
- S = charge for sludge processing and disposal if any [€/m^3]
- Or = Ratio of an industry's COD concentration to the average domestic COD
- Sr = Ratio of an industry's SS concentration to the average domestic SS

This formula could both increase and decrease the charge per m^3. The former could penalise polluters who have not yet installed enough in-house treatment; the latter could reward enterprises that pre-treat or have low strength wastewater.

Administrative efficiency and good governance

Tariffs can promote good governance in many ways. The charges resulting from the tariff should be clear and understandable to customers, so that they can understand how they might modify their use of the service. The tariff should also be easily calculable by the utility, in terms of the total sum to be recovered and the charge to be levied on each customer. The tariff should be immune from interference of the utility's employees, who might use the tariff to collect bribes, and from politicians, who might use the tariff to collect votes. Essentially, this means that any classes, categories, and/or blocks used to vary the tariff are predictable and not open to manipulation. The tariff should not disrupt otherwise rational private decisions, especially investment decisions and others with long-term implications. Decisions by consumers based on current tariffs should not be negated when the tariff is changed; this calls for subsequent minor rather than major changes once the new tariff has been implemented. Where possible, the tariff should be developed in consultation with the public as a whole.

Ability to pay for wastewater services

In the absence of recommendations on affordability, the overall level of affordability recommended for water and wastewater charges is 5% of monthly household income for both a low-income household to meet its basic needs and a medium-income household to meet its average needs. In general, most socio-economic surveys assess the affordability or ability of both 'average' and 'poor' households to pay for water to meet both their likely minimum demand and lifeline demand in terms of litre per capita and day (lpcd) using the following criteria:

- Average consumers (120-180 lcpd) could pay 3-5 percent of household incomes for good quality piped water supply and wastewater management services in urban areas.

- Poor urban households (40-90 lcpd) could pay 4-5 percent of household incomes for water supply and wastewater charges.

For non-domestic customers, especially industrial customers, wastewater tariffs should be less than the costs of on-site treatment to meet equivalent discharge standards.

In Vietnam, Decree No. 67/2003/NĐ-CP from June 13, 2003, defines the tariff for domestic wastewater as being equal to 10% of the water supply tariff. Although this percentage is too small to cover the real cost of wastewater management, it is a very good first regulatory step to introduce the principle of the polluter pays principle to a population with a limited ability to pay. This low percentage is likely to be revised in time to reach a higher value compatible with the real cost of wastewater management infrastructure across the country.

10.3.5 Sensitivity and risk analysis

The critical factors affecting the success of a natural WWTS are:

- Any unexpected occurrence in the construction of the plants, which might considerably change the cost of the investment in progress;
- The forecasts of the demand dynamics;
- The rate of change in tariffs or fees, largely depending on the decisions taken by the regulatory bodies;
- The lack of capacity to respond to shocks in the investment (which often requires excess capacity in the first operating periods); and
- The efficiency of the management.

In this regard, the sensitivity and risk analysis should consider at least:

- The cost of the investment;
- The rate of demographic growth (for civil use) and the forecasts of any migration flow;
- The development rate of crops and the national and/or international dynamics of the sale prices of agricultural products (for irrigation purposes if relevant);
- The variation in tariffs or fees over a period of time;
- The demand and price dynamics of the water which may be recycled in case of reutilisation (when relevant); and
- The operating costs (maintenance, management, etc) and their time dynamics, even with reference to the evaluated suitability of management systems.

The risk analysis of a project studies the probability that a project will achieve a satisfying performance (in terms of IRR or NPV), as well as the variability of the result compared to the best estimate previously made. The recommended procedure for assessing risks is based on two steps:

1. A sensitivity analysis, i.e., the impact that assumed changes in the variables determining costs and benefits have on the financial and economic indices calculated (most often in terms of IRR or NPV); and

2. A study of probability distributions of selected variables and a calculation of the expected value of the project performance indicators.

The sensitivity analysis selects the “critical” variables and parameters of the model, i.e., those whose variations, positive or negative, compared to the value used as the best estimate in the base case, have the greatest effect on IRR or NPV; these critical variables and parameters cause the most significant changes in these parameters. Choosing the critical variables depends on the specific project. In general, it is recommended to consider those parameters for which a variation (positive or negative) of 1% gives rise to a corresponding variation of 1% (one percentage point) in IRR or 5% in the base value of the NPV.

The procedure to conduct a sensitivity analysis is as follows:

1. Identify all the variables used to calculate the output and input of the financial and economic analyses, grouping them together in homogeneous categories.

2. Identify possible deterministically dependent variables, which would give rise to distortions in the results and double counts. The variables considered must be as far as possible independent variables.

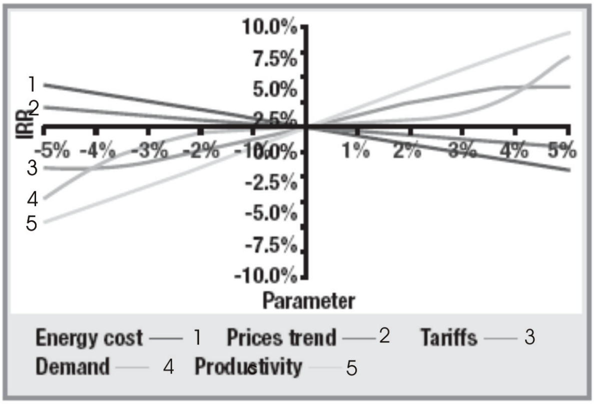
3. Conduct a qualitative analysis of the impact of the variables to select those that have little or marginal elasticity. The subsequent quantitative analysis can be limited to verifying the more significant variables, if doubts exist.

4. Choose the significant variables and evaluate their elasticity by calculating the IRR and NPV. Each time, assign a new value (higher or lower) to each variable and recalculate the IRR and NPV, thus noting the differences (absolute and percentage) with the base case.

Figure 10-8 shows a sample presentation of sensitivity analysis results.

The role of the sensitivity analysis is to identify critical variables, for which it may be important to obtain further information. The risk analysis generates expected values of financial and economic performance indicators (e.g., IRR or NPV). A risky project has a high probability of not overcoming a certain threshold of IRR; it is not a project where the IRR probability distribution has a great standard error.

FIGURE 10-8
EXAMPLE OF SENSITIVITY ANALYSIS RESULTS



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11. ENVIRONMENTAL IMPACT ASSESSMENT

The chapter introduces the concept of Environmental Impact Assessment (EIA) and presents how to conduct an EIA. This chapter has four sections:

1. Introduction;
2. Legal and institutional frameworks;
3. EIA process; and
4. Case studies

11.1 Definition of EIA

An EIA evaluates the potential consequences for the environment (water resources, air quality, habitat, flora and fauna, health, noise, visual amenity, etc.) of a given plan or project and develops preventing or mitigation measures to limit or prevent adverse impacts. It reviews alternatives to the project. It has to integrate transboundary and global environmental aspects and take into account the variations in project and country conditions, policies, legislation, guidelines, etc. The process of mitigating and managing adverse environmental impacts has to be included throughout project implementation.

11.2 Legal and Institutional Frameworks

Carrying out the EIA of a project is a requirement imposed by the national laws and regulations or by the project's promoter. This section presents a selection of relevant legal or regulatory frameworks including:

1. European Commission's legislation;
2. Belgian legislation;
3. Danish legislation;
4. Chinese legislation;
5. Vietnamese legislation;
6. Requirements of World Bank; and
7. Requirements of Asian Development Bank.

11.2.1 European Commission's legislation

> EC Directives are the main European legal texts on a given subject and the European member states have to transpose these texts in their own legislation. Member states can add new rules in their transposition's laws but they have to include at least the rules established by the EC in the directive.

In 1985, the EC published Directive ***85/337/CEE*** on the assessment of the effects of certain public and private projects on the environment. This directive was amended later by Directive 97/11/CE and Directive 2003/35/CE.

The EIA directive applies to the assessment of the environmental effects of public and private projects, which are likely to have significant effects on the environment, by their nature, size, or location. These projects concern the execution of construction works or of other installations or schemes, or other interventions in the natural surroundings and landscape including those involving the extraction of mineral resources. Typical projects activities subject to an EIA are in Table 11-1.

TABLE 11-1
TYPE OF PROJECTS SUBJECT TO EIA

Type of projects for which EIA is mandatory	Type of projects to be assessed on a case-by-case basis or following specific threshold or criteria:
▪ Refinery; gasification; liquefaction; ▪ Thermal and nuclear power production; ▪ Mineral sources extraction; groundwater abstraction; ▪ Chemical productions; electrical power production; ▪ Construction of railways, airports, motorways, large roads; ▪ Incineration or chemical treatment of waste; ▪ Works of transfer of water; ▪ Wastewater treatment; ▪ Extraction of petroleum; storage of petroleum; ▪ Transport of gas, oil or chemical (large pipelines); ▪ Agriculture (intensive rearing of poultry or pigs); ▪ Paper production; ▪ etc.	▪ Agriculture (restructuring land holdings, water management, intensive livestock installation, etc.); ▪ Forestry (afforestation and deforestation, etc.) and Aquaculture (intensive fish farming), Extraction industry; ▪ Energy industry; ▪ Production and processing of metals; ▪ Mineral industry; ▪ Chemical industry; ▪ Food industry; ▪ Textile, leather, wood and paper industries; ▪ Rubber industry; ▪ Infrastructure projects; ▪ Other projects (installations for disposal of waste or wastewater treatment plant, (not included in Annex I), etc.); and ▪ Tourism and leisure.

The EIA identifies, describes, and assesses in an appropriate manner, in the light of each individual case, the direct and indirect effects of a project on human beings, fauna and flora, soil, water, air, climate and landscape, but also on the material assets and the cultural heritage, and finally on the interaction between the factors mentioned here above.

The developer has to provide at least:

- A description of the project (information on the site, design and size of the project);
- A description of the measures planed to avoid, reduce, and if possible remedy significant adverse effects;
- The data required to identify and assess the main effects that the project is likely to have on the environment;
- An outline of the main alternatives studied by the developer and an indication of the main reasons for his/her choice, taking into account the environmental effects; and
- A non-technical summary of the information mentioned in the first four bullets.

Any request for development consent and any information should be made available to the public within a reasonable time to give the public the opportunity to express their opinion on the project. The member states have to determine the detailed arrangements for such information and consultation (public concerned, places where the information can be consulted, the ways the public may be informed, the manner in which the public is to be consulted, the time limits). The public shall be informed about any decision to grant or to refuse a development consent taken by the competent authorities.

The neighbouring States that could be concerned by a project shall also be informed and given the opportunity to express their opinion to participate to the EIA procedure.

11.2.2 Belgian legislation

In Belgium, environmental responsibilities belong to Belgium's three regions: (1) Wallonia, (2) Flanders, and (3) Brussels. The three regions have to transpose any European directive in their own laws. For consequent activities (industrial, agricultural and other class 1 activities), an environmental license ("*permis d'environnement*") for building and operation, has to be obtained from the authorities; the EIA is included in that procedure. The activities subject to an EIA are listed in the by-law of the Walloon Government of 4 July 2002 (MB 21/09/02) and modified the 22 January 2004 (MB 25/03/04).

Wallonia

The Walloon Region transposed Directive 85/337/CEE with the decree of 27 May 2004 relating to the First Book of the Environment Code (articles D62 to D77) and the by-law ("*arrêté*") of the Walloon government of 17 march 2005 relating to the First Book of the Environment Code (articles R52 and R 86 and the annex VII). The decree specifically requires that the developers use a consultant authorized by the government to undertake the EIA. The decree also requires two public surveys, before the EIA and before the environmental license delivery.

The by-law of the Walloon government of 17 March 2005 establishes the list of projects subject to an EIA and the EIA's content and form. The documents also describe the criteria and procedure for the consultants' accreditation, the conditions for the public information and surveys, and how to inform the neighbouring regions and countries. The competent authorities have to inform the neighbouring States and **Regions** (due to the specific division of the Country) that could be concerned by a project.

Brussels

The Region of Brussels transposed the directive in the ordinance of 24 June 2004 (Articles 21 to 29 essentially), and in the Brussels Code of the territory setting, the COBAT of 9 April 2004 published on 26 May 2004 (essentially under sections 1 and 2 of section 2 in Chapter III of the 4th title).

The requirements and procedures are similar to those of the Walloon Region. The main difference is the constitution of a Committee of experts from the different regional and local administrations concerned ("*Le Comité d'Accompagnement de l'étude EIA*"). The Committee follows the study during all the procedure. After a first public survey, the Committee gives its opinion on the draft assessment and the consultant's choices and decides the time that the consultant should have to carry out the assessment. Once the EIA report is available, the Committee decides if the report is complete and defines the public who should be consulted for the second public survey, which takes place before the administration delivers the "environmental license".

Flanders

In Flanders, the EIA legislation is included in the Decree of 5 April 1995 on environmental policy, more specifically under title IV "Environmental impact and safety reporting". For the "Environmental impact reporting on projects", section III has to be consulted. Like in Wallonia, an EIA has to be conducted for any request of an environmental license.

Based on the criteria in Appendix II of this decree, the Flemish Government designates the categories of projects subject to the environmental impact statement. The neighbouring countries and or regions and also the public concerned have to be kept informed and have of course the right to give their opinion in a given time. The EIA project is drawn up under the responsibility and at the expense of the initiator. For this, the initiator must use the services of a team of accredited EIA experts under the supervision of an accredited EIA coordinator. The decree describes the minimum content of an EIA study and the necessary procedures to undertake it.

11.2.3 Danish legislation

The EIA has assumed an increasingly prominent role in the Danish planning system and in the environmental rules and regulations. The EIA requirement is in the Planning Act (Lov om Planlaeggning No. 551, 28 June 1999 part 3) and in Composite Order No 428 of 2 June 1999 on additional rules adopted pursuant to the Planning Act.

At the first stage in the procedure, the developer submits his plans to the authority (county), which decides whether an EIA is required. Annexes 2 and 3 of the Planning Act are largely identical to Annexes II and III to the Directive. Annex 1 lists all projects subject to the EIA procedure; Annex 2 lists projects where an EIA is required if it is thought likely to have a significant impact on the environment. They are considered case-by-case. The public must be consulted and its comments have to be considered in the project design.

The requirements on the content of the assessment are essentially the same as before the amendment of the Directive in 1997. Requirements for the consideration of alternatives were amended, however, and certain minor adjustments were made. Besides the alternatives, which the developer himself asked to be studied, alternatives proposed by members of the public must now also be considered.

When the EIA procedure is completed, and the counties have definitively adopted the necessary regional planning guidelines in respect of the project, an EIA permit or one of the permits or licenses referred to of the Order must be issued. The EIA permit may impose conditions depending on a specific assessment of each case.

The counties then monitor compliance with the EIA permit. The EIA consent must be published.

A particularity of Denmark's transposition of the Directive is that, if a project is already covered by other permits/licenses/exemptions, these take the place of an EIA permit.

11.2.4 Chinese legislation

At a National level, since 2002, the EIA process in China is under the Environmental Impact Assessment Law (2002-10-28). Several other national laws and regulations, on environmental protection management of construction projects provide also a legal background to EIA. Technical regulations for EIA consist of environmental quality standards, basic health standards, public safety standards, standards for controlling toxic and radioactive substances, and pollutant emission standards.

EIA for large projects are normally handled in conjunction with the State Environmental Protection Agency (SEPA), which plays a leading role. Small and local projects with investments under RMB 30 million are generally reviewed and approved by local environmental agencies (Environmental Protection Bureaus, EPBs).

The project proponent/owner will then commission an EIA specialist/institution, that holds a Certificate for Assessment issued by either the SEPA or a related provincial authority, to prepare the Terms of Reference for the EIA report to be approved by the Environment Agency (EPB, SEPA). The environmental agency decides on the proper format of the EIA report. EPB screens the project to decide to which one of three categories the project belongs:

1. Project with significant impacts for which a full EIA is required;
2. Project with limited impact and easy mitigation, for which only a simplified EIA is required; and
3. Project with little or no impact for which only an EIA table is required.

The project proponent has to finalise a contract with the EIA specialist/institution who will then prepare the EIA study and reports. The EIA report has to be drafted with reference to local environmental quality standards and pollutant emission standards. Once finished, the EIA report is first reviewed by the commercial and industrial authorities that have jurisdiction over the project, followed by the Environmental Agency (EPBs, SEPA). If the project has significant environmental impacts or involves complicated environmental issues, the EIA specialist/institution may have to testify before a panel of experts organised by the environmental agency. The environmental agency is the ultimate authority to accept or reject the EIA report

The environmental agency will ensure that the project design, construction, and completion comply with the environmental prescriptions specified in the EIA report:

1. Design; the proponent will prepare and submit to the environmental agency the project's environmental plan specifying the environmental protection measures in the EIA report and providing an investment budget;

2. Construction; the contractor is required to provide regular reports on specific matters arising during construction, e.g., difficulty to comply with emission; and
3. Completion; the project proponent should submit an application for test operation to the EPB and to other concerned municipal authorities.

11.2.5 Vietnamese legislation

In 1999, the Vietnamese Government issued the EIA guidelines for eight types of projects (development of industrial zones and urban areas, traffic projects, development of beer-alcohol-potables industrial factories, thermo-electric power stations, textile and dyeing industrial factories, cement factories and exploitation – stone & clay processing factories).
Later, Environmental Impact Assessment (EIA), Strategic Environmental assessment (SEA) and Environmental Standards have been included in the separated chapters of Vietnamese Environmental Protection Law of 2005.

For some projects, the European directive EC 85/337 (1997) is the reference. Two books on wastewater and water quality published by the World Health Organization are also considered: “Analysis of Wastewater for Use in Agriculture” (1996) and “Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring” (1992).

11.2.6 Requirements of World Bank

The Bank's Environmental Assessment policy and procedures are in Operational Policy/Bank Procedures - **OP/BP 4.01**. There is additional information on these references in the ***Environmental Assessment Sourcebook*** (Washington, D.C.: World Bank, 1991) and subsequent updates.

OP 4.01 gives general definitions and requirements; it states that the Bank requires an environmental assessment (EA) of projects proposed for Bank financing, to help ensure that they are environmentally sound and sustainable, and thus to improve decision making. The Bank undertakes environmental screening of each proposed project to determine the appropriate extent and type of EA. The Bank classifies the proposed project into one of four categories, depending on the type, location, sensitivity, and scale of the project and the nature and magnitude of its potential environmental impacts:

A. project likely to have significant adverse environmental impacts;
B. potential adverse environmental impacts on human populations or environmentally important areas of the project are less adverse than those of Category A projects;
C. project likely to have minimal or no adverse environmental impacts. Beyond screening, no further EA action is required for a Category C project; and
FI. project involving investment of Bank funds through a financial intermediary (FI), in subprojects that may result in adverse environmental impacts.

For “normal projects” in Category A, the borrower retains independent EA experts not affiliated with the project to carry out the EA. For highly risky projects in Category A or projects involving serious and multidimensional environmental concerns, the borrower should normally also hire an advisory panel of independent, internationally recognised environmental specialists to advise on all aspects of the project relevant to the EA.

During the EA process, the borrower has to consult the public and the local nongovernmental organisations (NGOs) as early as possible. For Category A projects, the borrower consults these groups at least twice: (a) shortly after environmental screening and before the terms of reference for the EA are finalised; and (b) once a draft EA report is prepared.

BP 4.01 states the responsibilities of each actor and respective obligations. The appraisal mission for any project and its requirements are in BP4.01. The environmental assessment (EA) of a proposed Bank-financed operation is the responsibility of the borrower. The borrower is assisted and supported by a Task Team (TT) that reviews the project, records all information needed, makes sure that all documents are complete, summarises the key elements to be supplied (classification of project, procedure used to prepare the report, alternatives considered, predicted impact of project and alternatives, etc). During project implementation, the TT supervises the environmental aspects. Finally, the BP requires an Implementation Completion Report that evaluates environmental impacts, noting whether they were anticipated in the EA report; and the effectiveness of any mitigating measures taken.

