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Constructed wetlands under different geographic conditions: Evaluation of the suitability and criteria for the choice of plants including productive species

Master Thesis

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Abstract

Constructed wetlands are a cost-effective, nature-orientated alternative for wastewater treatment that can be used in nearly all regions worldwide from cold/boreal to tropical conditions. Thus, a lot of various treatment wetland systems are in operation throughout the world that use a great variety of different and indigenous plant species that are adapted to the prevailing climatic conditions. This thesis aims to provide a systematic overview of suitable emergent wetland plants (macrophytes) for all regions and climate zones worldwide, and further on, it suggests alternative species that have not found a widespread use in constructed wetlands until present.

A literature research is the proceeding of this thesis. Numerous case studies, practical experiences and reports from all over the world were investigated in order to get the required information. The plant species were selected on the basis of three defined selection criteria. A defining criterion was plant productivity and biomass utilization. While the availability in a certain climate zone and a high pollutant removal capacity are prerequisites, the economical utilization of the harvestable plant biomass can be a crucial and beneficial decision factor for plant selection in constructed wetlands.

From nearly all regions and climate zones worldwide, 46 different wetland plant species were selected for this thesis and were presented in recommendation tables. The most species were found in regions with increased research intensities (Europe, North America, Australia and Southeast Asia). A comparison of the removal efficiencies showed that plant-specific differences in treatment performance are not existent or significant, and thus, is not an important selection criterion.
The most plants are high productive species and have also a high potential as a renewable energy and fuel source, particularly species of the *Typha* and *Phragmites* genera, but also the most other grass species (*Poaceae*) including bamboos. Further, this investigation showed that the biomass utilization options for the most plant species are versatile and include: agricultural purposes (fertilizer and composting), animal and cattle feed, energy and fuel source, building and construction material, handicrafts, and industrial purposes (mainly paper making).

The high productivity and economic versatility of many wetland species can provide an alternative resource base particularly in developing countries. To draw conclusions from the investigation conducted in this thesis, at present it is not a widespread practise to harvest and use the biomass of constructed wetlands for secondary purposes. There is an economical potential in this research field, but further researches are recommended and to be undertaken due to the high productivity and versatility of many emergent plant species.

List of abbreviations

°N	North latitude
°S	South latitude
(A)	Alternative
AUD	Australian dollar
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
Conc.	Concentration
CW	Constructed Wetland
DO	Dissolved Oxygen
Dry wt	Dry Weight
ET	Evapotranspiration
HLR	Hydraulic Loading Rate
HRT	Hydraulic Residence Time
MPIP	Max Planck Institute Process
NZD	New Zealand dollar
RBTS	Reed Bed Treatment System
RZM	Root Zone Method
Sp.	Species
Spp.	Subspecies
KN	Kjeldahl Nitrogen
T. angustifolia	Typha angustifolia
T. latifolia	Typha latifolia
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USD	US dollar
VSB	Vegetated submerged bed
VF	Vertical Flow

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1 Introduction

1.1 Background

This Master Thesis was written at the Institute of Wastewater Management and Water Protection at the Hamburg University of Technology, Germany (TU-HH). Among others, this institute researches new concepts of biological wastewater treatment, development of new ecological sanitary concepts and reuse of wastewater. Constructed wetlands, an ecological nature-orientated technology for wastewater treatment, are one field of research. This Master Thesis is a part of a beginning research project at the TU-HH in the field of constructed wetlands including their implementation in developing countries.

Constructed wetlands are considered as a cost-effective, natural alternative for wastewater management in a wide variety of climatic conditions worldwide. Technologies that involve natural treatment systems are generally termed as “ecological engineering”. Ecological engineering has been defined as the management of natural processes where small amounts of supplementary energy control a system in which the main energy is derived from natural sources (Odum, 1963). The term “constructed wetland” refers to a technology designed to apply ecological processes found in natural wetland ecosystems.

While conventional technical treatment plants, e.g. activated sludge processes, focus on wastewater treatment in larger urban regions, constructed or artificial wetland systems have been considered as a cost-effective and appropriate treatment method in rural and low-density areas. The use of constructed wetlands for water purification is becoming more and more accepted and effective in many parts of the world including developing as well as developed countries (Denny, 1997; Kadlec and Knight, 1996).
Constructed wetlands are complex ecosystems that include physical, chemical and biological processes. One essential structural component in these ecosystems is the plant vegetation which performs a number of important functions in wetlands. Wetland plants, like all other plants, require specific environmental conditions. One of the most important factors that affect the availability of plant species in certain regions is climate, primarily determined by temperature, rainfall and sunlight.

This thesis investigates the choice of plant species for wastewater treatment in constructed wetlands under different climatic conditions. Objectives and main focuses will be provided in the next chapters.

1.2 Objectives

Wetlands for wastewater treatment can be constructed in nearly all regions throughout the world and on all continents apart from the Polar Regions (Arctic and Antarctic). Consequences are numerous studies, experiments and investigations that use a great variety of different, native and indigenous plant species adapted to the climatic conditions predominant in the given region.
Although there are lot of various constructed wetland systems in operation worldwide, so far, no summary has been suggested that provides a recommendation which plant species can be used for a constructed wetland in a definite climate region. The most studies are conducted in a confined local area and usually use species that are na-

tive to the corresponding region (apart from some cosmopolitan plant species). However, a systematic and global presentation of suitable plant species for all climate zones throughout the world does not exist. This thesis aims to fill this gap by pursuing two main objectives:

1. With consideration of defined criteria (see Chapter 1.3), plant species that are commonly used in constructed wetlands are presented; species that can be referred as standard plants for wastewater treatment in the corresponding climate zone.

2. The second main objective of this thesis is to find alternatives; plant species that are less common and typical, but also meet specific criteria and requirements making their use in constructed wetlands possible.

1.3 Criteria for the choice of plants

There are numbers of potential criteria that can affect the choice of plants for constructed wetlands. Three of them were considered as the most important ones and form the basis for the plant choice:

- Availability in climate zone
- Pollutant removal capacity (treatment efficiency) and tolerance ranges
- Plant productivity and biomass utilization options

Especially the last point, plant productivity and biomass utilization, requires further consideration: whereas availability in a certain climate zone is a prerequisite and many wetland plants have the capacity to purify contaminated and polluted waters, the potential utilization of the plant biomass can be a crucial and advantageous factor for plant selection. In particular, the use of the harvested biomass as a renewable energy or fuel source, e.g. for direct combustion, is a crucial aspect to be considered here.