The **Sourcebook** cited above is a reference manual with the information needed to manage the process of environmental assessment according to the requirements of OP and BP 4.01. Anyone responsible for a Bank–supported project with potentially significant environmental impacts should consult the sourcebook.

The Sourcebook summarises Bank EA requirements and outlines the Bank's environmental review process, from screening at the time of project identification, to the post-completion evaluation. The last chapters provide sectoral guidelines for EA; each type of project is briefly described, potential impacts are summarised, and special issues are noted. Possible alternatives to the project are outlined, and references on management, training needs, and monitoring requirements are added. Each review concludes with a table of potential impacts and the mitigating measures that can be used. Sample Terms of Reference for various project types are in one section of each chapter.

11.2.7 Requirements of Asian Development Bank (ADB)

The major elements of ADB's environment policy and the operational procedures to incorporate environmental considerations into ADB's business process are described in an organisational manual, the **OM F1.** The first part of the document addresses the **Bank policies** (BP) and the second part the **Operational Procedures** (OP).

As for the World Bank, the borrower is responsible for his EA. The project classification is similar to the World Bank’s and depends on the significance of environmental impacts, actually of its most environmentally sensitive component, including direct and indirect impacts. In general, the requirements specify the level of analysis needed for the assessment, the reporting requirements, public consultation, and information disclosure. The ADB requires an Environmental Impact Assessment (EIA) for Category A projects and an Initial Environmental Examination (IEE) for Category B projects.

As expected, the ADB requires public consultation in the EA process. The consultation has to be done as early as possible so that the views of the affected groups are taken into account in the design of the project and its environment mitigation measures. For Category A projects, the ADB ensures that the borrower (or private sector sponsor) carries out public consultation at least twice.

An ADB **Environmental Assessment Guidelines** handbook explains how to fulfil the requirements outlined in ADB's Environment Policy in the OM F1. Information on ADB's policies and procedures for conducting and reporting on the EA is also provided for all types of projects. It also describes the best practices for consulting the concerned public and providing access to information.

The content and format of EIA and IEE are in the Guidelines Handbook of the ADB (see Table 11-2).

TABLE 11-2
OUTLINE OF EIA REPORTS

EIA (Category A projects)	IEE (Category B Projects)
A. Introduction	A. Introduction
B. Description of the Project	B. Description of the Project
C. Description of the Environment	C. Description of the Environment
D. Alternatives	
E. Anticipated Environmental Impacts and Mitigation Measures	D. Screening of Potential Environmental Impacts and Mitigation Measures
F. Economic Assessment	
G. Environmental Management Plan	E. Institutional Requirements and Environmental Monitoring Plan
H. Public Consultation and Disclosure	F. Public Consultation and Disclosure
	G. Findings and Recommendations
I. Conclusions	H. Conclusions

As a Category B project is expected to have less adverse effects on the environment, the IEE has only to describe mitigation measures and is not required to present alternatives to the project or an economic assessment.

The EIA has to propose alternatives and consider all the adverse effects that these alternatives could have on the environment. Mitigation measures planned should also be described. The EIA should also include an economic assessment in the overall economic analysis of the project and should include costs and benefits of environmental impacts; costs, benefits, and cost-effectiveness of mitigation measures; and discussion of impacts that have not been expressed in monetary values, in quantitative terms where possible.

Both studies should include an Environmental Management Plan and an Environmental Monitoring Plan. An EIA study is more complete and complex than an IEE; the IEE also has to provide Findings and Recommendations.

11.3 EIA process

The general objectives of the EIA are to provide:

- Baseline information on the environmental, social, and economic conditions in the project area;
- Information on potential impacts of the project and the characteristics of the impacts, magnitude, distribution, who will be the affected group, and their duration;
- Information on potential mitigation measures to minimise the impact including mitigation costs;
- Assessment of the best alternative project at most benefits and least costs in terms of financial, social, and environment; an alternative location of the project, project design or project management may also be considered; and
- Basic information for formulating environmental management plan.

The EIA requires an in-depth analysis because of the potential significance of environmental impacts from the project. EIAs require:

- Comprehensive analysis of the potential impacts;
- Work to be carried out to formulate practical mitigation measures;
- In-depth economic valuation of impact to screen and evaluate the best alternative; and
- In-depth analysis to prepare an adequate environmental management plan.

The most used general procedural elements of environmental assessment are:

- Screening;
- Scoping;
- Impact analysis and mitigation and impact management;
- Consultation;
- Documentation and information;
- Decision making;
- Public participation;
- Monitoring (Environmental Management Plan); and
- Resources.

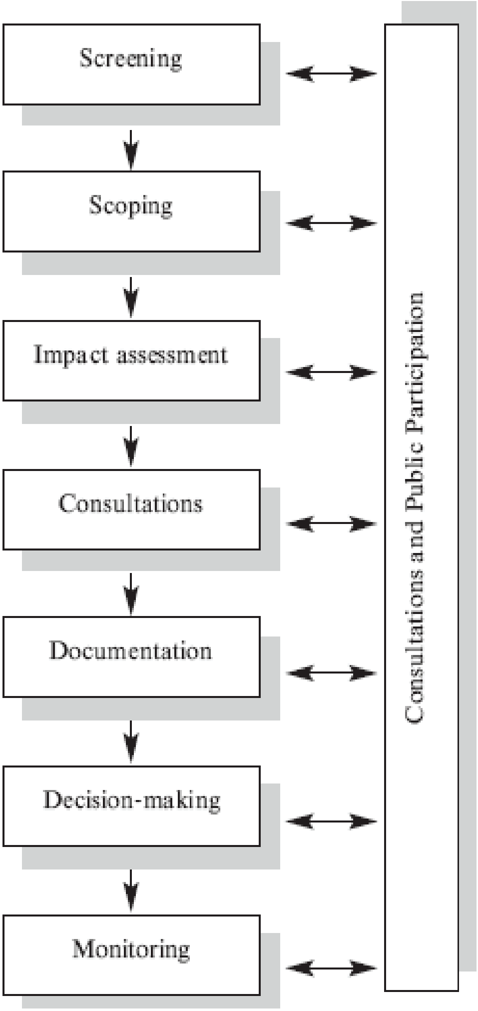
Figure 11-1 summarises the main steps of the EIA process.

11.3.1 Screening (Initial Environmental Evaluation)

Screening is the process of determining whether an EIA is required for a particular project. Screening should go hand in hand with project concept development so that environmental opportunities and risks can be appropriately and easily integrated into subsequent design stages.

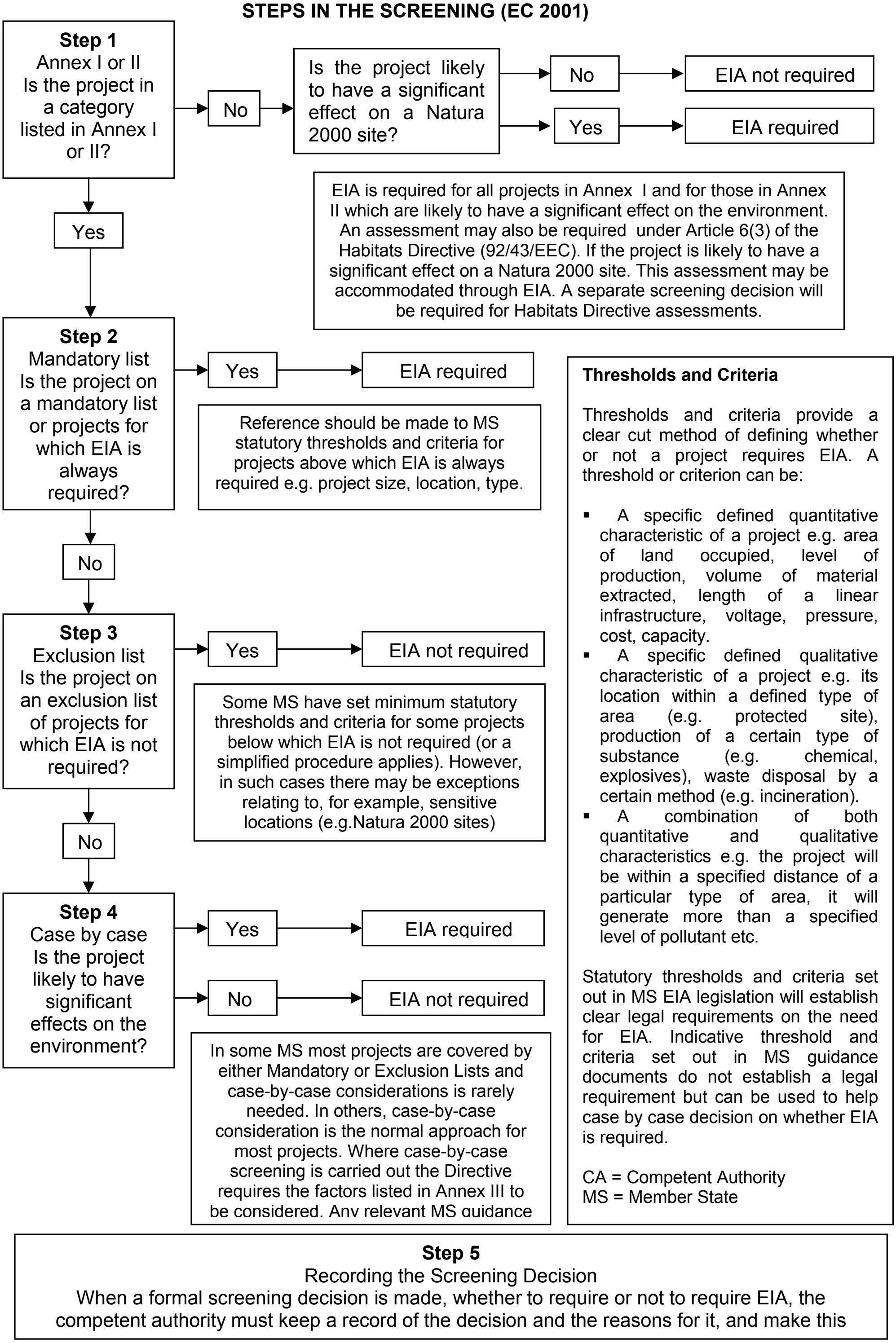
The Environmental Helpdesk for EC Development cooperation proposes a list and a questionnaire helping with the screening of a project for EIA. These lists should be used together with national lists to determine whether an EIA is required. These lists are on http://www.environment-integration.org/Download/D123/EIA_Screening.pdf. The EC has developed guidance for EIA Screening (EC, 2001). A chart allows to identify quite rapidly if a project is subject to an EIA (see Figure 11-2).

FIGURE 11-1
PROCEDURAL ELEMENTS OF AN ENVIRONMENTAL ASSESSMENT



- Screening: determine the need for environmental assessment;
- Scoping: identify elements to be assessed and alternatives, exclude irrelevant information;
- Impact assessment;
- Consultations: seek input and advice of other governmental agencies, independent experts, interest groups and public during scooping and after completion of the assessment;
- Public participation: involve the public in the environmental assessment;
- Documentation and information: present the information of environmental assessment;
- Decision –making: take conclusions and recommendations of environmental assessment into account;
- Monitoring: identify follow –up measures of overall impact of projects.

FIGURE 11-2
STEPS IN THE SCREENING (EC 2001)



Step 1
Annex I or II
Is the project in a category listed in Annex I or II?

Is the project likely to have a significant effect on a Natura 2000 site?

EIA is required for all projects in Annex I and for those in Annex II which are likely to have a significant effect on the environment. An assessment may also be required under Article 6(3) of the Habitats Directive (92/43/EEC). If the project is likely to have a significant effect on a Natura 2000 site. This assessment may be accommodated through EIA. A separate screening decision will be required for Habitats Directive assessments.

Step 2
Mandatory list
Is the project on a mandatory list or projects for which EIA is always required?

Reference should be made to MS statutory thresholds and criteria for projects above which EIA is always required e.g. project size, location, type.

Step 3
Exclusion list
Is the project on an exclusion list of projects for which EIA is not required?

Some MS have set minimum statutory thresholds and criteria for some projects below which EIA is not required (or a simplified procedure applies). However, in such cases there may be exceptions relating to, for example, sensitive locations (e.g.Natura 2000 sites)

Step 4
Case by case
Is the project likely to have significant effects on the environment?

In some MS most projects are covered by either Mandatory or Exclusion Lists and case-by-case considerations is rarely needed. In others, case-by-case consideration is the normal approach for most projects. Where case-by-case screening is carried out the Directive requires the factors listed in Annex III to be considered. Any relevant MS guidance

Thresholds and Criteria

Thresholds and criteria provide a clear cut method of defining whether or not a project requires EIA. A threshold or criterion can be:

- A specific defined quantitative characteristic of a project e.g. area of land occupied, level of production, volume of material extracted, length of a linear infrastructure, voltage, pressure, cost, capacity.
- A specific defined qualitative characteristic of a project e.g. its location within a defined type of area (e.g. protected site), production of a certain type of substance (e.g. chemical, explosives), waste disposal by a certain method (e.g. incineration).
- A combination of both quantitative and qualitative characteristics e.g. the project will be within a specified distance of a particular type of area, it will generate more than a specified level of pollutant etc.

Statutory thresholds and criteria set out in MS EIA legislation will establish clear legal requirements on the need for EIA. Indicative threshold and criteria set out in MS guidance documents do not establish a legal requirement but can be used to help case by case decision on whether EIA is required.

CA = Competent Authority
MS = Member State

Step 5
Recording the Screening Decision
When a formal screening decision is made, whether to require or not to require EIA, the competent authority must keep a record of the decision and the reasons for it, and make this

11.3.2 Scoping (EC, 1999)

Scoping is mainly the identification of the issues to be covered by the EIA. The scoping is usually performed with the help of a checklist. This is designed to help users identify the likely significant environmental effects of proposed projects during scoping. It is to be used in conjunction with the Checklist of Criteria for Evaluating the Significance of Impacts. There are two stages:

1. Identify the potential impacts of projects;
2. Select those likely to be significant and therefore require most attention in the assessment.

A useful way of identifying the potential impacts of a project is to identify all the activities or sources of impact that could arise from the construction, operation or decommissioning of the project, and to consider these alongside the characteristics of the project environment that could be affected, to identify where there could be interactions between them.

The scoping will also assist in consultations, in identifying the requirement for baseline surveys and studies, and in determining appropriate methods for the assessment. Scoping must begin early in the EIA process, at a stage when alternatives can still be considered and mitigation measures can still be included into the project design.

The key elements of the scoping process are:

- setting geographical and time frame boundaries for the assessment;
- mapping the boundaries;
- collecting the baseline data;
- assessing the impacts; and
- considering alternatives.

11.3.3 Impact analysis and mitigation and impact management

The key stages in assessing impacts are:

- Identify where indirect and cumulative impacts and interactions will potentially occur;
- Identify the cause and effect relationship – the pathway that impacts will follow which will show how project activities will affect the existing environment;
- Determine the response of the resource to a change in the environment, and assess the magnitude and significance of the impacts;
- Develop mitigation measures to address the impacts; and
- Develop monitoring projects to gauge the indirect and cumulative impacts, and impact interactions, and establish mechanisms for addressing significant impacts if identified.

Assess the magnitude and significance of the impact

Once the impacts have been identified, the next step is to ascertain the magnitude of the impact and its significance. Establishing significance criteria for indirect and cumulative impacts, as well as impact interactions may be more complex than for direct impacts as broader issues can be expected to apply.

Other factors to take into consideration when assessing the magnitude of these impacts are:

- What changes would occur anyway in the environment if the project did not go ahead?
- How have past actions contributed to the current baseline condition?
- When determining the significance of an impact, as well as taking into account the magnitude, consideration needs to be given to:
    - The duration, i.e. will the impact be temporary or permanent;
    - The extent, e.g. the percentage of a habitat that may be lost;
    - The frequency of the impact;
    - The 'value' and resilience of the receptor affected; and
    - The likely success of mitigation.

Thresholds to determine significance vary depending on the environmental parameter and its importance. The criteria used in the assessment should be clearly stated.

There are various methods to identify and assess indirect and cumulative impacts and impact interactions, some of which will be more suitable for one particular project than another and some will be needed in the same EIA process. These methods, taken from EC 1999, are summarised in the paragraphs below.

Expert opinion

Expert opinion is a 'tool' for assessing indirect and cumulative impacts as well as impact interaction. Exchange of views and the effective liaison between members of the project team are of primary importance, especially with respect to indirect impacts, cumulative impacts, and impact interactions. With these kinds of impacts, a number of different scientific disciplines are often required to analyse the network of interactions that occur. Using expert opinion alone may be enough to identify and assess indirect and cumulative impacts and impact interactions for simple projects.

Consultation and questionnaires

Consultations and questionnaires are information-gathering techniques that can assist in defining the scope of the assessment and identifying where and how indirect and cumulative impacts and impact interactions may occur. They are often used at the scoping stage of a project. People consulted may include:

- Relevant statutory and non-statutory authorities;
- Experts on a particular subject matter associated with the project and its potential impacts; and
- Local businesses and community who may be affected by the project.

Questionnaires are another method for obtaining information, particularly from businesses, local interest groups, and residents who may be potentially affected by a proposed project. They can either form the basis of an interview or be used as postal questionnaires.

Network analysis

Network and systems analysis identifies the pathway of an impact using a series of chains (networks) or webs (system diagrams) between a proposed action and the receptor of an impact. Analysing the response of a receptor to a particular action and identifying where there are knock-on effects on other receptors or environmental elements enable consideration of indirect impacts and interactions between both the actions of a project and the impacts themselves. Cumulative impacts can also be identified in network and systems diagrams where different actions or developments can affect the same environmental element or receptor.

Checklists

Checklists are often used to identify direct impacts. These can also be applied to identify cumulative impacts in particular. Successful use of this tool however, relies on the experience of the practitioner in identifying the activities and key sensitive resources. Checklists are often used to identify impacts at the scoping stage of a project, providing a structured approach for the practitioner to follow. However, using a checklist does not mean that other activities, such as consultations, are not required during scoping. The form of the checklist can vary according to the type and detail of information required.

Spatial analysis

Overlay mapping (transparent maps) and GIS (Geographical Information System) can identify the spatial distribution of impacts and assist in identifying where cumulative impacts and impact interactions may occur as a result of a project. Both methods involve preparing maps or layers of information that are then superimposed on one another.

Matrices

Matrices can evaluate to some degree the impacts of a project’s activities on resources, and can also consider the cumulative and indirect impacts, as well as impact interactions on a resource. They cannot, however, be used to quantify the actual significance of the impacts. Weighting of matrices to reflect factors such as duration, frequency and extent can be used to ‘score’ or rank impacts, provided the criteria used are clearly set out.

Carrying capacity and threshold analysis

This approach considers the capacity of a resource and its resilience to environmental change. This can be particularly useful when assessing the cumulative impact of a number of actions or developments on one resource, if it is possible to ascertain the threshold or limiting factor. Regulatory authorities establish the thresholds for emission levels, which can be used to assess the magnitude and significance of an impact.

Modelling

Modelling enables the quantification of cause and effect relationships by simulating environmental conditions. The most common form of modelling is computer based and predicts the chemical and physical impacts of a particular action on the environment.

Mitigation

Mitigation and its relationship to indirect and cumulative impacts and impact interactions can be considered in two ways:

- Mitigation of these impact types; and
- Indirect or cumulative impacts or impact interactions caused by mitigation measures (also known as an ‘impact shifts’).

When considering mitigation measures to address cumulative impacts from a number of projects, there may be a need for co-operation between developers. Mitigating indirect and cumulative impacts and impact interactions may differ from mitigating direct impacts. Mitigation has to be considered on a project-by-project basis.

Problems and uncertainties

There are often uncertainties and problems when assessing indirect and cumulative impacts and impact interactions; this can be due to a number of factors:

Boundaries

When identifying a geographic boundary suitable for the assessment, there is always the issue of where the cut-off point is for areas to be included. Boundaries are useful tools for rationalising the scope of the assessment but they should be flexible.

Baselines conditions

When establishing baseline conditions for the assessment, suitable data may not exist or be unavailable, be incomplete or at an inappropriate scale. Obtaining information on activities in the past, present, and future can be difficult. Obtaining baseline information where there are trans-boundary impacts, whether local, regional or national, can also be problematic.

Understanding interactions and pathways

Where there are interactions and pathways, it is important to understand the system response. This understanding enables the assessment to reflect as accurately as possible the impacts of a particular action. Complex interactions will give rise to non-linear responses, which are not always clearly understood and therefore are difficult to assess.

Assumptions

Any assumptions used in the assessment should also be well-documented so that the decision maker is fully aware of the basis on which the assessment was made.

Reporting

The results of the assessment of the indirect and cumulative impacts and impact interactions need to be reported in the Environmental Statement. There are two key approaches for reporting these impacts:

- Integrating the assessment into each topic section; or
- Producing a separate chapter.

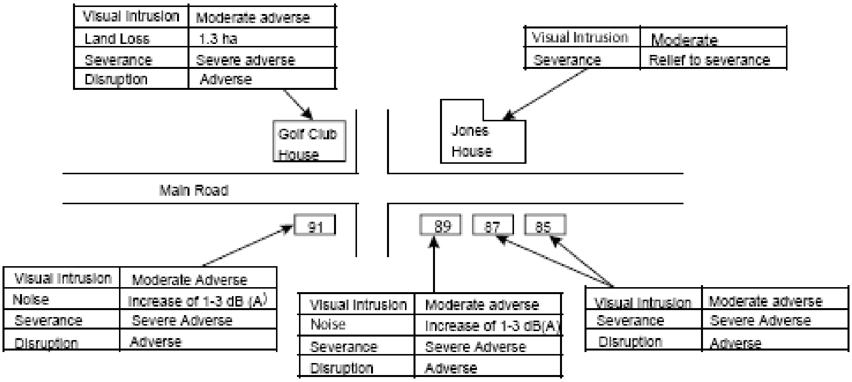
Use of tables

In addition to the above, it may also be useful to have a summary, setting out the overall impacts, which should be considered cumulatively for individual receptors. Presenting the information in a table that focuses on the receptors clearly shows where receptors will experience more than one type of impact. This is useful to convey the overall impacts to the decision makers and public.

Use of schematic diagrams

Schematic diagrams can also present the expected impacts of the project (see Figure 11-3).

FIGURE 11-3
SCHEMATIC DIAGRAM



Other methods

Other methods of reporting indirect and cumulative impacts, as well as impact interactions are matrices (using quantitative or qualitative information or indices), figures, and maps.

11.3.4 Consultation

Consultation is seeking input and advice of government agencies, independent experts, interest groups, and the public during scoping and after completion of the assessment. Information and data on potential indirect and cumulative impacts and impact interactions can then be obtained. The developer should request information on the scope of the assessment and on future activities foreseen to assess these impacts properly. The competent authorities should then advise the developer in establishing the boundaries of the assessment for indirect and cumulative impacts and impact interactions.

11.3.5 Documentation and Information

The developer has to ensure that all the information of environmental assessment is provided in the report. The authorities are usually there to help the developer and initiator in writing and completing the report.

11.3.6 Decision making

Once the report is submitted, the authorities review the report's conclusions and recommendations. After the review, the authorities can authorise the project and/or impose specific conditions and requirements, or refuse the project. The decision process varies from a country to another. Steps and delays can be very different. References have then to be taken from the national, regional or local legislation.

11.3.7 Public participation

As mentioned in the second paragraph of this chapter, public consultation is very important in an EIA. The public should actually be involved in the environmental assessment from the beginning up to the final decision. They should be given the opportunity to give their opinion on the project. Everyone concerned should be consulted, from public authorities or institutions to individuals.

Public participation in EIA is critical in helping to integrate economic, social and environmental objectives, *i.e. move towards more sustainable development by acting as a device to strengthen and increase public awareness of the delicate balance between economic and environmental trade-offs*. It also safeguards against bad or politically motivated decisions. Public participation is necessary to minimise or avoid public controversy, confrontation, and delay, and can make a positive contribution to the EIA process.

The legislation defines formal opportunities for public participation in EIA. While the rights of involvement in many countries are limited to opportunities for viewing and commenting on finalised reports, in principle, the public should be consulted at least twice (shortly after environmental screening and before the terms of reference for the EA are finalised; and once a draft EA report is prepared) but could be at every stage in the EIA process. Table 11-3 summarises the main objectives of public involvement at each stage of the EIA process, including a detailed description of these objectives.

TABLE 11-3
SUMMARY OF OBJECTIVES OF PUBLIC INVOLVEMENT IN EIA

Stage of EIA process	Objectives of public involvement
Screening	Identification of significant impacts
Scoping	▪ Identification of public's interest and values ▪ Identification of priorities for assessment ▪ Encouraging public understanding of the proposed project
Assessment	▪ The public can contribute local knowledge and values to the prediction, evaluation and mitigation of impacts ▪ Improvement in quality and acceptability of EIA report
EIA Report Review	Public contribute to evaluation of quality and acceptability of report
Decision	Public comment on acceptability of project impacts
Monitoring	Public evaluate impacts that occur and support project environmental management process

There are a number of advantages in involving the public early on in the EIA process. If participation occurs early on, then the interaction between the public, developer, and decision-making body should continue throughout the EIA process to see the full benefits.

All of the information on the project should be provided to the public on time so that the public opinion should be taken into account in developing the project and the report. Surveys, questionnaires, conferences, meetings are the main methods used to complete these tasks. Good practical guidance on adequate public consultation and suggested approaches on how to achieve it are in the Environmental Assessment Guidelines of the Asian Bank (ADB 2003).

11.3.8 Monitoring (Environmental Management Plan)

Assessing indirect and cumulative impacts and impact interactions is an iterative process in which the potential for such impacts is re-assessed through all stages of the project. Monitoring impacts is the last step; once a project has started, it is an opportunity to check the accuracy of the predictions and ensure that the mitigation measures implemented are effective. There are inherent uncertainties associated with assessing impacts, which are not a direct result of the project and may also be linked to other projects or activities.

To monitor impacts, there should be indicators against which to gauge the magnitude and significance. Furthermore, there should be an appropriate time frame for the monitoring programme, particularly as some impacts are not immediately apparent. The geographical scale of the monitoring should also be appropriate to the nature of the impact and resource being monitored. When monitoring mitigation measures, there should be a measure of the efficiency in avoiding, reducing or remedying the impacts. Where necessary, this should highlight problem areas and ways in which the measures can be more effective.

As mentioned above, an environmental management plan is required in some legislation (e.g., Asian Bank); its form and content depend on these texts.

11.4 Case study: Wuhan Wastewater and Storm Water Management

11.4.1 Project scope

The Project consists in improving the quality of the treated or untreated wastewater discharged in the environment and managing storm water in the region.

11.4.2 Project description

The project consists of five wastewater management components and four storm water management components. The wastewater management components include expanding and/or upgrading four plants. New collection systems have then to be built. The project also includes the construction of a WWTP. The storm water management components include the construction of pipelines, box culverts, pumping stations, open canal and/or renovation of existing canals.

11.4.3 Alternatives to the project

The “no project” alternative has been considered but rapidly rejected. Without the project, pollution will continue to affect surface water and ground water and the water quality of the receiving waters will deteriorate. Flooding will continue and may be exacerbated in the future as development continues. With the project, living conditions in significant urban and suburban areas of the city will improve as a result of increased collection and treatment of wastewater and reduced flooding.

Alternatives for wastewater collection have been considered but have been quite limited as they concern the upgrading of existing WWTP. Alternate materials for the pipes and alternate sites for wastewater treatment were considered. The proposed sites were finally selected based on land acquisition and resettlement requirements, likely environmental impacts, projected capital and O&M costs, and the type of wastewater collection system required. The proposed processes were selected based on effluent quality required, construction and operating cost, available site area, and existing processes already used.

Three alternatives for industrial wastewater treatment were considered:

1. Major industries having their own wastewater treatment facilities meeting environmental discharge standards and municipal WWTPs for domestic wastewater only;
2. Installation of pre-treatment facilities at individual industrial sites to meet sewer discharge standards, and construction of municipal WWTPs for domestic and pre-treated industrial wastewater; or
3. Larger municipal WWTPs to accommodate all domestic and industrial wastewaters.

The second option was the most environmentally safe and friendly and has the least negative impact.

Alternatives for effluent reuse have not been considered as Wuhan has abundant surface water resources. Alternatives for sludge disposal considered included landfill, incineration, and beneficial reuse in landscaping. Beneficial reuse has been the preferred method of disposal if the quality is acceptable; otherwise, the sludge will be disposed of in a landfill.

11.4.4 Positive impacts and environmental benefits

The quality of the water will improve and there will be significant health benefits from decreased exposure to diseases transported by wastewater. The frequency and severity of flooding will also decrease, which will then bring other substantial benefits. The project will also result in the direct and indirect creation of jobs.

11.4.5 Mitigation measures during design

Everything will be done during design to reduce all negative impacts on the environment (noise, odours, etc).

11.4.6 Impacts and mitigation measures during construction

Construction activities are expected to generate several adverse impacts (air pollution by dust (excavation, demolition, vehicle movement), by gas (vehicles), noise, traffic congestion, solid and liquid waste, excavated material in excess, interruption of municipal services (sewers, gas lines, water supply, communication cables, etc), land occupation and modification).

Mitigation measures during construction include:

- Keep construction sites, transportation routes, and materials-handling sites wet by water-spraying;
- Use vehicles that comply with relevant emission standards;
- Control noise from construction machinery (choice of machinery and good time of work);
- Prepare public traffic plans;
- Collect and treat sewage and other wastewater from construction camps with septic tanks before discharge;
- Plan temporary land occupation to minimise the disturbance and reinstate land to its original condition upon completion of construction;
- Manage all construction waste properly;
- Respect all archaeological or other cultural properties, suspend construction, and contact authorities;
- Take safety measures at the construction sites to protect the public (warning signs); and
- Train all contractors and construction supervisors before construction begins.

11.4.7 Impacts and mitigation measures during operation

- *Odour* concentration generated by the plants have been estimated by an air diffusion model and it has been decided to propose odour control facilities for two WWTP. Overall, the project should have a positive impact on air quality related to odour, treating water not yet treated.

- *Chlorine* will be managed by installing safety detectors and chlorine scrubber systems, minimising the amount of chlorine stored on-site, placing a buffer zone around the chlorine room, providing gas masks and breathing apparatuses for workers, and training them on safe operational procedures.
- *Corrosive, toxic, and explosive gases and liquids* which could accumulate in the system will also be managed.
- *Sludge* will be disposed of in landfills. An impermeable layer will allow collecting leachate which will also be treated.
- *Control plan* will be established to be sure the plants are working perfectly (indicators, contingency plans, public consultation, etc.).

11.4.8 Land acquisition and resettlement

People will be affected physically and economically by the project (e.g., acquisition of land, temporary use of land for wastewater collection systems, WWTPs, stormwater drainage, and pumping stations, and people whose livelihoods are affected during construction). All persons affected will be compensated and resettled in a timely and adequate manner, in accordance with the resettlement plan, so that they will be at least as well off as they would have been without the project.

11.4.9 Economic assessment

An economic analysis was done over a 25-year period inclusive of the project construction period, in accordance with ADB's *Guidelines for the Economic Analysis of Projects*. Project benefits and costs were estimated on a without- and with-project basis. Policy and planning documents and regulations were thoroughly reviewed to verify that water quality standards are justifiable and that the project is consistent with both State, Provincial, and Municipal pollution control and water management plans and with local infrastructure development policies and plans. Public perceptions and preferences were also evaluated using household and business surveys; compared to a range of public services, storm water and wastewater service improvements were ranked first in priority.

11.4.10 Environmental Management Plan

The environmental management plan (EMP) covers all phases of the project, from preparation and construction to commissioning and operation, and aims to monitor environmental impacts and their mitigation. The EMP has been incorporated into the design stage, and will be incorporated into the construction and operation management plans. The EMP will ensure effective implementation of various identified mitigation measures.

Plans for public involvement during design, construction, and operation have been developed during project preparation. These plans include public participation in monitoring impacts and mitigation measures during construction and operation, evaluating environmental and economic benefits and social impacts, and interviews after project completion. There will be several types of public involvement, including site visits, workshops, investigation of specific issues, interviews, and public hearings as presented in the EMP.

The EMP presents a detailed Environmental Monitoring Program, which complements the monitoring proposed in the project design and monitoring framework. The EMP will evaluate the extent and severity of environmental impacts compared to predicted impacts, the performance of the environmental protection measures and compliance with related rules and regulations, and trends of impacts. During construction and operation, the implementing agencies will monitor the performance of their facilities and the environmental impact of the project.

11.4.11 Public involvement

There were two rounds of public consultation during the EIA:

1. meetings with members of the public and other stakeholders concerned; and
2. a questionnaire survey of project-affected people and beneficiaries from different age groups, genders, educational backgrounds, and occupations.

Additional consultation was undertaken through inclusion of some queries in the household socioeconomic and enterprise surveys undertaken for the poverty and social analysis.

Most participants support the project and believe that adverse impacts can be alleviated with advanced technologies and appropriate mitigation measures; for the proposed Caidian wastewater subproject, affected people wanted fair resettlement and land acquisition compensation, in compliance with relevant state and provincial policies, and wanted to be paid on time and in full. They expressed hope that the project would have minimal impacts on the surrounding communities, and that project facilities being constructed would be of high quality.

The issues and concerns raised by the public through the public consultation process have been appropriately addressed during the EIA and mitigation planning. Specific mitigation measures will avoid or minimise the adverse impacts that most concern the public, and specific proposals have been incorporated into the EMP.

Future plans for public involvement during construction and operation include public participation in monitoring impacts and mitigation measures; evaluating environmental, economic, and social impacts; and gauging public opinion through interviews after the project is completed.

11.4.12 Conclusion

Economic (wastewater tariffs, cost estimates, assurances, etc.), legal (regulations, standards, policies) and technical (wastewater collection, sludge disposal, industrial pollution control plan for pre-treating industrial wastewater) management will be the main risk of failure of the project. Management plans have to be prepared and submitted to the ADB.

The project will bring significant benefits to urban and suburban areas of Wuhan and to water bodies. The project will also result in significant health benefits. Reductions in the frequency and severity of flooding will bring additional substantial benefits.

Appropriate mitigation and compensation measures will avoid or reduce to acceptable levels the adverse impacts generated by the project. Main measures include careful selection of WWTP sites to avoid sensitive locations; control of noise, dust, and release of wastewater during construction; control of soil erosion during earthworks; control of odour and noise during operation; and landscaping after project completion. Adverse impacts that will be mitigated to acceptable levels include the relocation of 1,799 persons and the permanent loss of about 62.5 ha of land, which will be appropriately compensated.

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12. LEGAL & REGULATORY REQUIREMENTS

12.1 Overview of Legal Requirements

The legal and regulatory requirements that the developer of a WWTP has to meet vary widely from country to country based on the existing national water pollution control and water resources protection regulatory framework. They may also vary from region to region within a country based on the local availability and demand for water and water quality to be expected in the receiving water. These legal requirements can be grouped into five themes:

1. **Discharge of pollutants into receiving water or land**
    - Water quality standards in receiving water
    - Pollutant Discharge Elimination System Permit

2. **Design of plant**
    - Plan siting
    - EIA for project development

3. **Construction of plant**
    - Construction work impact
    - National Historic Preservation

4. **Operation of plant**
    - Operation risks
    - Monitoring requirements
    - EHS rules and regulations

5. **Embedding of plant in local context**
    - Fish & Wildlife and Nature Protection
    - Wild and Scenic Landscape Protection

In addition to all mandatory regulatory requirements above, the operator of a WWTP may opt for a voluntary certified Environmental Management System (EMS ISO 14000 series) to ensure sustained and complete compliance with environmental regulatory requirements. Such a certification is often not mandatory but appreciated by environmental agencies supervising plant operation because of the reduced risk of environmental impacts due to environmental negligence. EMS-certified plants are often less heavily controlled and monitored by enforcement agencies.

12.2 Discharge of wastewater into receiving water

Water resources protection or pollution control authorities often define a “discharge of a pollutant” to mean any addition of any pollutant to receiving waters from any point source. The term “pollutant” is defined as dredged spoil, solid waste, sewage, sewage sludge, chemical wastes, biological materials, industrial, municipal, and agricultural waste, etc. discharged into a receiving water body. A “point source” is a discernible, confined and discrete conveyance, such as a pipe, ditch, channel or sewer, etc. from which pollutants are or may be discharged.

12.2.1 Receiving Water Quality Standards

Like river basin authorities, national or regional water resources protection authorities develop water quality standards for all waters of the country including wetlands. These standards often consist of three major components:

1. **Designated Uses** - These are environmental goals for each water body within a region or river basin. Each body of water is given one or more designated uses, such as “ground water recharge” or “aquatic life support.” The goal of the water resources management authority is to achieve, protect, and maintain these designated uses.

2. **Water Quality Criteria** – Water resources and pollution control authorities develop water quality criteria to support the designated uses of each water body in their respective jurisdictions. The criteria are either narrative statements or numeric limits on factors affecting the water body’s health. A number of advanced countries are also establishing biological criteria, in addition to the more traditional physical and chemical criteria, to help determine the health of wetlands.

3. **Anti-degradation Policy** – Water resources and pollution control authorities establish anti-degradation policy and procedures for implementation. Anti-degradation policies, at a minimum, will maintain and protect existing in-stream water uses and the level of water quality necessary to protect the existing uses. These policies also ensure the protection of water quality for a particular water body where the water quality exceeds levels necessary to protect fish and wildlife propagation and recreation on and in the water.

In the EU, water quality standards are being brought in line with the requirement of the Water Framework Directive (WFD) (2000/60/EC), which combines protection of ecological status with long-term water use and sustainable development. It is a new instrument for spatial planning and integration of policies, a legal framework of common approach, principles, environmental and sustainability objectives established at the river basin level. The objectives are to respect protected nature and drinking water areas, ban direct discharges to ground water, and price water use. Some countries define receiving water as a national standard, others define receiving water quality based on beneficial uses. Table 12-1 shows the limit values in receiving water in Austria before the introduction of the WFD.

12.2.2 Pollutant Discharge Elimination System Permit

Pollution control authorities prohibit discharging a pollutant from a point source, except in accordance with a permit. In many countries and all developed countries, wastewater dischargers wishing to discharge treated effluent to receiving surface water or ground surface (e.g., spray irrigation) or subsurface (e.g., subsoil dispersal) must obtain a permit that sets terms and conditions for these activities. An application may take several months to process, so the application should be submitted to the relevant authority about half a year prior to starting construction.

TABLE 12-1
LIMIT VALUES IN RECEIVING WATER GUIDELINES 1987 IN AUSTRIA

Parameter	Chemical bond	Receiving water limit values (mg/l)
Total ammonium	$(NH_4 + NH_3) - N$	0,5
Ammonia	NH_3-N	0,05
Nitrate	NO_3-N	8
Nitrite	NO_2-N	0,05
Phosphorus (solved)	P	0,2
Biochemical Oxygen Demand	BOD_5	3
Chemical Oxygen Demand	COD	10
Dissolved Organic Carbon	DOC	2

A wastewater discharge permit will commonly contain numerical and narrative limits on the amounts of specified pollutants that may be discharged. These “effluent limitations” implement both technology-based and water quality-based requirements of the relevant water protection law. Technology-based limitations represent the degree of control that point sources can reach with various levels of pollution control technology. In addition, if necessary to achieve compliance with applicable water quality standards, the permit may contain water quality-based limitations more stringent than the applicable technology-based standards.