However, wastewater treatment is considered as the primary purpose and function of constructed wetlands. Not all plant species that include a high productivity or have other ancillary benefits are able to tolerate the hydraulic and high-loaded organic and eutrophic conditions often found in municipal wastewaters. Therefore, utilization of plant biomass, e.g. for agricultural, industrial or energetic purposes, has to be considered as a secondary, beneficial side-effect and sub-product of wastewater treatment by means of macrophytes. Primary goal is to select plant species in terms of their suitability for treatment of domestic and municipal wastewaters.

1.4 Proceeding and content

Principle proceeding in this thesis is a literature research. Numerous case studies and practical applications throughout the world, full-scale as well as pilot-scale treatment systems, practical experiences and reports have been investigated and evaluated concerning the three criteria described above. In order to get information, published literature concerning constructed wetlands has been studied, e.g. Kadlec and Knight (1996), Reed (1995), Vymazal (1998c) or Wissing (2002). However, most of the information in this field originates from various conferences and workshops, above all the biennial international conferences under the auspices of the International Association of Water Quality (IAWQ: *Wetland systems for water pollution control*). Conference proceedings appear in a variety of journals such as *Water Science and Technology* and *Ecological Engineering,* in books, e.g. Moshiri (1993) and Hammer (1989), but also in the Internet.

The main focus of this thesis is a table that provides recommendations and proposals of plant species suitable for constructed wetlands in the respective climate zone and geographic region. The following question should be answered: which plant species can be generally used for a constructed wetland in a certain region and, possibly, are there alternative species. Further, this table provides a comparison of the plant-specific productivities for each climate zone and attempts to evaluate the versatility of utilization options and potential as renewable energy source.

The thesis consists of two main sections.

1. The first section comprises the Chapters 2 - 6 providing technical definitions and fundamentals in the field of constructed wetlands. Different types and systems are introduced as well as important hydraulic parameters. Subsequently, information about typical constituents found in municipal and domestic wastewaters and their removal processes is given. Furthermore, the role and function of plants in constructed wetlands are discussed in detail.

2. The second section (Chapters 7 - 11) contains the plant-specific investigations. Each plant species is introduced, described and evaluated concerning its suitability for constructed wetlands according to the case studies that were available for this thesis. Data about biomass yields, nutrient uptake capacities and utilization options, but also plant specific features are given (if available). The information and findings gathered in these investigations form the basis for the recommendation tables in Chapter 12. Finally, the output is discussed (Chapter 13) and conclusions are drawn (Chapter 14).

2 Definitions in the field of constructed wetlands

2.1 Definition of wetlands

Wetlands have been defined as “land where the water surface is near the ground surface for long enough each year to maintain saturated soil conditions, along with the related vegetation” (Reed, 1995). The land is wet or under water for a part or throughout the year. Wetlands can be described as a transition zone between pure aquatic and pure terrestrial ecosystems, and are characterized by saturated substrates (soil), presence of water, and vegetation distinctly from other ecosystems and fauna. Especially the dominance of a typical plant vegetation adapted to flooded or saturated conditions is characteristic for wetland ecosystems.
Duration and depth of inundations can vary significantly from temporary to permanent flooding depending on the wetland type. The latter can be classified as e.g. freshwater swamps and floodplains with woody tree species and shrubs; bogs with peat and mosses; and marshes which include emergent, herbaceous plant species. There are many other habitats which belong to wetlands such as coastal beaches, littorals (tidal zones) and mangrove wetlands (forested saltwater wetlands). Apart from peat bogs

all wetlands have in common that they can be considered among the most productive ecosystems in the world including a high biodiversity. Many ecological processes such as biological, physical or chemical transformations as well as removal of organic matter, suspended solids and metals can be performed by wetlands. Consequently, these complex processes have to be considered and managed in design and dimensioning of constructed wetlands (Farahbakhshazad, 1998; Gopal, 1999; Wissing, 2002).

Natural marsh systems can be principally divided into two physical categories based on water salinity: freshwater marshes that are inundated with freshwater (salinity: ≤ 1,000 mg/L) and salt marshes that are inundated with brackish or saline waters (salinity: > 1,000 mg/L), (Kadlec and Knight, 1996).
The characteristic plant species found in freshwater marshes as well as in salt marshes are emergent, herbaceous macrophytes, also known as helophytes, adapted to intermittent to continuous flooding. Biologically, they are located between pure water plants (hydrophytes) and terrestrial land plants (terraphytes).

2.2 Definition of constructed wetlands and principal components

Constructed wetlands have been defined as a “designed or man-made complex of saturated substrates, vegetation and water, used for human use and benefits”, mainly waste treatment purposes (Reed, 1995). They are designed for optimum wastewater treatment and allow much more reliable control over the hydraulic regime in the system and therefore perform better compared to natural wetlands that can also be used for wastewater treatment. Their origins base on the initial works of Dr. Seidel in 1966 who investigated the role of common bulrush *(Scirpus lacustris)* in wastewater treatment. Seidel developed many process variants; numerous succeeding concepts and systems have been derived from her studies. Thus, the term “constructed wetland” could be largely ascribed to Seidel.
Constructed wetlands are usually designed as a secondary treatment for removal of suspended solids and organic matter (TSS, BOD and COD) and as a tertiary (advanced) treatment for nutrient removal (nitrogen and phosphorus). Primary treatment (also called pre-treatment) occurs normally conventionally in septic tanks, three-room digesters or Imhoff tanks, but also in pond systems.
Constructed wetlands have been used either for treatment of point-source pollutions which are primarily municipal and domestic, but also for industrial wastewaters or treatment of non-point-source pollutions such as agricultural runoff, landfill leachate or, particularly in the USA, acid mine drainage (Reed, 1995).

The emergent plants are the critical component in constructed wetland systems as they can both directly and indirectly contribute to the treatment processes and, additionally, they produce biomass which can be used for economical purposes. The following principal components of constructed wetlands are briefly introduced below:

1. Emergent macrophytes

Emergent macrophytes are herbaceous (soft tissue and non-woody) vascular plants (higher plants) and have a structure consisting of aerial stems, leaves and an extensive root and rhizome system. They are rooted in the soil and emerge or stand upright above the water surface. Emergent wetland species can grow within a water level ranging from 0.5 m below the soil surface to a water depth of 1.5 m or more, thus, they have different inundation tolerances depending on the species. Depth penetration of the root system and exploitation of the soil layer differs from species to species (Brix, 1993). Moreover, wetland plants show different biomass production rates (growth rates) and prefer specific environmental conditions (e.g. temperature, light demand, salinity tolerance and pH).

A wide variety of wetland plants have been used and tested in constructed wetlands after the initial work of Seidel in 1966. The three plant species most commonly used throughout the world are: common reed *(Phragmites australis)*, bulrushes *(Scirpus sp.)* and cattails *(Typha sp.).* Furthermore, rushes *(Juncus sp.)* and sedges *(Carex sp.; Cyperus sp.)* are also commonly used species.
Emergent macrophytes are the primary plants used in constructed wetlands for wastewater treatment throughout the world.