Permit requirements vary case by case and information in the application documentation often provided by the permitting authority helps determine which regulatory requirements to apply in the permit. The application often has to request information on design flows of the facility, the route which treated wastewater will travel to a surface-water body, and a description of the existing treatment system or the system to be built. The application may also request information on the design influent concentrations for biological oxygen demand (BOD), total suspended solids (TSS), total phosphorus and ammonia nitrogen, and a description of industrial flows to the treatment works. It is important to make the permit application as complete as possible. The permitting authority staff may contact the applicant during the process of reviewing and developing the permit to get additional information.

The following key elements are usually part of the permitting process:

Survey and Design

The first step toward obtaining a permit is to have an engineer identify the planning area, proposed design flows, and possible treatment alternatives. In some countries, the engineer must be a registered professional or the company should have a license for such design activities.

A site evaluation must verify that the system’s proposed location meets the site suitability requirements for the proposed discharging process. If it is subsurface discharge, a hydro-geological study may also determine the system’s potential effects on ground water quality. A site evaluation consists of determining the suitability of the proposed location by digging soil pits and/or taking soil borings to identify any limiting soil features, including determining the depth to the seasonally high water table and bedrock. The site evaluation also gathers information necessary for design, including soil texture, percolation rate, setbacks, and slope.

The hydro-geological study in case of sub-surface infiltration will determine any effects the system will have on ground water quality and possible ground water mounding. Because of the study's complexity, a hydro-geologist may be required for this part of the project. The hydro-geologist will need the design flow information and site evaluation report from the engineer to conduct the study. The goals of the study are to:

- Identify the depth to the static ground-water level and any perched water or areas likely to be seasonally saturated;
- Determine the direction of ground-water flow (both horizontally and vertically);
- Determine background ground-water quality at the location;
- Estimate the height of ground-water mounding from the proposed system;
- Determine whether drinking water standards can be met at the property boundary;
- Determine piezometer locations for monitoring ground-water mounding during system operation;
- Determine the number and placement of monitoring wells necessary to monitor the system's effects on ground-water quality.

The number of monitoring wells necessary will vary depending on the complexity of the hydrogeology and the size of the treatment system. The wells should include at least one nested set to determine whether the system is in a ground-water recharge or discharge zone. A control well is often also placed in a location that will represent the background conditions of the site.

Effluent Limitations

The authority sets effluent limitations to protect water quality standards and the designated uses of waters in the country or region. All municipal and other point source dischargers of sewage are required, at a minimum, to provide secondary treatment. Minimum secondary treatment effluent limits for WWTP (up to a population equivalent of 5,000) according to the EU Urban Wastewater Directive (91/271/EEC) are in Table 12-2.

Effluent limits which are more stringent than the minimum secondary treatment requirement may be assigned to a discharge where stream flows are not adequate to protect water quality standards and designated uses (for example, seasonal ammonia limits). The permitting authority considers a number of factors in developing effluent limits for a particular discharge, including the characteristics of the receiving water (use classification, water-quality standards, flow characteristics) and the discharge (design flow, discharge duration and frequency). Toxic pollutants may also be evaluated to ensure protection of humans, aquatic life, and wildlife.

TABLE 12-2
TYPICAL EFFLUENT STANDARDS FOR WWTP (UP TO 5,000 P.E.)

Substance or characteristic	Limiting concentration or range (mg/L)
5-day BOD (BOD_5)	25
COD	125
Total suspended solids	30
pH range	6.0 - 9.0
Nitrogen (TKN)	15
Phosphorus (TP)	2

Source: EU UWWT Directive 91/271/EEC

For new or expanded discharges, additional submittals and review may be required.

The review of effluent limits should be completed as early as possible in the permitting process so that any issues can be addressed in a timely manner. Delays may result if inadequate information is provided or water quality concerns which need additional evaluation are identified during review.

Public Participation

After all necessary information has been submitted with the permit application, the Permitting Authority will determine if there should be an environmental review process. In some cases, an EIA (see Chapter 11) may be required (often mandatory if design flow is greater than 200 m^3 per day). If the project triggers an EIA, there will also be a public notice and comment period on the results of the EIA. The comments generated during this process, along with any information collected during the application process, will be considered in developing the permit.

A draft permit is then often completed and put on public notice for a month or so for review by any interested parties and stakeholders. Comments received during this period may result in revisions to the draft permit. When all concerns are adequately addressed, a final permit is issued and its conditions become effective upon issuance.

Certified Operator

The permit also often requires that the permitted entity employ a certified operator to run the treatment facility. The certification level required for the operator depends on the complexity of the facility's operation.

Permit Fees

The permitting authority may charge a permit assessment fee and an annual permit fee to assess the permit and monitor the periodic compliance of the operation of the plant with the permit.

Permit Monitoring Requirements

The permitted entity has to monitor the treatment system and submit Discharge Monitoring Reports to the permitting or monitoring authority. The monitoring requirements vary depending on the waste stream characteristics, size of the facility, receiving water concerns, and type of treatment.

12.3 Design of plant

12.3.1 Siting of Plant

Most countries have restrictions on the siting of WWTP to avoid conflicting land use at or near a WWTP and/ or the discharge points of treated water into receiving waters. These restrictions are usually very specific; the siting of a wastewater treatment plant should be discussed with the water regulatory agency issuing the permit very early during the design process

12.3.2 EIA

An EIA is required for the development of any new infrastructure and facilities with significant environmental impact. A WWTP is usually a facility with significant environmental impact. For more information on EIA, see Chapter 11.

12.4 Construction of plant

12.4.1 Construction risk mitigation

To mitigate significant construction impact, the developer of the WWTP usually has to develop an Environmental Protection Plan (EPP) based on a review of the proposed construction activities and methods. An EPP for construction should:

- If a subsurface wastewater disposal system is proposed, confirm that the area for the disposal field will be marked off or flagged off to prevent soil compaction by heavy equipment;
- Provide detailed information on the construction phase of the proposed project, including timeframes and approximate dates for all project components/activities and for all future phases of development;
- If work within a natural/existing wetland cannot be avoided, provide detailed information on any activities proposed within the wetland or its 30m buffer, including the timing of such activities;
- Describe the source of any organic soils/plant materials, etc. to be used during construction. Often existing natural wetlands cannot be used as a source for such materials;
- Provide a complete list of plant species to be used in the constructed wetland. Only non-invasive native plants should be permitted; and
- If an impervious liner is installed, provide details on construction material, thickness, etc.

12.4.2 Historical Site Preservation

Some countries have legislation to preserve significant historical features (buildings, objects, sites or landscape) which may hamper or impact the siting of a natural WWTP in specific location.

12.5 Operation of plant

12.5.1 Operation risks

A detailed description of the proposed project's operation and maintenance characteristics should include but not be limited to:

- To what level of its nominal capacity will the **facility** be operating at the beginning of its operation?
- For municipal systems, a prediction of probable loading growth and future extension of municipal services. How many years of additional capacity does the design provide? The submission must also include a detailed listing of the number of residential, institutional, commercial and industrial users to be serviced with the system;
- For municipal systems, will any special industries or significant users use the treatment facilities? Assess the possibility of either hazardous chemicals in the system or significant changes in the system loading as a result of such users;
- Will the facility be designed to receive hauled septage from septic service companies or other industrial facilities?
- Are pump or lift stations required? If so, please locate them on a map. Will they have emergency power? If the pumping station does not have back-up power, what mitigation measures are proposed to minimize environmental impacts from by-pass events?
- Capacities of any pumps, aerators, etc, that will be part of the project;
- If the system is an extension of an existing municipal wastewater treatment lagoon with a combined (storm and sanitary) sewer system, how does the system operate during storm events?
- If the project is a wetland designed to treat run-off or effluent, state how many wetland cells are being proposed? Would the cells operate in series or in parallel? Is supplemental treatment (e.g. aeration) being proposed?
- What will be the proposed use for the constructed wetland, following the end of its operational life?
- Description of the point of **discharge** into the receiving environment, including the diffusion/dispersion method for the discharge;
- For river or marine discharge locations, information on the flow volume and an anticipated dilution factor to be achieved from the facility. Include a description of the mixing zone. Will the receiving stream always have a minimum volume of water for final dilution of the treated effluent?
- Will the system discharge to the receiving environment be batch or continuous? If the discharge will be on a batch basis, when or how often are discharges likely to occur?
- Projected characteristics of the treated effluent (e.g., BOD, TSS, TKN, TP, etc.) and projected effluent flow volumes;

- Characteristics of raw influent wastewater loadings to the wastewater treatment facility (chemical and physical) so that reviewers can check the adequacy of the design;
- Will there be disposal of **sludge** in the future? How much will be produced and how and where will it be treated or disposed of?
- Who will be responsible for **maintaining** the system? For residential subdivisions with communal water and wastewater systems outside incorporated areas, a public entity (municipality, commission) should often own and maintain the infrastructure associated with the development;
- Detailed information on the type and frequency of all maintenance activities.

12.5.2 Monitoring requirements

A WWTP has to monitor the treatment system and submit discharge monitoring reports to the relevant authority controlling the compliance of the plant. The monitoring requirements vary depending on the waste stream characteristics, size of the facility, receiving water concerns, the beneficial uses of the receiving waters and the type of treatment. Table 12-3 shows typical requirements for many municipal and/or domestic treatment facilities currently permitted in the US. Other parameters that municipal WWTP are frequently required to monitor include phosphorus and ammonia nitrogen.

TABLE 12-3
TYPICAL MONITORING REQUIREMENTS FOR WWTP

Monitoring location	Parameter	Frequency
Influent	Flow	Daily
	CBOD	Monthly
	TSS	Monthly
	pH	Monthly
	Total phosphorus	Monthly
Effluent	CBOD	Monthly
	TSS	Monthly
	PH	Monthly
	Dissolved oxygen	Monthly
	Chlorine residual	Daily
	Faecal coliform	Monthly
	Total phosphorus	Monthly
Emergency incident monitoring	Flow	(estimated total gallons)
	CBOD	2/week during incident
	TSS	2/week during incident
	Faecal coliform	2/week during incident

Source: US EPA

Table 12-4 shows monitoring requirements typically required for large ground- and subsurface-discharging wastewater systems.

TABLE 12-4
TYPICAL MONITORING REQUIREMENT FOR SUBSURFACE-DISCHARGING WWTP

Monitoring location	Parameter	Frequency	Standard
Overall system	Visual check	Weekly or monthly	▪ ISTS: no water surfacing ▪ RIB and spray: aquatic plants, floating mats, dike condition, ice cover, precipitation ▪ All: rodent problems, odours, or other maintenance concerns
Monitoring wells	Total Kjeldahl nitrogen	3/year	
	Ammonia nitrogen	3/year	
	Nitrate nitrogen	3/year	10 mg/L
	Chlorides	3/year	250 mg/L
	Water level elevation	3/year	
	Specific conductance	3/year	
	Temperature	3/year	
	pH	3/year	
Influent to facility (RIB and spray only)	Flow	Daily	
	$CBOD_5$	Quarterly	
	TSS	Quarterly	
	pH (only RIB)	Quarterly	
Pond effluent to RIB	Total Kjeldahl nitrogen	Monthly*	
	Ammonia nitrogen	Monthly*	
	Nitrate nitrogen	Monthly*	
	Chlorides	Monthly*	
	pH	Monthly*	
	Flow to each basin	Daily	
Soil tests at spray sites	pH	Annually	
	Texture	Annually	
	Phosphorus	Annually	
	Exchangeable potassium	Annually	
	Organic matter	Annually	
Piezometers	Water level elevation	3/year	

Source: US EPA
* during discharge

Note: - ISTS: individual Sewage Treatment System
- RIB: Rapid Infiltration Basins

12.5.3 EHS rules and regulations

To comply with Environment, Health and Safety (EHS) regulation in place, WWTP operators have to:

- Protect public health and the environment (by treating and disinfecting wastewater, monitoring storm-water runoff, and other health related environmental monitoring, etc.);
- Maintain wastewater piping, pumps, and other equipment through preventive, planned, and emergency maintenance;
- Keep records and prepare reports about professional health issues of staff;

As operators of WWTP are most often also responsible for the sewerage systems connected to the WWTP, there should be rules and by-laws for discharging wastes into sewers to avoid health and safety hazards and the risk of disturbing the smooth operation of the WWTP. This means establishing and respecting rules that prohibit any discharge that may, alone or in combination with other waste substances, result in the presence of toxic or poisonous solids, liquids, gases, vapours or fumes in the sewer system or at the WWTP at levels that create a hazard, public nuisance, or threaten the health and safety of workers. This concerns the following products:

- Excessive quantities of animal/vegetable oils
- Petroleum products
- Corrosive materials
- Very colourful wastes
- Excessive flows
- Explosive mixtures
- Toxic pollutants and hazardous substances
- High temperature wastes
- Noxious materials
- Wastes causing permit violations
- PCBs and dioxins
- Pesticides/fertilizers
- Radioactive wastes
- Asbestos

12.6 Embedding of plant in local landscape and nature

Some countries have regulation linked to coastal zone management and non-point sources pollution control programmes, which include requirements for protecting and restoring wetlands that are relevant for natural WWTP using constructed wetland or land application.

12.6.1 Fish & Wildlife and Nature Protection Requirements

Many countries have laws and regulations to protect endangered species and conserve ecosystems upon which threatened and endangered species of fish, wildlife, and plants depend. Such legislation commonly prohibits unauthorized taking, possession, sale, and transport of threatened and endangered species. They often also require relevant agencies to insure that any action authorised, funded or carried out by them is not likely to jeopardise the continued existence of listed species or modify their critical habitat. Natural WWTP may be located in areas habited by endangered species and in such cases additional regulatory requirements may apply.

Many developed countries also have legislation that authorizes governmental agencies to cooperate with public and private organisations in protecting wildlife (including fish) and its habitat. Such legislation also requires that impacts to wildlife be given equal consideration in water-resource development programs. If such legislation is in place, relevant agencies must be contacted regarding any projects that modify streams or other bodies of water, which may be the case for constructed wetlands or similar.

Legislation on migratory birds may also be relevant. Some countries have legislation for protecting and managing migratory and non game birds. Some natural WWTP may be or become resting or nesting sites for migratory birds in which case some related requirement may need to be considered.

12.6.2 Wild and Scenic Landscape Protection

Some countries have legislation that protect certain rivers and receiving waters such as lakes that possess outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural, or other similar values; preserves them in a free-flowing condition; and protects them and their immediate environment for the benefit and enjoyment of present and future generations. Such legislation provides limitation for the control of lands and for dealing with the disposition of lands in these areas. Some rivers may be classified as wild, scenic or recreational, and various prohibitions on the use of the waters and land may then apply. To preserve a current free-flowing condition, a designated river may be protected from dam building and other authorised structural changes that would adversely affect the values upon which its designation was based.

12.7 Minimum requirements for a certified voluntary EMS

This section covers the minimum requirements of an EMS for certification by an Environmental Auditor under an accredited licensee system. The decision to issue a letter of certification of an EMS under an accredited licensee system is at the discretion of the Environmental Auditor assessing the plant. However, for accreditation, it is expected that the EMS – whether part of a Safety, Health and Environmental Management System or as a stand alone EMS – will have certain elements in place. This section provides guidance on the elements and extent of implementation of the elements generally expected for EMS certification, in terms of the elements presented in ISO 14001:1996.

12.7.1 Premises

Accredited licensee status applies then to a particular WWTP site. The EMS must be assessed in respect of the particular site and operations for which accredited licensee status is sought.

12.7.2 Environmental policy

The operator of the WWTP must have an environmental policy in place. The policy can be documented as part of the health, safety or quality policy or it can be a stand alone environmental policy. It should be appropriate to the nature, scale and environmental impacts of the WWTP activities, products or services. As a minimum, the policy should contain commitments to prevent pollution, comply with all relevant laws and regulations, and continuously improve environmental performance.

12.7.3 Environmental aspects, impacts and issues

The WWTP operator must be able to demonstrate that it is aware of its environmental aspects and has determined which of these aspects have or can have significant impacts on the environment. It must be aware of the activities, products and services, which give rise to such impacts or potential impacts, and have developed procedures to effectively deal with these issues.

12.7.4 Legal requirements

The organisation must be able to demonstrate that it is aware of the key environmental regulatory requirements affecting its operations at the WWTP premises, and have procedures in place to become aware of changes to these requirements. This includes knowledge of all requirements of other regulatory agencies.

12.7.5 Program to achieve continuous environmental improvement

The facility should be able to demonstrate the existence of programs established to achieve a continuous improvement in environmental performance at the premises. This will commonly be expressed through the use of objectives, targets and action plans designed to achieve a particular outcome – such as waste minimisation or reduction, or removal of an environmental impact.

12.7.6 Organisational responsibility

The organisation must have a structure in place that defines environmental roles, responsibilities, and authorities. Particular focus and priority need to be accorded to responsibilities in relation to operations associated with significant environmental aspects and impacts. In particular, employees at all levels and functions must be aware of the significant environmental aspects and impacts of their activities.

12.7.7 Training

A suitable environmental training program must be in place. This must be directed at all staff whose work may create a significant impact on the environment. The training can be part of a safety, health or quality training program but must include relevant environmental training. It is expected that the adequacy of training will be established by questioning staff who manage significant environmental aspects.

12.7.8 Documentation

The organisation shall have properly maintained procedures – in either written or electronic form – for managing significant environmental aspects of the facility. The procedures must be:

- appropriately located;
- up-to-date; and
- reviewed regularly.

The procedures must adequately cover environmental aspects where an absence of procedures could lead to unacceptable environmental impacts occurring.

A number of key procedures should be examined to ensure they adequately cover the environmental management of the environmental aspect to minimise environmental impact. Procedures to be assessed include those covering:

- air emissions;
- wastewater discharges;
- noise emissions;
- performance monitoring;
- prescribed waste management;
- chemical spills management;
- training;
- environmental complaint management; and
- notification of authorities of environmental incidents.

12.7.9 Checking and corrective action

The organisation must monitor and measure on a regular basis the key characteristics of its operations and the activities that can have a significant impact on the environment.

Significant discharges to the environment must be adequately monitored to determine compliance with regulatory requirements and provide information relating to continuous improvement programs. It is essential that the organisation can demonstrate the existence of an effective process for dealing with non-compliance with regulatory requirements.

12.7.10 Environmental records

The organisation must maintain satisfactory environmental records – which may include training records, environmental licences and permits, environmental complaints, environmental monitoring data, environmental audit reports, prescribed waste transport certificates, and correspondence with regulatory agencies.

12.7.11 Emergency preparedness

The organisation must have appropriate procedures and capabilities to respond to accidents and emergency situations, and for preventing and mitigating the environmental impacts that may be associated with them. An assessment should be made of the competence of nominated staff responsible for such emergency response.

12.7.12 EMS audit and review program

The organisation should be able to demonstrate that an appropriate audit program exists for assessing the performance of the EMS, and that senior management reviews and acts on the findings of such audits.

12.7.13 Letter of Certification

If the Environmental Auditor concludes that the facility has a suitable EMS in place, a letter of certification can be issued.

12.8 **Strategic Environmental Assessment** (SEA)

The Strategic Environmental Assessment (SEA) incorporates environmental considerations into policies, plans, and programmes developed by public administration. It is sometimes referred to as Strategic Environmental Impact Assessment.

The SEA concept originated from regional development / land use planning in the developed world. In 1981, the U.S. Housing and Urban Development Department published the Area-wide Impact Assessment Guidebook. In Europe, the Espoo Convention on Environmental Impact Assessment in a Transboundary Context laid the foundations for the introduction of SEA in 1991.

The European SEA Directive (2001/42/EC) required that all member states of the European Union should have ratified the Directive into their own country's law by 21 July 2004. Many EU nations have a longer history of strong Environmental Appraisal including Denmark, the Netherlands, Finland, the United Kingdom, and Sweden. The newer member states to the EU have hurried in implementing the directive.

In general, a SEA is conducted before a corresponding EIA. This means that information on the environmental impact of a plan will cascade down through the tiers of decision making and be used in an EIA at a later stage for a project. This can reduce the amount of work that needs to be undertaken for every EIA.

The EU SEA Directive only applies to plans and programmes, not policies, although policies within plans are likely to be assessed and SEA can be applied to policies if needed.

The structure of SEA under the EU SEA Directive is based on the following phases:

- "Screening", investigation of whether the plan or programme falls under the SEA legislation;
- "Scoping", defining the boundaries of investigation, assessment and assumptions required;
- "Documentation of the state of the environment", effectively a baseline on which to base judgments;
- "Determination of the likely (non-marginal) environmental impacts", usually in terms of Direction of Change rather than firm figures;
- Informing and consulting the public;
- Influencing "Decision taking" based on the assessment; and
- Monitoring of the effects of plans and programmes after their implementation.

The EU directive also includes other impacts besides the environment, such as material assets and archaeological sites. Most western European states have broadened this further by including economic and social aspects of sustainability.

A SEA should ensure that plans and programmes take into consideration the environmental effects they cause. If these environmental effects are part of the overall decision making, it is called a Strategic Impact Assessment.

For low cost WWTS, it may be advantageous to consider a SEA for:

a) A national strategy to implement widely urban Wastewater Treatment Systems; in this case, the SEA may help assess to which extent specific incentives or rules should pro-actively encourage and favour low cost WWTS over other traditional types of WWTS and what could be the impact.

b) A proactive low cost WWTS development strategy for a region, province or wider area. In such a case, the SEA can help document the positive and negative economic, environmental, and social impact of such a strategy.

12.9 References

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13. INSTITUTIONAL ASPECTS

Effective management is the key to achieving the requisite level of environmental and public health protection in any given community. It is the single most important factor in any comprehensive wastewater management programme. Without effective management, even the most costly and advanced technologies cannot meet the goals of the community. As explained in the previous chapters, numerous technologies are currently available to meet a broad range of wastewater treatment needs. Without proper management, however, these treatment technologies will fail to perform as designed and will not adequately protect public health and the environment.

The literature on Onsite Wastewater Treatment Systems (OWTS) is replete with case studies showing that adequate management is critical to ensuring that OWTS are sited, designed, installed, and operated properly. Good planning and management are inseparable. The decision-making process leading to the selection of a system or set of systems appropriate for the community should factor in the capacity of the community to manage any given technology. Appropriate technologies should be affordable, operable, and reliable (Kreissl and Otis, 1999). Selecting individual unit processes and systems should, at a minimum, rely on those three factors. Although managing OWTS is obviously far more complicated than assessing whether the systems are affordable, operable and reliable, an initial screening using these criteria is a critical element of good planning.

Historically, selecting and siting OWTS has been an inconsistent process. Conventional septic tank and leach field systems were installed based on economic factors, the availability of adequate land area, and simple health-based measures aimed only at preventing direct public contact with untreated wastewater. Little analysis was devoted to understanding the dynamics of OWTS and the potential impacts on ground water and surface water. Only recently has there been an understanding of the issues and potential problems associated with failing to manage OWTS in a comprehensive, holistic manner.

According to many case studies and reports, a significant number of OWTS lack adequate management oversight, which results in inadequate pollutant treatment (USEPA, 2000). The lack of system inventories in many communities makes the task of system management even more challenging. As a result of the perception that onsite/decentralised systems are inferior, old-fashioned, less technologically advanced, and not as safe as centralised wastewater treatment systems from both an environmental and public health perspective, many communities have pursued the construction of centralised systems (collection systems and sewage treatment plants). Centralised wastewater collection and treatment systems, however, are not the most cost-effective or environmentally sound option for all situations (e.g., sewage treatment plants can discharge high point source loadings of pollutants into receiving waters). They are costly to build and operate and are often infeasible or cost prohibitive, especially in areas with low populations and dispersed households. Many communities lack both the revenue to fund these facilities and the expertise to manage the treatment operations. Centralised treatment systems can also contribute to unpredicted growth and development that might threaten water quality.

As development patterns change and increased development occurs in rural areas and on the urban fringe, many communities are evaluating whether they should invest in centralised sewage treatment plants or continue to rely on OWTS. The availability of innovative and alternative onsite technologies and accompanying management strategies now provides small communities with a practical, cost-effective alternative to centralised treatment plants. For example, the costs of purchasing and managing a OWTS or a set of individual systems can be 22 to 80 percent less than the cost of purchasing and managing a centralised system.

Regardless of whether a community selects more advanced decentralised systems, centralised systems, or some combination of the two, a comprehensive management programme is essential. Effective management strategies depend on carefully evaluating all feasible technical and management alternatives and selecting appropriate solutions based on the needs of the community, the treatment objectives, the economic capacity, and the political and legislative climate.

Management has become increasingly complex, especially given the need to develop a strategy based on changing priorities primarily driven by new development activities. Rapid urbanisation and suburbanisation, the presence of other sources that might discharge nutrients and pathogens, water reuse issues, increasingly stringent environmental regulations, and recognition of the need to manage on a watershed basis increase the difficulty of this task. Multiple objectives (e.g., attainment of water quality criteria, protection of ground water, efficient and affordable wastewater treatment) must be achieved to reach the goal of maintaining economically and ecologically sound communities. Investment by small communities in collection and treatment systems increases taxes and costs to consumers—costs that might be reduced substantially by using decentralised wastewater treatment systems. From a water resource perspective, achieving these goals means that public health, contact recreation activities, fisheries, shellfisheries, drinking water resources, and wildlife need to be protected or restored. From a practical standpoint, achieving these goals requires that the management entity develop and implement a programme consistent with the goal of simultaneously meeting and achieving all applicable requirements.

Changing regulatory contexts point to scenarios in which performance requirements tied to water quality standards or maximum contamination limits for ground water will determine system selection, design, and replacement. Cumulative effects analyses and anti-degradation policies could determine the level of technology and management needed to meet the communities' resource management goals. Comprehensive coordinated management programmes are needed to meet this challenge. These programmes require interdisciplinary consultations among onsite system management entities, water quality agencies, land use planners, engineers, wildlife biologists, public health specialists, and others to ensure that these goals and objectives are efficiently achieved with a minimum of friction or programme overlap.

Fortunately, there are solutions. Technologies that can provide higher levels of pollutant reduction than were practical in the past appear to be emerging. Better monitoring and assessment methods are now available to determine the effectiveness of specific technologies. Remote sensing is possible to help monitor and understand system operation, and more sophisticated inspection tools are available to complement visual inspections.

13.1 Identification of actors

Identifying direct and indirect actors, interest groups, their capability, and the people affected is essential for the feasibility of the project. It is also essential to identify their level of knowledge on domestic wastewater treatment and use to evaluate their acceptance level of the integrated model. Actors include all human groups, organisations, and institutions directly or indirectly related to the actions of the project:

- Community organisations involved
- National regulatory or executing institutions
- Regional or local institutions
- Supporting and advisory institutions

The objective is to identify and characterise the population and institutions of the study area ─mainly those directly involved─ and locate them within the local, regional, and national framework. Thus, it is necessary to use the following data on local conditions and the social, cultural, economic, organisational, infrastructure, and service contexts:

- Total population of the area involved in the project and distribution of the population according to sex, age, and ethnic characteristics;
- Population dynamic mechanisms: growth of the population, fecundity rate, migrations, rate of birth, mortality, morbidity, life expectancy at birth (considering differences of sex, age, and ethnic groups);
- Characteristics of the families: nuclear, extensive, percentage of women who are head of household, etc.;
- Earnings and economic activity: GDP per inhabitant/year; EAP according to sex and age;
- Education: percentage of literacy in adults by gender and ethnic group, percentage of regular education, elementary school, high school, and university education, according to gender and ethnic groups;
- Characteristics of the relationships and gender roles in the community, gender equity;
- Main productive activities and responsibilities of these actors, according to their location in urban or rural areas, sex, and age;
- Basic community services of water and sanitation;
- Basic urban and rural infrastructure;
- Nutritional status of the population;
- Basic health services;
- Customs, traditions, and customary law;
- Forms of community participation;
- Forms of community organisation in general;
- Presence of companies and productive or service partnerships;
- Presence of educational and research institutions;
- Non-commercial partnerships; and
- National, regional, and local entities and authorities.

13.2 Public education, outreach, and involvement

Public education and outreach are critical aspects of a management programme to ensure public support for programme development, implementation, and funding. In addition, a working understanding of the importance of system operation and maintenance is necessary to help ensure an effective Programme. In general, the public will want to know:

- How much will it cost the community and the individual?
- Will the changes mean more development in my neighbourhood? If so, how much?
- Will the changes prevent development?
- Will the changes protect our resources (drinking waters, shellfisheries, beaches)?
- How do the proposed management alternatives relate to the above questions?

A public outreach and education programme should focus on three components—programme audience, information about the programme, and public outreach media. An effective public outreach programme makes information as accessible as possible to the public by presenting the information in a non-technical format. The public and other interested parties should be identified, contacted, and consulted early in the process of making major decisions or proposing significant programme changes. Targeting the audience of the public outreach and education programme is important for both maximising public participation and ensuring public confidence in the management programme. For onsite wastewater system management programmes, the audiences of a public outreach and education programme can vary and might include:

- Homeowners;
- Manufacturers;
- Installers;
- System operators and maintenance contractors;
- Commercial or industrial property owner;
- Public agency planners;
- Inspectors;
- Site evaluators;
- Public;
- Students;
- Citizen groups and homeowner neighbourhood associations;
- Civic groups such as the local Chamber of Commerce; and
- Environmental groups.

PUBLIC EDUCATION

Public participation in and support for planning, design, construction, and operation and maintenance requirements are essential to the acceptance and success of a wastewater management programme. Public meetings involving state and local officials, property owners, and other interested parties are an effective way to garner support for the programme. Public meetings should discuss WTS problems and cover issues like programme goals, costs, financing, inspection, and maintenance. Such meetings provide a forum for identifying community concerns and priorities so that they can be considered in the planning process. Public input is also important in determining management and compliance programme structure, defining the boundaries of the programme, and evaluating options, their relative requirements and impacts, and costs.

Onsite management entities should also promote and support the formation of citizen advisory groups composed of community members to build or enhance public involvement in the management programme. These groups can play a crucial role in representing community interests and promoting support for the programme. Typical public outreach and education programme information includes:

- Promoting water conservation
- Preventing household and commercial/industrial hazardous waste discharges
- Benefits of the onsite management programme

Public outreach and education programmes use a variety of media options available for information dissemination, including:

- Local newspapers
- Radio and TV
- Speeches and presentations
- Exhibits and demonstrations
- Conferences and workshops
- Public meetings
- School programmes
- Local and community newsletters
- Reports
- Direct mailings, e.g., flyers with utility bills

PUBLIC OUTREACH

Educating homeowners about the proper operation and maintenance of their treatment systems is an essential programme activity. In most cases, system owners or homeowners are responsible for some portion of system operation and maintenance or for ensuring that proper operation and maintenance occurs through some contractual agreement.

The system owner also helps to monitor system performance. Increased public support and programme effectiveness can be promoted by educating the public about the importance of WTS management in protecting public health, surface water, ground water resources, and property values. Onsite system owners are often uninformed about how their systems function and the potential for ground water and surface water contamination from poorly functioning systems. Surveys show that many people have their septic tanks pumped only after the system backs up into their homes or yards. Responsible property owners who are educated in proper wastewater disposal and maintenance practices and understand the consequences of system failure are more likely to make an effort to ensure their systems comply with operation and maintenance requirements. Educational materials for homeowners and training courses for designers, site evaluators, installers, inspectors, and operation/maintenance personnel can help reduce the impacts from onsite systems by reducing the number of failing systems, which potentially reduces or eliminates future costs for the system owner and the management Programme.

This participatory process of consulting the various actors strengthens the future acceptance of the proposal. Therefore, its design should consider the future incorporation of the interested sectors and groups. It is advisable to use techniques such as:

- Surveys
- Semi-structured individual interviews
- Workshops of participatory planning
- Consultation of focal groups
- SWOT methodology

13.3 Characterisation of actors

The previously collected information will allow to know the actors' needs, interests, and relationships to define the management mechanisms for the proposed integrated system. To this end, it is essential to know beforehand the actors' perception of the project. It is strongly recommended to socialise the project before implementing the technical and economic studies.

13.3.1 Knowledge of actors about wastewater treatment and use

To propose training actions that enable people and institutions to adequately manage the processes, it is necessary to know the level of knowledge of the various actors about wastewater treatment and use. Thus, it is necessary to survey the:

- Community;
- Leaders;
- Authorities;
- Businessmen; and
- Teachers.

The actors of the project are expected to know the following main issues:

- Characteristics of urban wastewater and types of treatment;
- Treatment for the productive use of wastewater;
- Wastewater management for agriculture, according to the type of crop;
- Wastewater management for other productive purposes;
- Consideration of environmental management and natural resources;
- Agricultural techniques related to wastewater use; and
- Connections between treatment and use.

Since training needs may differ according to each type of actor, it is necessary to conduct a differentiated survey to know their level of knowledge to define future needs for dissemination, training, and technical assistance. After identifying the needs, a training plan should be established and executed throughout the project.

13.3.2 Acceptance level of integrated model by actors

Actors' perceptions of what an integrated system of wastewater treatment and productive use is may vary on an individual basis. Perceptions related to potential risks may lead to acceptance, indifference, or rejection of the project proposals. To achieve a good acceptance level, it is essential that actors know the risks, potential, and benefits of the proposal implementation. Clear information, showing all elements of the situation, turns perception into willingness, and willingness into acceptance. It is important to know the following aspects:

- The actors' perception of the integrated system (how they understand it, what they think, what attitudes they have regarding the integrated concept, etc.);
- Their willingness to be part of the experience (if they want to participate, refuse the issue, or show indifference); and
- Their acceptance level (if they accept their inclusion in the proposal, propose alternatives, etc.).

13.3.3 Actors' needs, interests, and relationships

Determining actors' needs, interests, and relationships is essential to introduce the proposal in their agendas. Actors should be classified in organised groups, including communities whenever their needs and interests are significant elements for the project. This classification is the basis to prepare the "map of actors," where the main groups and entities involved are defined, as well as their needs, interests, and relationships with other actors. This map should show existing and foreseeable alliances among them, as well as current and potential conflicts.

This map of actors should include:

- Characterisation: members, responsibilities, scope of their functions, type of organization;
- Needs: economic and social situation, main problems, and requirements;
- Interests: expectations of development, trends and goals, social influence;
- Relationships: joint efforts with other groups, coordination of actions, participatory approach, openness, and flexibility;
- Alliances: signed agreements, links with other groups, and merging of goals and commitments with third parties; and
- Conflicts: different interests, unsatisfied demands, negative experiences, overlapping of roles.

Preparing this map will clarify the intersectoral and inter-institutional situation of the proposal and will provide key elements for defining strategies to reinforce alliances, minimise conflicts, and strengthen synergies among groups.

13.4 Selection of management entities of integrated system

13.4.1 Types of management entities

Developing, implementing, and sustaining a management Programme requires knowledge of the political, cultural, and economic context of the community, the current institutional structure, and available technologies. Also required are clearly defined environmental and public health goals and adequate funding. A management programme should be based on the administrative, regulatory, and operational capacity of the management entity and the goals of the community. In many localities, partnerships with other entities in the management area (watershed, county, region, state, or tribal lands) are necessary to increase the capacity of the management Programme and ensure that treatment systems do not adversely affect human health or water resources. The main types of management entities are:

- Federal, state, and tribal agencies;
- Local government agencies;
- Special-purpose districts and public utilities; and
- Privately owned and operated management entities.

The following subsections describe the various types of management entities.

Federal, state, tribal, and local agencies

Federal, state, tribal, and local governments have varying degrees of authority and involvement in developing and implementing wastewater management Programmes. Many of these entities provide financial and technical assistance (see Table 13-1).

TABLE 13-1
RESPONSIBILITIES AND FINANCING CAPABILITIES OF VARIOUS AGENCIES FOR WASTEWATER MANAGEMENT

	State agency	County	Municipality	Special district	Improvement district	Public authority	Public non-profit corporation	Private non-profit corporation	Private for-profit corporation
Responsibilities	Enforcement of state laws and regulations	Enforcement of state codes, county ordinances	Enforcement of municipal ordinances; might enforce state/county codes	Powers defined; might include code enforcement (e.g. sanitation district)	State statutes define extent of authority	Fulfilling duties specified in enabling instrument	Role specified in articles if incorporation (e.g. homeowner association)	Role specified in articles of incorporation (e.g. homeowner association)	Role specified in articles of incorporation
Financing capabilities	Usually funded through appropriations and grants	Able to charge fees, assess properly, levy taxes, issue bonds, appropriate general funds	Able to charge fees assess properly, levy taxes, issue bonds, appropriate general funds	Able to charge fees, assess property, levy taxes, issue bonds	Can apply special property assessments, user charges, other fees; can sell bonds	Can issue revenue bonds, charge user and other fees	Can change fees, sell stock, issue bonds, accept grants/loans	Can charge user fees, accept grants/loans	Can change fees, sell stock, accept some grants/loans
Advantages	Authority level and code enforceability are high; programs can be standardized; scale efficiencies	Authority level and code enforceability are high; programs can be tailored to local conditions	Authority level and code enforceability are high; programs can be tailored to local conditions	Flexible; renders equitable service (only those receiving services pay); simple and independent approach	Can extend public services without major expenditures; service recipients usually supportive	Can provide service when government unable to do so; autonomous, flexible	Can provide service when government unable to do so; autonomous, flexible	Can provide service when government unable to do so; autonomous, flexible	Can provide service when government unable to do so; autonomous, flexible
Disadvantages	Sometimes too remote; not sensitive to local needs and issues; often leaves enforcement up to local entities	Sometimes unwilling to provide service, conduct enforcement; debit limits could be restrictive	Might lack administrative, financial, other resources; enforcement might be lax	Can promote proliferation of local government, duplication/ fragmention of public services	Contributes to fragmentation of government services; can result in administrative delays	Financing ability limited to revenue bonds; local government must cover debt	Local governments might be reluctant to apply this concept	Services could be of poor quality or could be terminated	No enforcement powers; company might not be fiscally viable; not eligible for major grant/loan programs

States and tribes might manage systems through various agencies. Typically, a state or tribal public health office is responsible for managing treatment systems. Regulation is sometimes centralised in one state or tribal government office and administered from a regional or local state office. Management responsibilities are usually delegated to the county or municipal level. Where such delegation occurs, the state might exercise varying degrees of local programme oversight.

Leadership and delegation of authority at the state level are important in setting technical, management, and performance requirements for local programmes. In states where local governments are responsible for managing systems, the state authority often allows flexibility for local programmes to set programme requirements that are appropriate for local conditions and management structures as long as the local programme provides equal or greater protection than that of state codes. Statewide consistency can be promoted by establishing:

- Administrative, managerial, and technological requirements;
- Performance requirements for natural resource and public health protection;
- Requirements for monitoring and laboratory testing;
- Education and training for service providers;
- Technical, financial, and administrative support;
- Periodic programme reviews and evaluations; and
- Enforcement of applicable regulations.

Many states set minimum system design and siting requirements and are actively involved in determining appropriate technologies. States can also delegate some or all of this authority to local governments. If states retain the responsibility for the administrative or technical portions of the management programme, the local governments' primary role is to implement the state requirements.