2. Substrate (soil layer)

Substrates used in constructed wetlands include mineral soils (e.g. clay, silt, sand and gravel) and organic soils (e.g. compost and decomposed plant litter). Its selection depends on the type of the wastewater and on the hydraulic regime chosen. The soil material strongly affects the movement of water through the wetland (hydraulic conductivity). The soil provides a huge surface area for attached microorganisms additionally to plant biomass and acts as filtration and adsorption medium for pollutants such as suspended solids.

3. Water

Hydrological factors are considered to be the most important design factors in constructed wetlands for maintaining wetland structure and function determining plant species composition and treatment effectiveness in a wetland project (EPA, 2000a; Mitsch, 1993). It contains all factors that have an effect on water level in the system including water input (e.g. influent or rainfall) and water losses (e.g. effluent or evapotranspiration). The water level determines the hydraulic regime of a constructed wetland depending on if the water flows inside the soil or as a free water body above the ground surface (Chapter 3).

4. Microfauna and fauna

Wetlands provide an ideal environment for microbial populations due to the high nutrient content and water supply. The microorganisms are adapted to the various conditions in the soil layer or free water body. Microbial populations in wetlands include bacteria, fungi, algae and protozoa. The diverse bacterial enrichment is the driving force for wastewater treatment in both constructed wetlands and conventional sewage treatment plants. Eventually, constructed wetlands can also provide habitats for a rich diversity of invertebrates (e.g. insects and worms) and vertebrates (e.g. amphibians, birds and mammals).

3 Constructed wetlands: types and classifications

Most diverse methods and variants exist in the field of wastewater treatment with constructed wetlands that make it difficult to clearly specify the separate types. They can be classified according to their loading pattern (continuous or intermittent flow), life-form category of the dominating vegetation (rooted emergent, floating or submerged macrophyte-based system), wastewater characteristic (municipal, agricultural or industrial) or soil hydraulics and material (Börner, 1992).

There are many other possibilities to classify wetland systems. The classification in this thesis is based on the work of Mitsch (1994), but it can also be found in numerous other works. This systematic approach distinguishes between the surface flow and the subsurface flow constructed wetlands whereas the surface flow systems are the older technology (Brix, 1994a). The subsurface flow systems are further divided into horizontal flow and vertical flow systems.

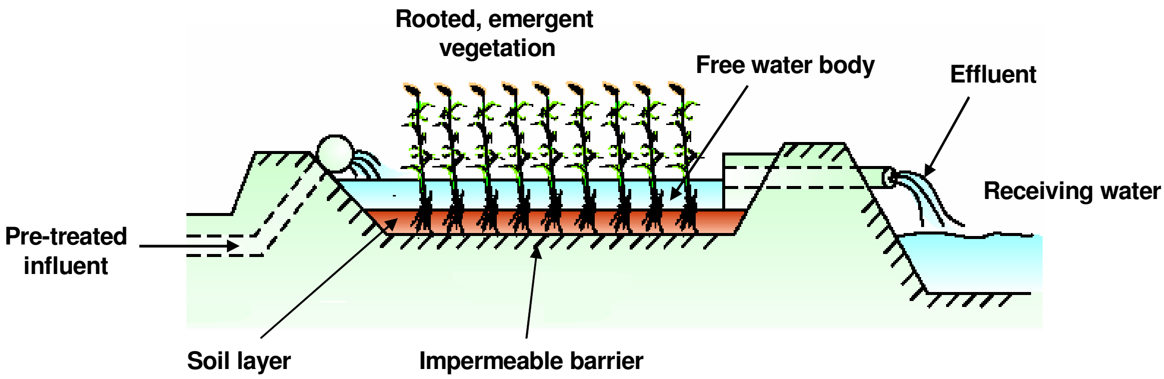
Wetland systems that use a free water surface, mimic natural wetlands and can provide a significant habitat for wildlife e.g. birds and mammals. While in the USA surface flow wetlands are more common, the prevailing systems in Europe are subsurface flow systems (IWA, 2000). The next chapters provide an overview about these constructed wetland systems and present the most important process developments.

3.1 Surface flow treatment wetlands

3.1.1 Design and treatment principles

Surface flow or free-water-surface wetland systems show, as the name suggests, a water flow primarily conducted aboveground and exposed to the atmosphere (free water body). Re-aeration at the surface is the major oxygen source in this wetland type (WPCF, 1990). Below the free water body, the bed contains a soil layer which serves as a rooting media for the emergent vegetation. At the bottom of the wetland system, an impermeable barrier (liner or native soil) is required to avoid infiltration, and thus, contamination of groundwater (Figure 3.1; Reed, 1995).

Figure 3.1: Surface flow constructed wetland (taken from: Kadlec and Knight, 1996; modified)



Water depths can be found in a range from < 0.1 m up to 0.8 m and more depending on the purpose of treatment, wastewater characteristics and climatic conditions: during colder or freezing seasons the wetland system can be operated with increased depths to offset the presence of an ice cover which will decrease the hydraulic residence time due to volume reduction. Normally, the water depth is equal to 0.5 m or less (Farahbakhshazad, 1998; Reed, 1995). Surface flow wetlands should be designed with a large aspect ratio (length-width-ratio) to ensure plug-flow conditions and optimal treatment performances. In consideration of improved removal efficiencies compared to increasing capital costs associated with a higher aspect ratio, Crites (1994) recommended an optimal aspect ratio of at least 2:1 as minimum (WPCF, 1990).

The emergent shoots, stalks and litter of the plants regulate the water flow, reduce the flow velocity and allow plug-flow conditions; hence, they form the main flow characteristic in the free water body (Reed, 1995; Tanner, 2001). However, the major part concerning wastewater treatment is performed by microorganisms attached to the submerged portions of the plants. Thus, the physical presence of the plant tissues together with a complete vegetation canopy appears to be more important than the composition of the wetland plant species themselves (WPCF, 1990).
The type of soil where the plants are rooted is not crucial, but the depth should be at least equal to the maximum possible root penetration which is necessary for the plant species chosen. Vymazal (1998a) recommended a soil depth of at least 0.2 - 0.3 m.

Similar to natural wetland systems that also include open water areas, surface flow wetlands require careful consideration regarding mosquito and odour control. High and excessive organic loadings can result in anaerobic conditions that favour the development of mosquito population and odour nuisances (WPCF, 1990).