Local government agencies

In many states, local governments have the responsibility for wastewater programme management. A variety of municipal, county, or district-level agencies administer these local management programmes. The size, purpose, and authority of county, township, city, or village government units vary according to each state's statutes and laws. Depending on the size of the jurisdiction and the available resources, a wastewater management programme can be administered by a well-trained, fully staffed environmental or public health agency or by a board composed of local leaders. In some states, the legislature has delegated some or most of the responsibility for system management to local governments.

County governments can be responsible for a variety of activities regarding the management of onsite systems. A county can assume responsibility for specific activities, such as OWTS regulation within its jurisdiction, or it can supplement and support existing state, city, town, or village wastewater management programmes with technical, financial, or administrative assistance. Counties can provide these services through their normal operational mechanisms (e.g., a county department or agency), or they can establish a special district to provide designated services to a defined service area. County agency responsibilities might include:

- Adoption of state minimal requirements or development of more stringent requirements;
- Planning, zoning, and general oversight of proposed development;
- Review of system designs, plans, and installation practices;
- Permitting of systems and construction oversight;
- Inspection, monitoring, and enforcement; and
- Reports to public and elected officials.

Township, city, or village governments can be responsible for planning, permitting, and operating wastewater facilities and enforcing applicable regulations. The precise roles and responsibilities of local governments depend on the preferences, capabilities, and circumstances of each jurisdiction. Because of the variability in state enabling legislation and organisational structures, the administrative capacity, jurisdiction, and authority of local entities to manage wastewater systems vary considerably.

Special-purpose districts and public utilities

Special-purpose districts and public utilities can provide public services that local governments do not or cannot provide. A special-purpose district or public utility is a quasigovernmental entity established to provide specific services or to conduct activities specified by the enabling legislation. Special districts (e.g., sanitation districts) provide single or multiple services, such as managing planning and development activities, conducting economic development programmes, improving local conditions, and operating drinking water and wastewater treatment facilities. The territory serviced by this entity is variable and can include a single community, a portion of a community, a group of communities, parts of several communities, an entire county, or a regional area. State enabling legislation usually outlines the authority, structure, and operational scope of the district, including service area, function, organisational structure, financial authority, and performance criteria.

Special-purpose districts and public utilities are usually given sufficient financial authority to apply for or access funds, impose service charges, collect fees, impose special assessments on property, and issue revenue or special assessment bonds. Some special-purpose districts have the same financing authority as municipalities, including the authority to levy taxes and incur general obligation debt. These districts are usually legal entities that might enter into contracts, sue, or be sued. There might be situations where eminent domain authority is needed to effectively plan and implement onsite programmes. Special-purpose districts and public utilities will most likely have to work closely with state or local authorities when programme planning or implementation requires the use of this authority.

Special districts and public utilities can be an effective option for managing wastewater treatment systems. The special district and public utility models have been adopted successfully in many states. A good example is the creation of water districts and sanitation districts, which are authorised to manage and extend potable water lines and extend sewerage service in areas near centralised treatment plants. The development of management functions under the authority of existing sanitation districts provides support for planning, installing, operating, maintaining, inspecting, enforcing, and financing these programmes. Traditional management entities (e.g., health departments) can partner with sanitation or other special districts to build a well-integrated programme. For example, a health department could retain its authority to approve system designs and issue permits while the sanitation district could assist with regional planning and conduct inspection, maintenance, and remediation/ repair activities.

Onsite management districts or public utilities, whether wholly or partially responsible for system oversight, can help ensure that treatment systems are appropriate for the site and properly planned, designed, installed, and maintained. Typical goals for the management district or utility are:

- Provide appropriate wastewater collection/ treatment service for every residence or business;
- Integrate wastewater management with land use and development policies; and
- Manage the wastewater treatment programme at a reasonable and equitable cost to users.

Management districts and public utilities are generally authorised to generate funds from a variety of sources for routine operation and maintenance, inspections, upgrades, and monitoring and for future development. Sources of funds can include initial and renewable permit fees, monthly service charges, property assessments, and special fees. Onsite wastewater management districts that are operated by or closely allied with drinking water supply districts can coordinate collection of system service charges with monthly drinking water bills in a manner similar to that used by centralised wastewater treatment plants. Although some homeowners might initially resist fees and other charges that are necessary to pay for wastewater management services, outreach information on the efficiencies, cost savings, and other benefits of cooperative management (e.g., financial support for system repair, upgrade, or replacement and no-cost pumping and maintenance) can help to build support for comprehensive programmes. Such support is especially needed if a voter referendum is required to create the management entity. When creating a new district, public outreach and stakeholder involvement should address the following topics:

- Proposed boundaries of the management district;
- Public health and natural resource protection issues;
- Problems encountered under the current management system;
- Performance requirements for treatment systems;
- Onsite technologies appropriate for specific site conditions;
- Operation and maintenance requirements for specific system types;
- Septage treatment and sewage treatment plant capacity to accept septage;
- Cost estimates for management programme components;
- Programme cost and centralised system management cost comparisons;
- Potential Programme partners and inventory of available resources;
- Proposed funding source(s);
- Compliance and enforcement strategies; and
- Legal, regulatory, administrative, and managerial actions to create, develop, or establish the management entity.

Another type of special district is the public authority. A public authority is a corporate body chartered by the state legislature with powers to own, finance, construct, and operate revenue-producing public facilities. A public authority can be used in a variety of ways to construct, finance, and operate public facilities.

Some state codes restrict or disallow a managed group of special districts from managing onsite systems. In other cases, programme staff does not have clear legal authority to enter private property to perform inspections and correct problems. These limitations can be addressed through special legislation authorising the creation of entities with explicit onsite management responsibilities. Changes in laws and regulations can provide special districts with the authority to manage onsite systems and conduct inspection, maintenance, and remediation activities.

Privately-owned and operated management entities

Private sector management entities are another option for ensuring proper management of wastewater treatment systems. These entities are often responsible for system design, installation, operation, and maintenance. In some cases, these private firms also serve as the sole management entity; for example, a firm might manage a programme for a residential subdivision as a part of a public-private partnership. There are several options for public/private partnerships.

Management programmes can contract with private firms to perform clearly defined tasks for which established protocols exist, such as site evaluation, installation, monitoring/inspection, or maintenance. An example of such an arrangement would be to contract with a licensed/certified provider, such as a trained septage pumper/hauler who could be responsible for system inspection, maintenance, and record keeping. Another example would be the case where treatment systems in residential subdivisions are serviced by a private entity and operated under a contract with the subdivision or neighbourhood association.

Private for-profit corporations or utilities that manage onsite systems are often regulated by the state public utility commission to ensure continuous, acceptable service at reasonable rates. Service agreements are usually required to ensure private organisations will be financially secure, provide adequate service, and be accountable to their customers. These entities can play a key role in relieving the administrative and financial burden on local government by providing system management services. It is likely that in the future private firms will build, own, and operate treatment systems and be subject only to responsible administrative oversight of the management entity.

Whether to privatise is the decision of local authorities. Each community must assess its individual situation and make the decision based on the most efficient means of achieving regulatory compliance and enhancement of the water environment and in meeting the needs of its customers as expressed through its elected officials.

Regulatory authorities and responsible management entities

Most regulatory authorities (e.g., public health departments and water quality authorities) lack adequate funding, staff, and technical expertise to develop and implement comprehensive management programmes. Because of this lack of resources and trained personnel, programme managers across the country are considering or implementing alternative management structures that delegate responsibility for specified management programme elements to other entities. Hoover and Beardsley (2000) recommend that management entities develop alliances with public and private organisations to establish environmental quality

GUIDELINES FOR PRIVATE MANAGEMENT OR OPERATION OF WASTEWATER TREATMENT SYSTEM

1. ***Rigorous Procurement Planning and Review of Contractual Arrangement****: Procurement specifications should take into account the full scope of services desired and make clear any differences between current and future service requirements. They should also include provisions that make it possible for ratepayers to benefit from competitive forces as the need arises to address contract modifications that result from unanticipated changes in customer demand, changes in law or other uncontrollable circumstances. Procurement and contracting processes should attempt to assign risk and responsibilities as well as accountability based upon the strength of the parties involved. Contracts and the accounting practices of prospective private operators or owners should be comprehensive, clear, and straightforward. All contracts should go through a rigorous local review process. The cost of procurement, administration, and monitoring needs to be included in the cost of the private alternative.*

2. ***Open and Fair Competition****: Full cost wastewater agencies, whether public or private, should be allowed to compete with private companies for wastewater treatment service contracts when practical. Fairness should be an overriding goal, and it is important to recognize that every competitor has its own set of strengths and weaknesses and that a fair process is one that is honest and transparent. Recognizing that the purchasers of service have the right to decide what they wish to buy and how they will buy them, selection criteria must be clearly defined early on and consistently applied once the purchasing process has started.*

3. ***Consideration of Current Workforce****: Competitive processes have the potential to result in reductions in workforce. If either a public team or private contractor is chosen, the fate of the present workforce should be carefully considered and addressed in the rules that govern the competitive process. Effort should be made to achieve reductions through attrition, placement in other municipal divisions, buyout arrangements, voluntary early retirement, or via the use of fair severance packages with outplacement services. The full cost of the accommodation should be taken into consideration during the evaluation of service options.*

4. ***Stable Rates****: Rates should remain at reasonable levels, especially with respect to economically disadvantaged citizens. Savings associated with competitive processes should be reinvested in additional productivity initiatives, infrastructure maintenance and improvement, or passed on to system customers in the form of rate relief.*

5. ***Basic Legal Compliance****: Facilities under both public and private sector management must meet or exceed all applicable laws and regulations.*

6. ***Asset Protection****: Any wastewater facility service contract should require that the operators keep pace with technology and maintain the facilities at standards viewed as acceptable in the industry.*

7. ***Performance Standards, Incentives, and Disincentives****: Clear, comprehensive, and detailed performance standards with incentives are always helpful to improve performance. They are essential for a fair and credible competitive process.*

goals, evaluate treatment system performance information, and promote activities that ensure system management programmes meet performance requirements.

English and Yeager (2001) have proposed the formation of responsible management entities (RMEs) to ensure the performance of onsite and other decentralised (cluster) wastewater treatment systems. RMEs are legal entities with the technical, managerial, and financial capacity to ensure viable, long-term, cost-effective centralised management, operation, and maintenance of all systems within the RME's jurisdiction. Viability is the capacity of the RME to protect public health and the environment efficiently and effectively through programmes that focus on system performance rather than adherence to prescriptive guidelines (English and Yeager, 2001). RMEs can operate as fully developed management programmes under existing oversight programmes (e.g., health departments, sanitation districts) in states with performance-based regulations; they are usually defined as comprehensive management entities that have the managerial, technical, and financial capacity to ensure that proposed treatment system applications will indeed achieve clearly defined performance requirements. System technology performance information can be ranked along a continuum that gives greater weight to confirmatory studies, peer-reviewed assessments, and third party analysis of field applications. Under this approach, unsupported performance assertions by vendors and results from limited field studies receive less emphasis in management entity evaluations of proposed treatment technologies (Hoover and Beardsley, 2001).

Management responsibilities can be assigned to an entity designated by the state or local government to manage some or all of the various elements of onsite wastewater Programmes. The assignment of management responsibilities to a comprehensive RME or to some less-comprehensive management entity (ME) appears to be a practical solution to the dilemma of obtaining adequate funding and staffing to ensure that critical management activities occur. The use of an RME, however, makes developing and implementing a management programme more complex. Increased coordination and planning are necessary to establish an effective management programme. An RME can perform all of the management programme activities described below; some may be executed by a management entity with a smaller scope of capabilities. In jurisdictions where management programme responsibilities are delegated to an RME, the regulatory authority (RA; e.g., local health department) must oversee the RME to ensure that the programme achieves the comprehensive public health and environmental goals of the community. Depending on state and local codes, a formal agreement or some other arrangement between the RME and the RA might be required for RME execution of some programme elements, such as issuing permits.

The involvement of an ME to perform some management programme tasks or an RME to perform the full range of management tasks should be tailored to each local situation. Given the evolving nature of wastewater management programmes, activities in some cases might be performed by an RME, such as a system utility or private service provider. In other cases, these responsibilities might be divided among several state or local government agencies, such as the local public health department, the regional planning office, and the state water quality agency.

When a less-comprehensive ME conducts a specified set of these activities, the RA usually retains the responsibility for managing some or all of the following activities:

- Defining management responsibilities for the RA and the ME;
- Overseeing the ME;
- Issuing permits;
- Inspecting onsite systems;
- Responding to complaints;
- Enforcement and compliance actions;
- Monitoring receiving water quality (surface and ground water);
- Regulation of septage handling and disposal;
- Licensing and certification programmes;
- Keeping records and managing databases for regulatory purposes; and
- Coordinating local and regional planning efforts.

The RA, however, will often delegate to the ME the responsibility for implementing some of the activities listed above. The activities delegated to the ME will be determined by the capacity of the ME to manage specific activities, the specific public health and environmental problems to be addressed by the ME, and the RA's legal authority to delegate some of those activities. For example, if the ME is an entity empowered to own and operate treatment systems in the service area, the ME typically would be responsible for all aspects of managing individual systems, including setting fees, designing and installing systems, conducting inspections, and monitoring those systems to ensure that the RA's performance goals are met. Otis, McCarthy, and Crosby (2001) have presented a framework appropriate for performance management that illustrates the concepts discussed above.

The integrated system also requires an integrated management. Selecting the model and mechanisms for each case should bear in mind the implementation and sustainability of the proposal. To this end, the management model should include:

- A leader entity to promote the system with participatory and coordination tools;
- A management area for the wastewater treatment component;
- A management area for the wastewater productive use component;
- Mechanisms to articulate, coordinate, regulate, plan, and converge the above mentioned components;
- Mechanisms to incorporate the general management components: the roles of authorities and cooperation and research entities;
- A global management strategy for the integrated system;
- An operation plan and a timetable for the strategy;
- A monitoring, follow-up, and assessment plan; and
- A strategy to include changes in the operation plan, according to assessment results.

It is important to highlight the key elements of the management model and its mechanisms and strategies to analyze the technical, environmental, economic, and social factors of the project. The map of actors, for instance, is essential to design a strategy based on the knowledge of the interactions, alliances, and potential conflicts among actors.

Selecting a management system is just as important as choosing appropriate technologies for addressing the community's wastewater disposal needs. The reliability of the management entity may ultimately determine the range of wastewater treatment and disposal options that a community can use effectively.

13.4.2 Appropriate wastewater management organisations

Public and private management of wastewater treatment utilities must preserve environmental gains and seek to make further improvements in water quality through responsible and cost effective utility management; the application of advanced yet, viable technology; continuous planning; and timely infrastructure replacement. The decision to privatise services or to sell critical environmental assets is of local concern, and the decision should rely on a thorough examination of local circumstances. Government officials, utility managers, plant operators, and financial analysts should use all appropriate financial and planning tools to carefully assess present and future capital needs and environmental objectives.

Choosing a management organisation ultimately depends on local needs and preferences. The type of management entity required depends upon the maintenance needs of the system. The easiest management system to establish may not necessarily be the one that best serves the intended purpose. Careful research and adequate public discussion are crucial to choosing the most appropriate management unit. Technical, financial, and legal advice should be obtained early in the process to adequately assess the options.

CAPABILITIES OF MANAGEMENT ENTITIES

- *Provide policy and management continuity;*
- *Charge fees for service;*
- *Compel users of the services to comply with the requirements of the management plan (such as service and inspection requirements);*
- *Maintain adequate financial responsibility;*
- *Shift liability (some management entities focus all liability in one organisation, while others distribute liability among organisations); and*
- *Hire and retain adequately qualified employees.*

As explained in Section 13.2, public education and participation in decision making are vital elements of any wastewater management Programme. The public has a vested interest and an important role in wastewater management. Technical solutions to wastewater problems are often available. Certain social and economic obstacles, however, may limit implementation of technically sound policies and management plans. Members of the public who should be educated about and involved in wastewater management include homeowners, developers, public officials, real estate professionals, and the business community. Many of these citizens should also be encouraged to play an expanded role in wastewater management decisions. Citizens may not, however, fully understand or appreciate the complexity of wastewater management alternatives and problems. Therefore, public support and cooperation requires an educated public.

Wastewater management decisions often generate considerable public interest and potential controversy. Public concerns may be based on negative attitudes and incomplete knowledge. Public education and participation programmes are most effective when based on adequate understanding of existing public attitudes and knowledge about the technical issues and policy alternatives. Such understanding can be gained through the public participation process itself. Local leaders need different types of information to make wastewater management decisions that are acceptable to a majority of local citizens. Better understanding of how different segments of the public perceive management alternatives leads to more effective technological solutions. Decisions are ultimately more acceptable to all parties involved if they fully understand the situation and have opportunities for participation.

The process of establishing a management system can begin either with the local health department or with those citizens who will benefit most from the establishment of a management entity. In any case, citizen input should be encouraged in the process of determining the scope of the management entity's territory, powers, and responsibilities. One management entity could serve residents in an entire area or a portion of the area; several different management entities could also function within one area.

More sophisticated wastewater management will likely come at some increased cost. The owner of a low-cost system may have to pay a monthly bill similar to those on a municipal sewer system. Even if the management entity's fee structure employs a user fee and excludes direct costs to the taxpayers, caution must be exercised to determine whether the citizens may still be affected indirectly. For instance, if the management entity is a city or county, all citizens might assume some risk for the cost of replacing failing systems that were not maintained properly.

There is substantial need for more sophisticated management of both on-site septic systems and small community wastewater treatment and disposal systems. While these systems are fairly easy to maintain, it is clear from recent studies that these systems have not always been maintained properly. Better management should facilitate more extensive use of complex technological options. There can be a number of institutional management entities depending on the needs and desires of the county or local community.

Water, wastewater, stormwater, combined sewer overflows and watershed protection or management infrastructure play a critical role in the strength of the economy and public health by ensuring clean, safe water for citizens, businesses and industries. Infrastructure includes not only physical structures such as waterlines, sewers, decentralized onsite water and wastewater systems, water and wastewater treatment plants, but it also includes non-physical measures such as best management practices and water conservation to protect and restore valuable water resources – streams, lakes, groundwater, and wetlands. Infrastructure can be owned by public, private, profit, non-profit, and investor-owned entities. Local entities can be public, private, profit, non-profit, and investor-owned.

The public often overlooks the importance of infrastructure until an event like a waterline failure or untreated sewage enters a waterway. Despite repeated episodes which attract public attention, many local officials remain reluctant to significantly increase user charges needed for infrastructure maintenance, rehabilitation and improvements. This reluctance persists despite other evidence that the public is willing to pay for clean water, such as the increased purchases of bottled water (which is more expensive than tap water). Consequently, the prices and expenditures on infrastructure hardly reflect the true cost of providing clean, safe water.

Building technical, financial and managerial capability at the local level, strengthening planning and management coordination among all levels of government, and defining needs, sources of funding, and shortfalls of financing for infrastructure have been identified as a strategic issue.

In many instances, new and replacement construction, rehabilitation and maintenance of critical infrastructure have been postponed, resulting in infrastructure deterioration. At the same time, demand for new infrastructure in developing areas has outstripped existing capacity. The problem is compounded by increasing costs to meet new federally mandated regulations to reduce certain pollutants, inadequate planning and the trend towards the federal government providing less investment in infrastructure.

Small commercial systems and individual property owners in rural areas not served by public water and sewer also have a responsibility and need to maintain the private infrastructure for water supply and wastewater treatment on private properties. These private, decentralised systems represent a different challenge for local government for compliance, monitoring, and maintenance. Addressing these infrastructure challenges is critical to ensure clean, safe water for public health and continued economic development through sustainable water management.

The primary goal of wastewater treatment is to protect public health and the water environment. National and municipal governments have vastly improved water quality through efficient management and operation of wastewater treatment facilities. The rising costs of regulatory compliance and plant upgrades, among other factors, now pose a major challenge to the excellent service and stable prices citizens have enjoyed under many publicly managed wastewater treatment facilities. Although publicly operated wastewater utilities occupy naturally strong positions in the market, private companies are actively pursuing opportunities to offer options for private management of local wastewater utilities. Communities around the world have incorporated private management of wastewater utilities. Their performance is governed via the terms and conditions of the service agreements developed for each business relationship.

13.5 Regulatory authority (RA)

13.5.1 RA’s responsibilities

Onsite wastewater programme managers should identify all legal responsibilities of the RA that might affect the implementation of an effective programme. Legal responsibilities can be found in state and local statutes, regulations, local codes, land use laws, and planning requirements. Other legal mechanisms such as subdivision covenants, private contracts, and homeowner association rules might also affect the administration of the programme. In many jurisdictions, legal authorities that do not specifically refer to onsite programmes and authorities, such as public nuisance laws, state water quality standards, and public health laws, might be useful in implementing the programme. A typical example would be a situation where the public health agency charged with protecting human health and preventing public nuisances interprets this mandate as sufficient authorization to require replacement or retrofit of a system that has surface seepage or discharges.

The extent and interpretation of authority assigned to the RA will determine the scope of its duties, the funding required for operation, and the personnel necessary to perform its functions. In many jurisdictions, the authority to perform some of these activities might be distributed among multiple RAs.

Where this is the case, the organisations involved should have the combined authority to perform all necessary activities and should coordinate their activities to avoid programme gaps, redundancy, and inefficiency. In some cases, the RA might delegate some of these responsibilities to an ME. When a comprehensive set of responsibilities are delegated to an RME, the RA should retain oversight and enforcement authority to ensure compliance with legal, performance, and other requirements.

TASKS OF REGULATORY AUTHORITY

- *Develop and implement policy and regulations*
- *Provide management continuity*
- *Enforce regulations and programme requirements through fines or incentives*
- *Conduct site and regional-scale evaluations*
- *Require certification or licensing of service providers*
- *Oversee system design review and approval*
- *Issue installation and operating permits*
- *Oversee system construction*
- *Access property for inspection and monitoring*
- *Inspect and monitor systems and the receiving environment*
- *Finance the programme through a dedicated funding source*
- *Charge fees for management programme services (e.g., permitting, inspections)*
- *Provide financial or cost-share assistance*
- *Issue and/or receive grants*
- *Develop or disseminate educational materials*
- *Provide training for service providers and staff*
- *Conduct public education and involvement programmes*
- *Hire, train, and retain qualified employees*

Each state or local government has unique organisational approaches for managing onsite wastewater systems based on needs, perceptions, and circumstances. It is vitally important that the authorising legislation, regulations, or codes allow the RAs and MEs to develop an institutional structure capable of fulfilling mandates through adoption of appropriate technical and regulatory programmes. A thorough evaluation of authorized powers and capabilities at various levels and scales is necessary to determine the scope of programme authority, the scale at which RAs and MEs can operate, and the processes they must follow to enact and implement the management programme. Involving stakeholders who represent public health entities, environmental groups, economic development agencies, political entities, and others in this process can ensure that the lines and scope of authority for an onsite management programme are well understood and locally supported. In some cases, new state policies or regulations must be implemented to allow for recognition of onsite MEs.

13.5.2 Certification and licensing of service providers and programme staff

Certification and licensing of service providers such as septage haulers, designers, installers, and maintenance personnel can help ensure management programme effectiveness and compliance and reduce the administrative burden on the RA. Certification and licensing of service providers is an effective means of ensuring that a high degree of professionalism and experience is necessary to perform specified activities.

RAs should establish minimum criteria for licensing/certification of all service providers to ensure protection of health and water resources.

13.6 Management programme components

Developing and implementing an effective wastewater management programme requires a systematic approach to determine the necessary programme elements. Changes and additions to the management programme should rely on evaluations of the programme to determine whether the programme has adequate legal authorities, funding, and management capacity to administer both existing and new systems and respond to changing environmental and public health priorities and advances in technologies.

The management programme elements described in the following sections are common to the most comprehensive management programmes.

13.6.1 Setting wastewater management programme goals

Developing and implementing an effective management programme requires first establishing programme goals. Programme goals should rely on public health, environmental, and institutional factors and public concerns. Funding availability, institutional capability, and the need to protect consumers and their interests typically affect the selection of programme goals and objectives. One or more entities responsible for public health and environmental protection, such as public health and water quality agencies, can determine the goals. The development of short- and long-term comprehensive goals will most likely require coordination among these entities. Community development and planning agencies as well as residents should also play a role in helping to determine appropriate goals.

Traditionally, the main goals of most management programmes have been to:

- **Reduce risks to public health**;
  - Reduce health risk due to sewage backup in homes.
  - Prevent ground water and well water contamination due to pathogens, nitrates, and toxic substances.
  - Prevent surface water pollution due to pathogens, nutrients, and toxic substances.
  - Protect shellfish habitat and harvest areas from pathogenic contamination and excessive nutrients
  - Prevent sewage discharges to the ground surface to avoid direct public contact.
  - Minimise risk from reuse of inadequately treated effluent for drinking water, irrigation, or other uses.
  - Minimise risk from inadequate management of septic tank residuals.
  - Minimise risk due to public access to system components.

- **Abate public nuisances**; and
  - Eliminate odours caused by inadequate plumbing and treatment processes.
  - Eliminate odours or other nuisances related to transportation, reuse, or disposal of residuals (septage).

- **Protect the environment**; and
  - Prevent and reduce adverse impacts on water resources due to pollutants discharged to onsite systems, e.g., toxic substances.
  - Prevent and reduce nutrient over-enrichment of surface waters.
  - Protect sensitive aquatic habitat and biota

- **Provide cost-effective wastewater treatment systems and management programmes**.

More recently, there has been an increased focus on preventing OWTS-related surface and ground water quality degradation and impacts on aquatic habitat. Programme goals have been expanded to address nutrients, toxic substances, and a broader set of public health issues regarding pathogens. Onsite wastewater-related nutrient enrichment leading to algae blooms and eutrophication or low dissolved oxygen levels in surface waters is of concern, especially in waters that lack adequate assimilative capacity, such as lakes and coastal embayments or estuaries. The discharge of toxic substances into treatment systems and eventually into ground water has also become a more prominent concern, especially in situations where commercial or institutional entities like gasoline service stations and nursing homes use onsite/decentralised treatment systems. The potential impacts from pathogens discharged from OWTS on shellfisheries and contact recreation activities have also moved some OWTS programme managers to adopt goals to protect these resources.

Historically, in many jurisdictions the public health agency has had the primary role in setting programme goals. Without documented health problems implicating onsite systems as the source of problem(s), some public health agencies have had little incentive to strengthen onsite management programmes beyond the goals of ensuring there was no direct public contact with sewage or no obvious drinking water-related impacts, such as bacterial or chemical illnesses like methemoglobinemia (“blue baby syndrome”). The availability of more advanced assessment and monitoring methodologies and technologies and a better understanding of surface water and ground water interactions, however, has led to an increased focus on protecting water quality and aquatic habitat. As a result, in many states and localities, water quality agencies have become more involved in setting onsite programme goals and managing onsite wastewater programmes.

Some water quality agencies (e.g., departments of natural resources), however, lack direct authority or responsibility to regulate onsite systems. This lack of authority points to the need for increased coordination and mutual goal setting among health agencies that have such authority. Regardless of which agency has the legal authority to manage onsite systems, there is the recognition that the management programme’s mission should include both public health and water quality goals. Achieving these goals requires a comprehensive watershed-based approach to ensure that all of the programme's goals are met. Partnerships with multiple agencies and other entities are often required to integrate planning, public health protection, and watershed protection in a meaningful way. Because of the breadth of the issues affecting onsite system management, many programmes depend on cooperative relationships with planning authorities, environmental protection and public health agencies, universities, system manufacturers, and service providers to help determine appropriate management goals and objectives.

13.6.2 Comprehensive planning

Comprehensive planning has three important components: (1) establishing and implementing the management entity, (2) establishing internal planning processes for the management entity, and (3) coordinating and involving the broader land-use planning process. Comprehensive planning provides a mechanism to ensure that the programme has the necessary information to function effectively.

It is necessary to ensure that onsite management issues are integrated into decisions regarding future growth and development. An effective onsite wastewater management programme should be represented in the ongoing land use planning process to ensure achievement of the goals of the programme and to assist planners in avoiding the shortcomings of past planning efforts, which generally allowed the limitations of conventional onsite technologies to drive some land use planning decisions. Such considerations are especially important in situations where centralised wastewater treatment systems are being considered as an alternative or adjunct to onsite or cluster systems. Comprehensive planning and land use zoning are typically interrelated and integrated: the comprehensive planning process results in developing overarching policies and guidance, and the land use zoning process provides the detailed regulatory framework to implement the comprehensive plan. Honachefsky (2000) provides a good overview of comprehensive planning processes from an ecological perspective. In general, the comprehensive plan can set the broad environmental protection goals of the community, and the zoning ordinance(s) can:

- Specify performance requirements for individual or clustered systems installed in unsewered areas, preferably by watershed and/or subwatershed.

- Limit or prevent development on sensitive natural resource lands or in critical areas.

- Encourage development in urban growth areas serviced by sewer systems, if adequate capacity exists.

- Factor considerations such as system density, hydraulic and pollutant loadings, proximity to water bodies, soil and hydrogeological conditions, and water quality/quantity into planning and zoning decisions.

- Restore impaired resources.

COMPREHENSIVE PLANNING PROGRAMME ELEMENTS

- *Define management programme boundaries.*
- *Select management entity(ies).*
- *Establish human health and environmental protection goals.*
- *Form a planning team composed of management staff and local stakeholders.*
- *Identify internal and external planning resources and partners.*
- *Collect information on regional soils, topography, rainfall, and water quality and quantity.*
- *Identify sensitive ecological areas, recreational areas, and water supply protection areas.*
- *Characterize and map past, current, and future development where OWTS are necessary.*
- *Coordinate with local sewage authorities to identify current and future service areas and determine treatment plant capacity to accept septage.*
- *Identify documented problem areas and areas likely to be at risk in the future.*
- *Prioritize and target problem areas for action or future action.*
- *Develop performance requirements and strategies to deal with existing and possible problems.*
- *Implement strategy; monitor progress and modify strategy if necessary.*

Integrating comprehensive planning and zoning programmes with onsite wastewater programme management also can provide a stronger foundation for determining and requiring the appropriate level of treatment needed for both the individual site and the surrounding watershed or subwatershed. The integrated approach thus allows the programme manager to manage both existing and new onsite systems from a cumulative loadings perspective or performance-based approach that is oriented toward the protection of identified resources. Local health departments (regulatory authorities) charged with administering programmes based on prescriptive codes typically have not had the flexibility or the resources to deviate from zoning designations and as a result often have had to approve permits for developments where onsite system-related impacts were anticipated. Coordinating onsite wastewater management with planning and zoning activities can ensure that parcels designated for development are permitted based on a specified level of onsite system performance that considers site characteristics and watershed-level pollutant loading analyses. To streamline this analytical process, some management programmes designate overlay zones in which specific technologies or management strategies are required to protect sensitive environmental resources. These overlay zones may be based on soil type, topography, geology, hydrology, or other site characteristics. Within these overlay zones, the RA may have the authority to specify maximum system densities, system design requirements, performance requirements, and operation/ maintenance requirements. Although the use of overlay zones may streamline administrative efforts, establishing such programmes involves the use of assumptions and generalizations until a sufficient number of site-specific evaluations are available to ensure proper siting and system selection.

Internally, changes in programme goals, demographics, and technological advances require information and coordination to ensure that the short- and long-term goals of the programme can continue to be met. Many variables affect the internal planning process, including factors such as the locations and types of treatment systems within the jurisdictional area, the present or future organisational and institutional structure of the management entity, and the funding available for programme development and implementation.

13.6.3 Defining system design criteria and approval process

Performance requirements for onsite systems can be grouped into two general categories—numeric requirements and narrative criteria. Numeric requirements set measurable concentration or mass loading limits for specific pollutants (e.g., nitrogen or pathogen concentrations). Narrative requirements describe acceptable qualitative aspects of the wastewater (e.g., sewage surface pooling, odour). A numerical performance requirement might be that all septic systems in environmentally sensitive areas must discharge no more than 2.3 kg of nitrogen per year, or that concentrations of nitrogen in the effluent may be no greater than 10 mg/L. Some of the parameters for which performance requirements are commonly set for WWTS include:

- Fecal coliform bacteria (an indicator of pathogens)
- Biochemical oxygen demand (BOD)
- Nitrogen (total of all forms, i.e., organic, ammonia, nitrite, nitrate)
- Phosphorus (for surface waters)
- Nuisance parameters (e.g., odour, colour)

Under a performance-based approach, performance requirements, site conditions, and wastewater characterization information drive the selection of treatment technologies at each site. For known technologies with extensive testing and field data, the management agency might attempt to institute performance requirements prescriptively by designating system type, size, construction practices, materials to be used, acceptable site conditions, and siting requirements. At a minimum, prescriptive system design criteria should consider:

- Wastewater characterization and expected effluent volumes;
- Site conditions (e.g., soils, geology, ground water, surface waters, topography, structures, property lines);
- System capacity, based on estimated peak and average daily flows;
- Location of tanks and appurtenances;
- Tank dimensions and construction materials;
- Alternative tank effluent treatment units and configuration;
- Required absorption field dimensions and materials;
- Requirements for alternative soil absorption field areas;
- Sizing and other acceptable features of system piping;
- Separation distances from other site features;
- Operation and maintenance requirements (access risers, safety considerations, inspection points); and
- Accommodations required for monitoring.

13.6.4 Construction and installation requirements

A comprehensive construction management programme will ensure that construction complies with design and specifications. If a system is not constructed and installed properly, it is unlikely to function as intended. For example, if the natural soil structure is not preserved during the installation process (if equipment compacts infiltration field soils), the percolation potential of the infiltration field can be significantly reduced. Most early failures of conventional onsite systems' soil absorption fields have been attributed to hydraulic overloading (USEPA, 1980). Effective onsite system management programmes ensure proper system construction and installation through construction permitting, inspection, and certification programmes.

Construction should conform to the approved plan and use appropriate methods, materials, and equipment. Mechanisms to verify compliance with performance requirements should be established to ensure that practices meet expectations. Typical existing regulatory mechanisms that ensure proper installation include reviews of site evaluation procedures and findings and inspections of systems during and after installation, i.e., before cover-up and final grading. A more effective review and inspection process should include:

CONSTRUCTION OVERSIGHT PROGRAMME ELEMENTS

- *Establish preconstruction review procedure for site evaluation and system design.*
- *Determine training and qualifications of system designers and installers.*
- *Establish designer and installer licensing and certification programmes.*
- *Define and codify construction oversight requirements.*
- *Develop certification process for overseeing and approving system installation.*
- *Arrange training opportunities for service providers as necessary*

- Pre-design meeting with designer, owner, and contractor
- Preconstruction meeting with designer, owner, and contractor
- Field verification and staking of each system component
- Inspections during and after construction
- Issuance of a permit to operate system as designed and built

There should be construction oversight inspections at several stages during the system installation process to ensure compliance with regulatory requirements. During the construction process, inspections before and after backfilling should verify compliance with approved construction documents and procedures. An approved (i.e., licensed or certified) construction oversight inspector, preferably the designer of the system, should oversee installation and certify that it has been conducted and recorded properly. The construction process for soil-based systems must be flexible to accommodate weather events because construction during wet weather can compact soils in the infiltration field or otherwise alter soil structure.

13.6.5 Operation and maintenance requirements

A recurring weakness of many existing WTS management programmes has been the failure to ensure proper operation and maintenance of installed systems. Few existing oversight agencies conduct inspections to verify basic system performance, and many depend on uninformed, untrained system owners to monitor tank residuals buildup, schedule pumping, ensure that flow distribution is occurring properly, check pumps and float switches, inspect filtration media for clogging, and perform other monitoring and maintenance tasks. Complaints to the regulatory authority or severe and obvious system failures often provide the only formal notification of problems under present codes. Inspection and other programmes that monitor system performance can help reduce the risk of premature system failure, decrease long-term investment costs, and lower the risk of ground water or surface water contamination (Eliasson et al., 2001; Washington Department of Health, 1994).

Various options are available to implement operation and maintenance oversight programmes. These range from purely voluntary (e.g., trained homeowners responsible for their system operation and maintenance activities) to more sophisticated operating permit programmes and ultimately to programmes administered by designated RMEs that conduct all management/maintenance tasks. In general, voluntary maintenance is possible only where systems are non-mechanical and gravity-based and located in areas with very low population densities. The level of management should increase if the system is more complex or the resource(s) to be protected require a higher level of performance.

OPERATION, MAINTENANCE, AND RESIDUALS MANAGEMENT PROGRAMME ELEMENTS

- *Establish guidelines or permit programme for operation and maintenance of systems*
- *Develop reporting system for operation and maintenance activities*
- *Circulate operation and maintenance information and reminders to system owners*
- *Develop operation and maintenance inspection and compliance verification programme*
- *Establish licensing/certification programmes for service providers*
- *Arrange for training opportunities as necessary*
- *Establish procedures for follow-up notices or action when appropriate*
- *Establish reporting and reminder system for monitoring system effluent*
- *Establish residuals (septage) management requirements, manifest system, and disposal/use reporting*

Alarms (onsite and remote) can alert homeowners and service providers that system malfunction might be occurring. In addition to simple float alarms, several manufacturers have developed custom-built control systems that can Programme and schedule treatment process events, remotely monitor system operation, and notify technicians by pager or the Internet of possible problems. New wireless and computer protocols, cellular phones, and personal digital assistants are being developed to allow system managers to remotely monitor and assess operation of many systems simultaneously (Nawathe, 2000), further enhancing the centralised management of WTS in outlying locations. Using such tools can save considerable travel and inspection time and focus field personnel on systems that require attention or regular maintenance. Telemetry panels at the treatment site operating through existing or dedicated phone lines can be programmed to log and report information such as high/low water alarm warnings, pump run and interval times, water level readings in tanks/ponds, amperage drawn by system pumps, and other conditions. Operators at a centralised monitoring site can adjust pump run cycles, pump operation times, alarm settings, and high-level pump override cycles (Stephens, 2000).

Some management entities have instituted comprehensive programmes that feature renewable/ revocable operating permits, mandatory inspections or disclosure (notification/inspection) upon property transfer and/or periodic monitoring by licensed inspectors. Renewable operating permits might require system owners to have a contract with a certified inspection/maintenance contractor or otherwise demonstrate that periodic inspection and maintenance procedures have been performed for permit renewal. Sellers of property can be required to disclose or verify system performance (e.g., disclosure statement, inspection by the local oversight entity or other approved inspector) prior to property transfer. Financial incentives usually aid compliance and can vary from small fines for poor system maintenance to preventing the sale of a house if the WTS is not functioning properly. Inspection fees might be one way to cover or defray these programme costs. Lending institutions can influence the adoption of a more aggressive approach toward requiring system inspections before approving home or property loans. In some areas, inspections at the time of property transfer are common despite the absence of regulatory requirements. This practice is incorporated into the loan and asset protection policies of local banks and lending firms.

RAs, however, should recognize that relying on lending institutions to ensure that proper inspections occur can result in gaps. Property transfers without lending institution involvement might occur without inspections. In addition, when inspections are conducted by private individuals reporting to the lending agents, the inspectors might not have the same degree of accountability that would occur in jurisdictions that have mandatory requirements for state or local licensing or certification of inspectors. RAs should require periodic inspections of systems based on system design life, system complexity, and changes in ownership.