Finally, it is recommended that free-water-surface systems receive an influent that is preferably secondary, but at least primary treated in order to keep the organic loading within reasonable limits and to prevent localized anaerobic conditions. For example, high levels of suspended solids commonly found in raw sewage can cause a dieback of some species at the wetland inlet due to the accumulation of solids (Gersberg, 1986).

3.1.2 Distribution

Numerous free-water-surface systems have been built in North America, particularly in the USA. They are focused mainly on the treatment of municipal wastewater with large water flows for nutrient polishing (advanced treatment), but also for purification of acid drainages from the mining industry (coal and copper), stormwaters and various industrial wastes. Most frequently used plant species in North America are bulrushes (*Scirpus sp.*) and cattails (*Typha sp.*), (Vymazal, 1998a).
Partially, these systems are very extensive and can have area sizes of 1,000 ha and greater. Such land-intensive treatment systems are often designed for advanced treatment of conventional secondary effluents (Kadlec and Knight, 1996). However, at this point it should be considered that these extensive biological systems are not only designed for wastewater treatment, but also for providing a habitat for wildlife and vegetation in form of large natural ecosystems (Wissing, 2002).

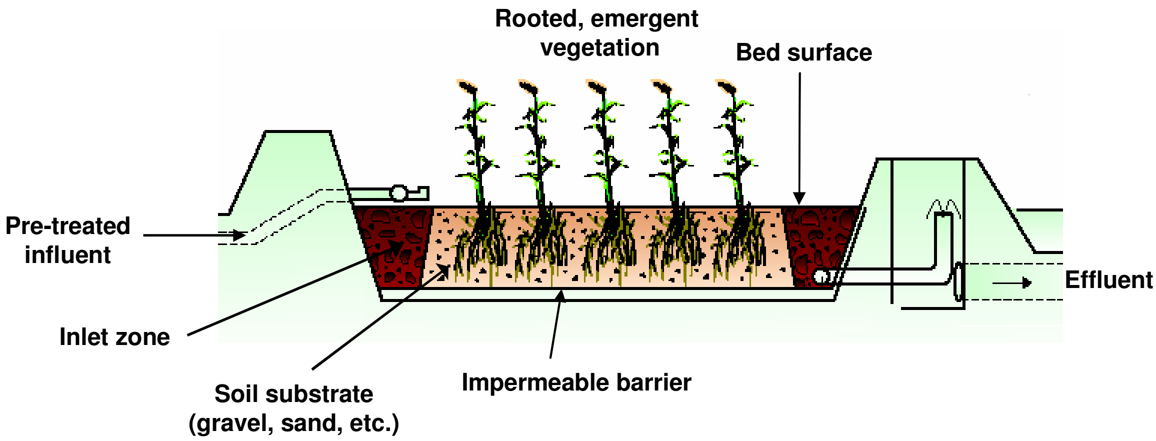
3.2 Subsurface flow treatment wetlands

Subsurface flow treatment wetlands can be divided into soil- and gravel-based wetlands on the one hand, and into horizontal and vertical flow systems on the other hand. In the following chapters the different types and developments are briefly introduced.

3.2.1 Horizontal flow systems

Main feature of horizontal flow systems is that the water level remains underneath the ground surface. The wastewater flows horizontally through a porous soil medium where the emergent plant vegetation is rooted, and is purified during the contact with the surface areas of the soil particles and the roots of the plants. This system includes an impermeable liner or native soil material at the bottom to prevent possible contamination of the groundwater (Figure 3.2; Reed, 1995).

Figure 3.2: Horizontal subsurface flow wetland (taken from: Kadlec and Knight, 1996; modified)



In contrast to the surface flow wetlands, the soil contributes to the treatment processes by providing a surface area for microbial growth and supporting adsorption and filtration processes. This effect results in a lower area demand and generally higher treatment performance per area than free-water-surface wetlands (Farahbakhshazad, 1998).

The soil material is of great importance because it influences both the hydraulic performance (conductivity and wastewater distribution in the inlet zone) and the phosphorus removal rate. It includes gravel, sand or finer grained clayey and silty soils depending on the hydrologic system. The critical requirement is to achieve a uniform distribution of the wastewater (hydraulic loading) in the inlet zone which means to prevent surface runoff and usage of the full treatment bed to ensure maximum treatment performance. The soil depth should be adapted to the depth of the root penetration and is recommended between 0.3 - 0.6 m for the most plant species. In cold /boreal climate zones a depth of 0.8 - 0.9 m is recommended to prevent frost penetration (Reed, 1995; WPCF, 1990).
The major oxygen source for these systems is the oxygen transfer into the root zone by plants because of the limited oxygen diffusion from the atmosphere into the gen-

erally anaerobic soil (Brix, 1998; Reed, 1995). Mosquitoes and odours are usually not a problem as long as the water level is maintained underneath the ground surface (Reed, 1995). To prevent soil-clogging it is recommended that subsurface flow systems receive at least primary treated wastewater. Exceptions are vertical flow wetlands that can also be used as pre-treatment unit in hybrid systems (Chapter 3.3).

3.2.2 Distribution and concepts

Both soil-based and gravel-based subsurface flow systems are the predominant wetland concept in Europe. The most common term for subsurface flow constructed wetlands in Europe is the "Reed Bed Treatment System" (RBTS) resulting from the fact that the most frequently used plant species is common reed (*Phragmites australis*).
Further plants typically used in Europe are reed sweet grass (*Glyceria maxima*), reed canary grass (*Phalaris arundinacea*) and broad-leaved cattail (*Typha latifolia*). In the USA, these systems are also termed as "Vegetated Submerged Beds" (VSB).
Gravel-based subsurface flow wetlands have also been used extensively in North America, especially in the USA, where they are termed as (vegetated) gravel-bed or rock-bed systems. Most commonly used plant species in North America are bulrushes (*Scirpus sp.*) and cattails (*Typha sp.*), but also common reed *(Phragmites australis)*, (IWA, 2000; Vymazal, 1998a). Gravel-bed systems are also widely distributed in North Africa, South Africa, Asia, Australia and New Zealand (Tanner, 1997; Vymazal, 2001a). In the next chapters, the most important subsurface flow systems are briefly introduced.

3.2.3 Krefeld or MPI - Process

The Krefeld- or Max Planck Institute Process (MPIP) according to Seidel (1976) has been one of the first developments in the field of constructed wetlands and is accredited to the Max Planck Institute at Krefeld in Germany. It is a multistage system and includes a combination of vertical flow filter beds and horizontal flow elimination beds (combined system), as described below.

1. Primary treatment (pre-treatment): filter beds, often 2 or 3 stages in cascades

- Vertical percolation of the water through the soil consisting of gravel, sand, or both,
- Discontinuous or intermittent charging,
- Plant species: mainly reed *(Phragmites australis)* due to deep root penetration.

2. Secondary treatment: elimination beds, often 2 or 3 beds in series.

- Continuously, horizontal flow through a soil layer of gravel and sand
- Main plant species:
  Common bulrush *(Scirpus lacustris)* and yellow flag / iris *(Iris pseudacorus),*

The most significant characteristic feature of the MPIP is the lacking of a mechanical pre-treatment unit (e.g. three-room digester or septic tank). The primary treatment is performed directly in the vertical filter beds. Many later vertical flow systems being constructed in Europe have been based on this original design (Brix, 1994a).

3.2.4 Haider/Rausch Process

The Haider/Rausch Process is a further development of the Krefeld Process according to Seidel. Both variants are similar to each other, however, with one significant difference: instead of pre-treatment in vertical filter beds, the Haider/Rausch Process uses conventional mechanical digesters such as three-room digesters, septic tanks or retting tanks. According to Haider (1987), this modification appeared to be necessary because of aesthetic and hygienic concerns when untreated raw wastewater is discharged directly on a vertical filter bed. However, treatment efficiencies are similarly high for both process variants.
Typical plant species in the multistage horizontal flow elimination beds (secondary treatment) are common reed *(Phragmites australis)* in the first bed and common bulrush *(Scirpus lacustris)*, yellow flag *(Iris pseudacorus)*, broad-leaved cattail *(Typha latifolia)* and soft rush *(Juncus effusus)* in further treatment stages (Haider, 1987).

3.2.5 Root zone method

The Root Zone Method (RZM) is a soil-based horizontal flow system and was developed by Prof. Kickuth in 1974. While Seidel used non-cohesive and porous media such as gravel or sand, the Kickuth Process is based on cohesive, fine grained natural soils.
The water flows horizontally through the root zone system of a soil layer containing of clay-minerals and silt fractions whereas, according to his theory, the roots were assumed to create and maintain hydraulic pathways by their permanent rooting activity and decaying processes. This would increase the low hydraulic conductivity of cohesive soils. The plant species commonly used in RZM systems is common reed (*Phragmites australis*), (Kickuth, 1977).
Numerous treatment plants of this type have been built in Germany, Austria and Denmark. However, Kickuth's theory has not been demonstrated in practise yet; the plant roots did not develop or improve the hydraulic conductivity of the soil medium. As a result, soil-clogging effects occurred in many RZM systems that were investigated. Consequently, water tends to flow at the surface of the wetlands (surface runoff) leading to short-circuiting, short hydraulic retention times, and thus, poor removal efficiency (IWA, 2000; Schierup, 1990).

3.2.6 Further developments

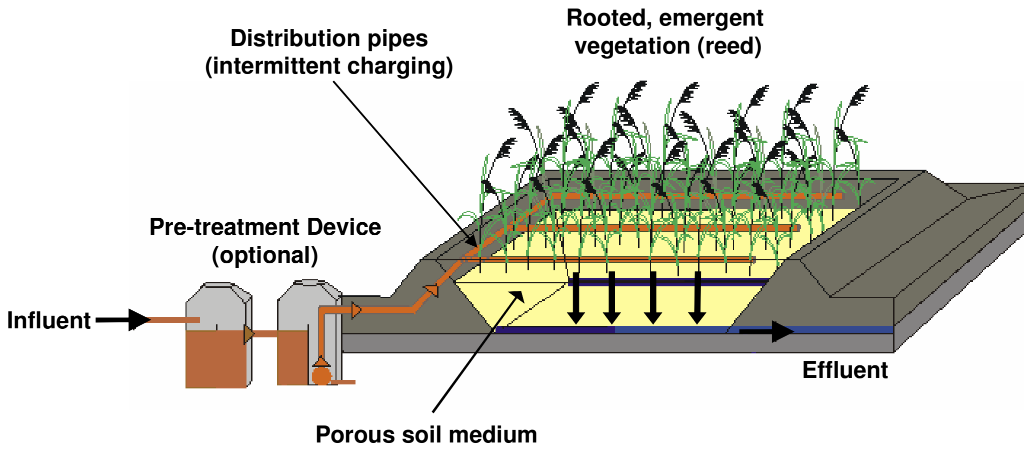
Based on the concepts of Seidel and Kickuth many other systems and variants have been developed and tested. Further concepts of the Krefeld Process and the Haider/Rausch Process were developed by e.g. Kraft (1985) and Fehr (Schütte and Fehr, 1992). These multistage variants differ primarily in their composition and construction of the soil layer. Typically, three or four treatment stages with decreasing grain sizes are found in flow direction. Also the RZM system has been developed. To improve the hydraulic properties, wetland systems according to Geller (1982) or Dafner (1992) have mainly used more porous and iron-containing, sandy soils despite clay and silt (Börner, 1992; Wissing, 2002).

3.3 Vertical flow systems

3.3.1 Design and treatment principles

Vertical flow systems are characterized by an intermittent (discontinuous) charging including filling and resting periods where wastewater percolates vertically through a soil layer that consists of sand, gravel or a mix of these. This principle corresponds to the vertical filter stage of the Krefeld Process according to Dr. Seidel (Figure 3.3; Chapter 3.2.3).

Figure 3.3: Vertical flow constructed wetland (taken from: www.bodenfilter.de, 2003; modified)



The plant species primarily used in vertical flow wetlands is common reed *(Phragmites australis)* due to its deeply penetrating, dense root and rhizome system. Typical depth of the soil layer is about 0.5 - 0.8 m (Cooper, 1996).

Key advantage of vertical flow systems is an improved oxygen transfer into the soil layer. Beside oxygen input by the plants and diffusion processes that both occur also in horizontal subsurface flow wetlands, vertical flow filter show a significant oxygen input into the soil through convection caused by the intermittent charging and drainage (Platzer, 1998).

Compared to horizontal subsurface flow systems, the additional aeration of the soil by convective processes allows higher nitrification capacities (Chapter 5.2.3) as well as removal of organic matter (Chapters 5.1.2 and 5.1.3). However, denitrification that requires anoxic conditions (Chapter 5.2.4) is usually lower in vertical flow beds compared to horizontal subsurface flow beds (Bahlo, 1995). They are also less effective for removal of suspended solids than horizontal surface flow and subsurface flow beds (Vymazal, 2001a).

3.3.2 Distribution and concepts

Although a vertical filter stage was already used in the Krefeld Process according to Seidel (1976), the main development and application of vertical flow systems started at the beginning of the nineties (Brix, 1994a). They are mainly distributed in Europe, especially in Germany, Austria, France and the UK. Nowadays, there are variously technical variants that mainly differ in their soil configuration (Wissing, 2002).