Management plans for onsite treatment systems must include information and procedures for maintaining the systems in accordance with the standards of the code as designed and approved. Any new or existing system that is not maintained in accordance with the approved management plan is considered a human health hazard and subject to enforcement actions. The maintenance requirements are specified in the code (e.g., all septic tanks are to be pumped when the combined sludge and scum volume equals one-third of the tank volume).

13.6.6 Residuals management requirements

The primary objective of residuals management is to establish procedures and rules for handling and disposing of accumulated wastewater treatment system residuals to protect public health and the environment. These residuals can include septage removed from septic tanks and other by-products of the treatment process (e.g., aerobic-unit-generated sludge). Planning a programme requires a thorough knowledge of legal and regulatory requirements for handling and disposal.

In addition to regulations, practical limitations such as land availability, site conditions, buffer zone requirements, hauling distances, fuel costs, and labour costs play a major role in evaluating septage reuse/disposal options. These options generally fall into three basic categories—land application, treatment in a wastewater treatment plant, and treatment in a special septage treatment plant.

The initial steps in the residuals reuse/disposal decision-making process are characterising the quality of the septage and determining potential adverse impacts associated with various reuse/ disposal scenarios. In general, programme officials strive to minimise exposure of humans, animals, ground water, and ecological resources to the potentially toxic or hazardous chemicals and pathogenic organisms found in septage. Other key areas of residuals management programmes include tracking or manifest systems that identify septage sources, pumpers, transport equipment, final destinations, and treatment methods, as well as procedures for controlling human exposure to residuals, including vector control, wet weather runoff management, and limits on access to disposal sites.

13.6.7 Education and training programmes for service providers and programme staff

Onsite system RAs, RMEs, and service provider staff should have the requisite level of training and experience to effectively assume necessary programme responsibilities and perform necessary activities. Professional programmes are typically the mechanism for ensuring the qualifications of these personnel. They usually include licensing or certification elements, which are based on required coursework or training; an assessment of knowledge, skills, and professional judgment; past experience; and demonstrated competency. Most licensing programmes require continuing education through recommended or required workshops at specified intervals.

Certification programmes for inspectors, installers, and septage haulers provide assurance that systems are installed and maintained properly. Violation of programme requirements or poor performance can lead to revocation of certification and prohibitions on installing or servicing onsite systems. This approach, which links professional performance with economic incentives, is highly effective in maintaining compliance with onsite programme requirements. Programmes that simply register service providers or fail to take disciplinary action against poor performers cannot provide the same level of pressure to comply with professional and technical codes of behaviour.

INSPECTION AND MONITORING PROGRAMME ELEMENTS

- *Develop/maintain inventory of all systems in management area (e.g., location, age, owner, type, size).*
- *Establish schedule, parameters, and procedures for system inspections.*
- *Determine knowledge level required of inspectors and monitoring programme staff.*
- *Ensure training opportunities for all staff and service providers.*
- *Establish licensing/certification programme for inspectors.*
- *Develop inspection programme (e.g., owner inspection, staff inspection, contractor inspection).*
- *Establish right-of-entry provisions to gain access for inspection or monitoring.*
- *Circulate inspection programme details and schedules to system owners.*
- *Establish reporting system and database for inspection and monitoring programme.*
- *Identify existing ground water and surface water monitoring in area and determine supplemental monitoring required.*

Some certification and licensing programmes for those implementing regulations and performing site evaluations require higher educational achievement. Regular training sessions are also important in keeping site evaluators, permit writers, designers, and other service personnel effective.

13.6.8 Inspection and monitoring programmes to verify and assess system performance

Routine inspections should be performed to ascertain system effectiveness. The type and frequency of inspections should be determined by the size of the area, site conditions, resource sensitivity, the complexity and number of systems, and the resources of the RA or RME. The RA should ensure that correct procedures are followed.

Scheduling inspections during seasonal rises in ground water levels can allow monitoring of performance during “worst case” conditions. A site inspection programme can be implemented as a system owner training programme, an owner/operator contract programme with certified operators, or a routine programme performed by an RME. A combination of visual, physical, bacteriological, chemical, and remote monitoring and modelling can assess system performance. The management programme should clearly define specific requirements for reporting to the appropriate regulatory agency. Components of an effective inspection, monitoring, operation, and maintenance programme include:

- Specified intervals for required inspections (e.g., every 3 months, every 2 years, at time of property transfer or change of use);
- Legal authority to access system components for inspections, monitoring, and maintenance;
- Monitoring of overall operation and performance, including remote sensing and failure reporting for highly mechanical and complex systems;
- Monitoring of receiving environments at compliance boundaries to meet performance requirements;
- Review of system use or flow records, (e.g., water meter readings);
- Required type and frequency of maintenance for each technology;
- Identification, location, and analysis of system failures;
- Correction schedules for failed systems through retrofits or upgrades; and
- Record keeping on systems inspected, results, and recommendations.

Comprehensive management programmes often include inspection programmes as part of a seamless approach that includes planning site evaluation, design, installation, operation, maintenance, and monitoring.

Outreach programmes to lending institutions on the benefits of requiring system inspections at the time of property transfer can be an effective approach for identifying and correcting potential problems and avoiding compliance and enforcement actions. Many lending institutions require system inspections as part of the disclosure requirements for approving home or property loans.

13.6.9 Compliance, enforcement, and corrective action programmes

Requiring corrective action when onsite systems fail or proper system maintenance does not occur helps to ensure that performance goals and requirements will be met. Compliance and enforcement measures are more acceptable to system owners and the public when the RA is clear and consistent regarding its mission, regulatory requirements, and how the mission relates to public health and water resource protection. An onsite wastewater compliance and enforcement programme should be based on reasonable and scientifically defensible regulations, promote fairness, and provide a credible deterrent to those who might be inclined to skirt its provisions. Regulations should be developed with community involvement and provided in summary or detailed form to all stakeholders and the public at large through education and outreach efforts. Service provider training programmes are most effective if they are based on educating contractors and staff on technical and ecological approaches for complying with regulations and avoiding known and predictable enforcement actions.

Various types of legal instruments are available to formulate or enact onsite system regulations. Regulatory programmes can be enacted as ordinances, management constituency agreements, or local or state codes, or simply as guidelines. Often, local health boards or other units of government can modify state code requirements to better address local conditions. Local ordinances that promote performance-based approaches can reference technical design manuals for more detailed criteria on system design and operation. Approaches for enforcing requirements and regulations of a management programme can include:

CORRECTIVE ACTION PROGRAMME ELEMENTS

- *Establish process for reporting and responding to problems (e.g., complaint reporting, inspections).*
- *Define conditions that constitute a violation of programme requirements.*
- *Establish inspection procedures for reported problems and corrective action schedule.*
- *Develop a clear system for issuing violation notices, compliance schedules, contingencies, fines, or other actions to address uncorrected violations.*

- Response to complaints
- Performance inspections
- Review of required documentation and reporting
- Issuance of violation notices
- Consent orders and court orders
- Formal and informal hearings
- Civil and criminal actions or injunctions
- Condemnation of systems and/or property
- Correcting system failures
- Restriction of real estate transactions (e.g., placement of liens)
- Issuance of fines and penalties

Some of these approaches can become expensive or generate negative publicity and provide little in terms of positive outcomes if public support is not present. Involvement of stakeholders in developing the overall management programme helps ensure that enforcement provisions are appropriate for the management area and effectively protect human health and water resources. Stakeholder involvement generally stresses restoration of performance compliance rather than more formal punitive approaches.

Information on regional onsite system performance, environmental conditions, management approaches by other agencies, and trends analyses might be needed if regulatory controls are increased. Most states establish regulatory programmes and leave enforcement of these codes up to the local agencies.

A regulatory programme focused on achieving performance requirements rather than complying with prescriptive requirements places greater responsibilities on the oversight/permitting agency, service providers (site evaluator, designer, contractor, and operator), and system owners. The management entity should establish credible performance standards and develop the competency to review and approve proposed system designs that a manufacturer or engineer claims will meet established standards. Continuous surveillance of the performance of newer systems should occur through an established inspection and compliance programme. The service providers should be involved in such programmes to ensure that they develop the knowledge and skills to successfully design, site, build, and/or operate the treatment system within established performance standards. Finally, the management entity should develop a replicable process to ensure proper evaluation and appropriate management of more new treatment technologies.

13.6.10 Data collection, record keeping, and reporting

To function effectively, wastewater management entities require a variety of data and other information that fall into four categories:

- **Environmental assessment**: climate, geology, topography, soils, slopes, ground water and surface water characterisation data (including direction of flow), land use/land cover information, physical infrastructure (roads, water lines, sewer lines, commercial development, etc.);

- **Planning**: existing and proposed development, proposed water or sewer line extensions, zoning classifications, population trends data, economic information, information on other agencies or entities involved in onsite wastewater issues;

- **Existing systems**: record of site evaluations conducted and inventory of all existing onsite systems, cluster systems, package plants, and wastewater treatment plants, including location, number of homes/facilities served, and size (e.g., 50-seat restaurant, three-bedroom home), system owner and contact information, location and system type, design and site drawings (including locations of property lines, wells, water resources), system components (e.g., concrete or plastic tank, infiltration lines or leaching chambers), design hydraulic capacity, performance expectations or effluent requirements (if any), installation date, maintenance records (e.g., last pumpout, repair, complaints, problems and actions taken, names of all service providers), and septage disposal records; and

- **Administrative**: personnel files (name, education/training, work history, skills/ expertise, salary rate, job review summaries), financial data (revenue, expenses, debts and debt service, income sources, cost per unit of service estimates), service provider/vendor data (name, contact information, certifications, licenses, job performance summaries, disciplinary actions, work sites, cost record), management Programme initiatives and participating entities, programme development plans and milestones, septage management information, and available resources.

Data collection and management are essential to programme planning, development, and implementation. The components of a management information system include database development, data collection, data entry, data retrieval and integration, data analysis, and reporting. A variety of software is commercially available for managing system inventory data and other information. Electronic databases can increase the ease of collecting, storing, retrieving, using, and integrating data after the initial implementation and learning curve have been overcome. For example, if system locations are described in terms of specific latitude and longitude coordinates, a data layer for existing onsite systems can be created and overlaid on geographic information system (GIS) topographic maps. Adding information on onsite wastewater hydraulic output, estimated mass pollutant loads, and transport times expected for specified hydrogeomorphic conditions can help managers understand how water resources become contaminated and help target remediation and prioritization actions. Models can also predict impacts from proposed development and assist in setting performance requirements for onsite systems in development areas.

RECORD KEEPING AND REPORTING PROGRAMME ELEMENTS

Establish a database structure and reporting systems, at a minimum, for:

- *Environmental assessments;*
- *Planning and stakeholder involvement functions*
- *Existing systems;*
- *Staff, service providers, financial, and other administrative functions;*
- *Inspection and monitoring programme, including corrective actions required;*
- *Septage and residuals management, including approved haulers, disposal sites, and manifest system records*

Other agencies might hold and administer some data necessary for onsite system management. For example, environmental or planning agencies often collect, store, and analyse land and water resource characterisation data. Developing data sharing policies with other entities through cooperative agreements can help all organisations involved with health and environmental issues improve efficiency and overall programme performance. The management agency should ensure that data on existing systems are available to health and water resource authorities so their activities and analyses reflect this important aspect of public health and environmental protection.

13.6.11 Programme evaluation criteria and procedures

Evaluating the effectiveness of onsite management programme elements such as planning, funding, enforcement, and service provider certification can provide valuable information for improving programmes. A regular and structured evaluation of any programme can provide critical information for programme managers, the public, regulators, and decision makers. Regular programme evaluations should be performed to analyse programme methods and procedures, identify problems, evaluate the potential for improvement through new technologies or programme enhancements, and ensure funding is available to sustain programmes and adjust programme goals. The programme evaluation process should include:

- A tracking system for measuring success and for evaluating and adapting programme components;
- Processes for comparing programme achievements to goals and objectives;
- Approaches for adapting goals and objectives if internal or external conditions change;
- Processes for initiating administrative or legal actions to improve programme functioning;

- An annual report on the status, trends, and achievements of the management programme; and
- Venues for ongoing information exchange among programme stakeholders.

A variety of techniques and processes can evaluate programmes to assess administrative and management elements. The method chosen for each programme depends on local circumstances, the type and number of stakeholders involved, and the level of support generated by management agencies to conduct a careful, unbiased, detailed review of the programme's success in protecting health and water resources. Regardless of the method selected, experienced staff should evaluate the programme at regular intervals and involve programme stakeholders.

A number of state, local, and private organisations have implemented performance-based management programmes for a wide range of activities, from state budgeting processes to industrial production operations. The purpose of these programmes is twofold: linking required resources with management objectives and ensuring continuous improvement. Onsite management programmes could also ask partnering entities to use their experience to help develop and implement in-house evaluation processes.

13.7 CASE STUDY: Providing Sustainable Wastewater Treatment and Reuse in Morocco - Water Resources Sustainability Project, 1996-2003

This USAID-funded project effectively improved water resources management in Morocco through a combined approach of appropriate technology, or "hard approaches", with good governance ("soft approaches"). More specifically, "hard approaches" refer to the technology and physical structures used for water development, storage, conveyance, productivity enhancement, and water and wastewater treatment. "Soft approaches" emphasize the human dimension of water management and use methods of good governance and sound institutional arrangements, including participatory and capacity-building elements at the local, national, and regional levels. This case study shows how complementarities of hard and soft approaches can enhance the sustainability of water and wastewater projects across a range of institutional settings, financial constraints, and technical capacities.

In 1996, USAID launched Morocco's Water Resources Sustainability Programme (WRS) to improve water resources management in the urban, agricultural, and industrial sectors through pilot projects and support for targeted institutional reforms. One such project involved the implementation of a wastewater treatment and reuse facility in Drarga, southern Morocco. The Commune of Drarga minimized hazards to human health from raw wastewater cesspools and well water contamination by building and operating a plant to treat domestic wastewater and reusing the treated effluents for irrigation. Soft approaches helped enable the plant to implement effective cost recovery features and ensure long-term plant operation. Soft approaches ensure that infrastructure and technology solutions to water and sanitation problems are sustainably implemented to yield results with lasting impact. Specific lessons learned will demonstrate the effectiveness of the following soft approaches to infrastructure development and technology transfer: community participation, public outreach, institutional strengthening, and capacity building.

13.7.1 The Treatment Challenge in the Town of Drarga

With water demand expected to exceed supply by the year 2020, improved management of water resources is key to Morocco's future sustainable development. The population of Drarga, currently over 8,000, is rapidly expanding and expected to double over the next ten years. In the early 1990's, the town constructed a potable water distribution system, yet wastewater collection was rudimentary and drained into untreated cesspools. Irrigation water is scarce, with some farmers drilling deep wells for water that deplete the area's groundwater supply. Key to meeting these challenges is installing substantial wastewater treatment facilities and systems for reusing treated wastewater in agriculture.

13.7.2 Selecting and Using Appropriate Technology

In Drarga, selecting appropriate, innovative technologies is one half of the equation. The remaining half is ensuring that beneficiaries implement these methodologies after the life of the development project through soft approaches in capacity building, participatory planning, problem solving, and resource sharing.

Treated wastewater storage basin in Drarga, Southern Morocco

Morocco has 63 wastewater treatment plants using technologies such as activated sludge, ponds, trickling filters, and stabilization and infiltration basins. Unfortunately, most of these plants are inoperable due to a lack of funds and technical capacity to sustain operation and maintenance. Selecting a sand filtration-percolation system for Drarga was based on the need for a low-cost, easy-to-operate treatment plant that could be adapted to the local environment and replicated throughout Morocco. The new system includes two 1,000 m^3 storage basins that can be easily expanded with population growth, and can distribute treated effluent to farmers for irrigation.

Many technological aspects of the project were conceived with cost recovery features in mind that recycle plant by-products. For example, revenue is generated by selling treated wastewater to farmers for irrigating a 6-hectare perimeter around the plant construction site. Reeds are harvested twice a year from the tertiary treatment beds and sold to generate revenue. Residual sludges from the anaerobic basins are pumped, dried, and combined with organic wastes from Drarga to produce compost. Methane gas generated from the anaerobic basins is recovered and converted to energy to run pumps at the plant, thereby reducing electricity costs.

13.7.3 Results

The project has yielded many successful results benefiting the community of Drarga. The Drarga plant treats over 800 m^3 per day of sewage. The plant is recovering all its operations and maintenance (O&M) costs and has been transferred to a capable operator. Such effective cost recovery has enabled the plant to operate continuously since October 2000 and consistently meet targets for the abatement of key pollution parameters such as BOD_5, nitrates, fecal coliforms, and parasites. Sanitary conditions throughout Drarga were greatly improved through the elimination of raw sewerage cesspools and residents observed a corresponding increase in property values.

Farmers using the treated water for irrigation receive multiple benefits. They gain access to a guaranteed amount of low-priced water, and save on the purchase of fertilizer given that the treated wastewater already contains fertilizer elements required by the crops. Additionally, the price of agricultural land within close proximity to this new source of irrigation water has increased eight-fold since the start of the project.

13.7.4 Soft Approaches - Keys to Success

A key aspect of the WRS project is the mobilization of the public to adopt integrated water resource management to ensure the sustainability of those resources. The project fosters public participation in several ways:

Public outreach - From its inception, WRS conducted public awareness activities to gain community acceptance of the changes in practices required and technological solutions implemented by the project. Participatory assessments evaluated how and if people distinguish between different sources of water (bottled water, tap water, well water, and wastewater), current irrigation practices, farmers’ willingness to pay for treated wastewater. This information complemented the technical analysis, completing the baseline assessment of the target area and providing critical input on wastewater treatment and irrigation options acceptable to the community. Furthermore, the participatory process helped build a network of community area residents committed to improving the quality of area water resources and taking ownership in the project. Ongoing consultation has enabled the project to gain the support and participation of beneficiaries. Public awareness activities focused on helping communities understand benefits due to changes in practices and to accept the technological solutions introduced by WRS.

An important tool in developing public participation and interest in project activities and disseminating the results of project actions is the involvement of the media (print, radio, and television) in project activities. The Moroccan media covered events such as the signing of collective agreements and progress of construction. In addition to national media, WRS asked the audio-visual centre at Ecole Nationale d'Agriculture de Meknes to videotape problems to be resolved by the project, the interventions of the project team at work, and the results of project activities. These videotapes were presented at meetings of the regional and inter-ministerial steering committees to present the pilot project progress.

Developing a partnership with community entities - A partnership enabled stakeholders to create a formal agreement on local financial participation and in-kind contribution (e.g., land, labour), which enhanced project ownership. Partners included the Al Amal water users association –future manager of the plant after completion, the Governor of Agadir –facilitator of administrative procedures, the Commune of Drarga who provided the land, and the Regional Agency for Planning and Construction (ERAC-Sud) which financed 30 percent of the project. This partnership was sealed through a signed collective agreement that includes the Ministry of Environment and the WRS project, and the arrangement facilitated frequent communication on progress, successes and difficulties as well as transparency among partners.

Capacity building - The partnership also provided an entry point for improving local capacity in the ability to manage the plant after USAID assistance ended. For example, during the planning phase of the project, partners went on a study tour in the United States were they visited several wastewater treatment and reuse plants with similar technologies and learned about O&M, cost recovery, and institutional issues related to the management of these facilities. Partners also received training in Morocco on plant operation, financial management, and wastewater reuse. Such organized workshops and study tours strengthened institutional capacities and bonds between project partners.

Involvement of Public Institutions - Since the task of water resources management is shared by multiple ministries, an inter-ministerial steering committee was created provide a forum for sharing concerns, coordinating activities, reviewing WRS activities, and providing local representatives to ensure that project interventions receive broad institutional support at the local level.

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