3.3.3 Hybrid systems

Hybrid systems or multistage systems are generally combinations of different constructed wetland systems. Usually, they comprise vertical flow and horizontal surface flow systems arranged in a staged manner. One typical system which belongs to the hybrid systems is the Krefeld Process (Chapter 3.2.3).
Usually, combined systems provide higher removal efficiencies than single-stage systems as they use the advantages of each system type to overcome the disadvantages of the other type (Vymazal, 2001a). Especially for removal of nitrogen, this effect can be significant: while nitrification can take place in the vertical flow stage, the horizontal flow bed provides denitrification due to its limited oxygen transfer capacity.
As a result, combined systems show generally very high efficiencies for removal of total nitrogen, but are also very effective for removal of organic matter (BOD and COD), (EPA, 2000a).

3.4 Comparison of horizontal surface and subsurface flow wetlands

The advantages and disadvantages of these two wetland types are not commonly valid because they depend on the specific situation and site conditions. However, some general major aspects could be stated (IWA, 2000; WPCF, 1990):

- Horizontal surface flow wetlands

Advantages:
- Lower installation costs (can be offset by the greater surface area needed)
- Lower operation and maintenance costs
- Simpler hydraulics
- Open water areas (provides wildlife habitat including a high biodiversity)
- High effectiveness in removal of suspended solids (TSS)

Disadvantages:
- Lower removal efficiency per area (more area required)
- Lower cold tolerance (more suitable in warmer climates)
- Potential problems with odours and mosquito populations
- Wastewater is exposed to potential human contact
- Higher evapotranspiration rates (increases pollutant concentrations) (Especially in warmer climates like the Mediterranean region)

- Horizontal subsurface flow wetlands

Advantages:
- Higher removal efficiency per area (less area required)
- Higher cold tolerance because of insulation through the upper media layer (More suitable in cold/boreal and temperate climate zones)
- No or minimal odour and mosquito problems (if subsurface flow is maintained)

Disadvantages:
- Higher construction costs, mainly caused by the substrate media (Can be offset by less area required)
- Higher operation and maintenance costs
- More sensitive to elevated concentrations of suspended solids (clogging effects at the inlet zone)

This comparison shows that subsurface flow wetlands are more effective in removal of wastewater pollutants whereas less area is required. They have also higher climatic tolerance ranges making their use in nearly all climate zones and regions worldwide possible. Furthermore, the variety of suitable emergent plant species that can be chosen appears to be higher compared to the surface flow wetlands (see Chapter 3.5).

Horizontal and vertical subsurface flow wetlands can be considered as a more efficient system type and they are to be preferred to the surface flow systems due to their generally higher performance.

3.5 Plant species in surface and subsurface flow wetlands

In general, the plant species that can be used for surface flow wetlands are also suitable for subsurface flow wetlands. Typical plant species that can be used in both system types are: *Juncus sp.*, *Phragmites sp.*, *Scirpus sp.*, *Typha sp.*, *Glyceria maxima* and *Phalaris arundinacea* (IWA, 2000). However, not all plant species that are suitable for subsurface flow wetlands can also be chosen for surface flow beds. Such species are e.g. *Canna sp.*, *Cyperus involucratus*, *Carex fascicularis* and *Pennisetum purpureum*. This depends on the plant-specific hydroperiod tolerance ranges (see Chapter 4.1). *Cyperus papyrus* appears to be more suitable for surface flow wetlands, but its use in subsurface flow systems may also be possible (Brix, 1992; personal evaluation of existing data). There are also species that are not suitable for use in subsurface flow wetlands (mainly gravel beds) such as *Eleocharis sphacelata* (Tanner, pers. comm.).
Phragmites australis and *Vetiveria zizanioides* are well-recommended species for vertical flow systems due to their vertically growing root and rhizome structure.

To draw conclusions, all plant species apart from *Eleocharis sphacelata* that were selected for this thesis are suitable for use in subsurface flow wetlands. However, their use in surface flow wetlands requires more exact hydrological considerations.

4 Hydraulic design criteria for constructed wetlands

4.1 Hydroperiod

The hydroperiod is defined as the period of time during which a wetland system is covered by water and describes the seasonal pattern of water level fluctuations. It is determined by duration, frequency, and depth of flooding. The hydroperiod is a result of the balance of inflow, outflow and storage in the system and depends further on seasonal differences in precipitation and evapotranspiration (EPA, 2000a).

Hydroperiod is one of the most important parameters for wetland design due to its direct influence on the plant species community and productivity. The choice of appropriate plant species depends primarily on two parameters: the tolerance to alternating water levels (flood tolerances) and, secondary, the duration of flooding. A lot of wetland species cannot survive under permanently inundated conditions often associated with low oxygen concentrations in the sediment. These plant-specific hydroperiod tolerance ranges should be considered when choosing suitable species for constructed wetlands.
The height of water level under inundated conditions is also an important hydraulic parameter to be considered for selection of plant species and concerns primarily surface flow wetlands. Due to these limitations, not all species occuring in natural wetlands are suitable for constructed wetlands. The individual tolerance ranges to flooding depend further on site-specific factors such as oxygen concentration in the water, presence of nutrients or toxic substances and the competitive ability with other wetland species (WPCF, 1990).

4.2 Hydraulic loading rate

The hydraulic loading rate (HLR) refers to the loading on a water volume per unit area over a specified time interval. It is defined as the volumetric averaged flow rate divided by the wetland surface area (ITRC, 2003). Typically, hydraulic loading rates are specified in [cm/d] or [mm/d].

The HLR depends on soil material (which is a critical parameter for subsurface flow wetlands), flow rate, area-size and the resulting hydraulic residence time (Chapter 4.3). It has to meet the hydroperiod tolerances of the plant community chosen as well as the loading rates of constituents found in municipal wastewater (TSS, BOD, COD and nutrients). Finally, the HLR is determined by the required and desired removal efficiency (WPCF, 1990).
The data below indicate practical values found in literature for the different types of constructed wetlands. The significant differences concerning the range of the values show that there are a lot of parameters and criteria that can affect the actual HLR. For example, systems designed for tertiary treatment can be loaded higher than wetlands designed for secondary treatment. Generally, the HLR of subsurface flow systems can be chosen higher due to the higher removal efficiency per area.

- Surface flow wetlands

0.7 - 5.0 cm/d for secondary treatment (WPCF, 1990)
1.9 - 9.4 cm/d for tertiary treatment (Vymazal, 1998a)

- Horizontal subsurface flow wetlands

2.0 - 5.0 cm/d for secondary treatment (Vymazal, 1998a; WPFC, 1990)
< 20 cm/d for tertiary treatment (Vymazal, 1998a)

- Vertical flow wetlands

4.0 - 6.0 cm/d (recommendations according to Bahlo, 1997)

4.3 Hydraulic residence time

The hydraulic residence time (HRT), also termed hydraulic detention time, is defined as the average residence time during which the water remains within the wetland system. The HRT can be described as a function of the "reactive" volume of the wetland divided by the volumetric average flow rate (ITRC, 2003).

In subsurface flow systems, the "reactive" volume is defined as the volume of water in the soil in consideration of the void fraction that is defined as the fraction of the total soil volume through which water can flow. The void fraction, also termed media porosity, ranges usually from 0.3 - 0.45 depending on the soil material chosen, e.g. sand, gravel or clayey soils (Vymazal, 1998a).
In surface flow systems, the "reactive" volume is defined as the volume of the free water body above the substrate minus the portion occupied by the submerged plant parts, e.g. stems, leaves, detritus, but also settled solids. The porosity of surface flow wetlands has proved difficult to exactly measure, thus, porosity values for surface flow wetlands in the literature are highly variable. For example, Reed (1995) recommended wetland porosity values ranging from 0.65 - 0.75 for fully vegetated surface flow beds.

The HRT can differ significantly depending on whether secondary treatment or tertiary treatment is intended. Generally, tertiary treatment requires longer retention times. Typical recommendations found in diverse literature are listed below.

- Surface flow wetlands:

5 - 10 d (WPCF, 1990)
5 - 14 d (Wood, 1995)

- Horizontal Subsurface flow wetlands:

5 - 10 d (WPCF, 1990)
2 - 7 d (Wood, 1995)
> 5 d (Vymazal, 2001a)

However, it should be considered that these values are theoretical HRTs. If short-circuiting occurs, the actual HRT can be less than the theoretical one which can result in lower removal efficiencies (EPA, 2000a). A further factor that can affect the HRT is evapotranspiration (Chapter 4.5).
To meet advanced treatment standards in surface flow as well as in subsurface flow wetlands, the HRT should be at least 5 days (Vymazal, 1998a; WPCF, 1990). Reed

(1995) suggested a hydraulic retention time of at least 6 to 8 days to ensure adequate nitrification rates. It can be concluded that there are no universally applicable recommendations in the literature.

4.4 Infiltration capacity

The infiltration capacity is defined as “the net water loss due to transference of water through the wetland sediment into the groundwater” (WPCF, 1990). The infiltration rate has to be kept as far as possible very low in order to protect the groundwater from possible contamination with wastewater constituents. This can be achieved either through clayey natural soils that have a permeability less than approximately 10^{-6} m/s or through a synthetic liner (e.g. PVC or concrete). If a synthetic liner is chosen, irrespective of the material, an important consideration is to provide an adequate depth, because the vertical root penetration of the wetland vegetation can cause damages to the liner if the soil layer where the plants are rooted is not deep enough (EPA, 2000a; EPA, 2000b).

4.5 Evapotranspiration

Evapotranspiration (ET) describes the atmospheric water losses from a wetland system through transpiration by the emergent plant portions and evaporation from the water surface and soil (USDA, 2002).
The ET is an important factor for wetland design, particularly in systems with large surface areas in warmer regions, since it can significantly affect the overall water balance in a wetland system (EPA 2000a). Among others, the evapotranspiration rate is affected by the following, mainly climatic, parameters (USDA, 2002):

- Solar radiation (diurnal fluctuations)
- Cloud cover
- Wind velocity
- Season (especially summer months)
- Climate zone (especially arid, hot and warm/Mediterranean climates)
- Amounts of open water exposed to winds
- Part of water surface which is occupied by vegetation stands and litter

Many wetland plants show considerable transpiration rates, more than terrestrial plants do. The water losses can be significant, especially in large vegetation stands of tall plant species. Arid and hot climates as well as warm summer months in all latitudes can affect the performance of constructed wetlands. The water volume in the system can decrease due to the high water losses which results in increased concentrations of remaining pollutants even to toxic levels.
Furthermore, the reduced water volume slows the water flow, and thus increases the hydraulic retention time. This can increase the potential for anoxic and anaerobic conditions resulting in a poorer treatment performance. In free-water-surface systems, an increased risk of mosquito developments can also occur (Reed, 1995). If the ET losses exceed the water inflow, supplemental water should be provided to keep the wetland wet (EPA, 2000a).

4.6 Precipitation

Precipitation (rainfall) is a further parameter that can influence the overall water balance in wetland systems. While ET reduces the water volume in a wetland resulting in increased hydraulic retention times, precipitation can lead to contrary effects: temporarily raised water levels and water volumes, decreased HRTs and diluted pollutant concentrations in the system (EPA, 2000b).
Precipitation has usually a minimal effect on the treatment efficiency of wetland systems in temperate climates. Precipitation and evapotranspiration ratios are fairly offsetting, and thus, the overall impact on water level and effluent concentration is insignificant, particularly in subsurface flow wetlands since they have relatively small surface areas compared to surface flow systems (EPA, 2000b).

However, precipitation is a strongly climate-dependent parameter which can become significant in very wet and rainy climate zones. Tropical, but primarily subtropical regions show high seasonal variations in precipitation characterized by long dry summer months and heavy rainfall in the monsoon season. The monsoon rain can temporarily flood the wetland system and, consequently, impair the treatment performance (Gopal, 1999).
Tropical and subtropical temperatures allow plant growth throughout the year compared to temperate and cold/boreal climate zones; but the high seasonal precipitation rates may be considered as a restriction.

5 Municipal wastewater: constituents and removal processes

5.1 Suspended solids and organic compounds

Domestic and municipal wastewaters consist of a wide variety of contaminants. The most important ones are suspended solids (measured as TSS), organic compounds (measured as BOD_5 and COD), nitrogen, phosphorus, trace metals and pathogens (bacteria and viruses).

In general, all types of constructed wetlands have been found to be very efficient in removal of both suspended solids and organic matter from wastewater. The mechanisms for removal of organics include biological degradation processes mediated by bacteria, fungi and aquatic invertebrates. The major processes for removal of suspended solids are sedimentation and filtration. Treatment efficiencies and detention times of both contaminants are very similar.

5.1.1 Suspended solids: TSS

Suspended solids are settleable and flotable particles in wastewater consisting of organic and inorganic matter suspended in the wastewater. Removal occurs through flocculation, sedimentation, filtration and other physical mechanisms. The numeric value is measured by a specific analytical test as TSS concentration in mg/L (Total Suspended Solids), (EPA, 2000b; Vymazal, 1998a).

Typical TSS concentrations in domestic raw wastewater according to Metcalf & Eddy Inc. (1991):

- Low strength wastewater: 120 mg/L
- Medium strength wastewater: 210 mg/L
- High strength wastewater: 400 mg/L

Typical removal rates have been recorded from 66 % - 92 % for 193 various wetland systems with a median percent reduction of 79 % in Kadlec and Knight (1996). TSS effluent concentrations are generally less than 20 mg/L and often less than 10 mg/L in both types of constructed wetlands (Brix, 1994c). It should be considered that the removal efficiencies are poorer at low TSS influent concentrations due to the internal background production. According to Reed (1995) and Kadlec and Knight (1996), TSS background concentrations of about 2 - 5 mg/L TSS can be expected.

In all types of horizontal flow systems, most of the TSS is rapidly removed within the first few meters at the vegetated inlet-zone of the wetland basin (Reed, 1995). According to EPA (2000a), approximately 80 % of TSS is removed in the first two days (HRT: 2 d). Temperature variations do not significantly affect the treatment efficiency because the removal mechanisms for TSS are mainly based on physical processes.

The influent should be at least primary pre-treated to avoid the high TSS concentrations typically found in raw wastewaters. These could either damage or even lead to a die-back of vegetation stands near the inlet zone or lead to clogging effects in the inlet zone of subsurface flow systems (Reed, 1995; Vymazal, 1998a).

5.1.2 Organic compounds: BOD

The removal of organic compounds takes place mainly through biological decomposition processes by heterotrophic microorganisms. The organic strength of wastewater can be measured as BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand). However, BOD is the more important and frequently used parameter for domestic or municipal wastewaters (Kadlec and Knight, 1996). COD is discussed in Chapter 5.1.3.

BOD (or more properly BOD_5) is defined as the amount of dissolved oxygen (DO) that is consumed by microbial activity for the biochemical degradation of organic matter in a water sample in a given time (5 days) at a certain temperature (20 °C) in the dark (EPA, 2000b). Hereafter the term BOD will be used.

Typical BOD concentrations in domestic raw wastewater according to Metcalf & Eddy Inc. (1991):

- Low strength wastewater: 110 mg/L
- Medium strength wastewater: 190 mg/L
- High strength wastewater: 350 mg/L

Likewise TSS, the decomposition of BOD in all types of constructed wetland systems is usually very efficient and has been reported to be typically between 70 % and 95 % (Reed, 1995; WPCF, 1990) for pre-treated municipal or domestic wastewaters. Effluent concentrations of less than 20 mg/L are typical (Brix, 1994c). The BOD removal rate is poorer at low input concentrations due to the internal background production of about 1 - 6 mg/L BOD (Kadlec and Knight, 1996). Decomposition processes occur relatively fast in the first few meters at the inlet zone of horizontal flow systems and, similar to TSS, within a HRT of 2 - 3 days (EPA, 2000a; Reed, 1995).

The removal rate of BOD is temperature-dependent since higher temperatures have a positive effect on microbial activity according to the Q10 rule: "The growth rate, reproduction, metabolism and the mobility of organisms, e.g. rates of biochemical reactions, usually double when temperature is increased by 10°C within the given tolerance range of an organism."
However, many studies and practical observations of existing constructed wetlands in cold/boreal climates and during winter operation in temperate climates have showed that the BOD removal efficiency decreases only slightly by about 10 % (Börner, 1992; Wissing, 2002): much less as may be expected by the theoretical Q 10 rule. The reasons are diversified: growth of bacterial strains which are more insensitive to cold temperatures, body heat of wastewater and protection against freezing through the soil layer and plant litter (Wissing, 2002).

5.1.3 Organic compounds: COD

Chemical Oxygen Demand (COD) is defined as the amount of chemical oxidant, usually potassium dichromate, required to oxidize the organic matter (Kadlec and Knight, 1996).

Typical COD concentrations in domestic raw wastewater according to Metcalf & Eddy Inc. (1991):

- Low strength wastewater: 250 mg/L
- Medium strength wastewater: 430 mg/L
- High strength wastewater: 800 mg/L

COD concentrations are generally higher than BOD because of the strong oxidant that can attack a larger group of organic compounds. The typical COD/BOD ratio in municipal wastewaters amounts to 1.25 - 2.5 (Metcalf & Eddy Inc., 1991). Industrial wastewaters usually have higher ratios.
Constructed wetlands are also very effective in removal of COD from wastewaters. However, the COD removal performance is usually slightly lower than of BOD since some groups of organic compounds cannot be biologically decomposed by microorganisms. This results in background levels ranging from 30 to 100 mg/L COD (Kadlec and Knight, 1996).

5.1.4 Role of plants in removal of organic compounds

Heterotrophic microbial organisms attached to the roots, rhizomes and soil particles are known to be the major contributor to both BOD and COD reduction. The bacteria use organic matter available in wastewater as their energy source and for the cell synthesis. The microorganisms are more dependent on the chemical and physical conditions than on their biological surroundings, thus, the composition of microbial population is similar in most wetlands regardless of the prevailing plant species (WPCF, 1990).
Direct BOD or COD removal by plant uptake is not existent or can be neglected (IWA, 2000). However, emergent macrophytes provide a surface area for microorganisms and have the capability to transfer oxygen from their leaves to the roots (Chapters 6.2 and 6.8). Oxygen which is released into the root zone can be utilized by aerobic bacteria for oxidation of organic carbon. This shows that the plants play only an indirect role for removal of organic compounds.
Several studies that compared the BOD and COD removal efficiencies of vegetated beds to unvegetated control beds showed no significant differences between the planted and unplanted filter beds. In some cases, the removal performance was even slightly better in the unvegetated filter beds (Coleman, 2001; Thomas, 1995; Wolverton, 1983).

5.2 Nitrogen removal in constructed wetlands

5.2.1 Nitrogen in wastewater

Nitrogen (N) in municipal wastewater is usually present as organic compounds, e.g. urea and amino acids, and as inorganic form, almost exclusively ammonium (NH_4^+). The bacterial conversion of organic N into inorganic ammonium in untreated wastewaters is defined as ammonification (mineralization).

According to Metcalf & Eddy Inc. (1991), the following nitrogen concentrations are typical for domestic raw wastewater:

Total nitrogen:

- Low strength wastewater: 20 mg/L
- Medium strength wastewater: 40 mg/L
- High strength wastewater: 70 mg/L

Free NH_4^+-N (ammonium):

- Low strength wastewater: 12 mg/L
- Medium strength wastewater: 25 mg/L
- High strength wastewater: 45 mg/L

Oxidized nitrogen compounds in domestic or municipal raw wastewater such as nitrates (NO_3^-) and nitrites (NO_3^-) are usually not present.

The removal of nitrogen is of interest for many reasons. Particularly, ammonium can cause a significant oxygen demand through biological nitrification resulting in strong depletion of the DO concentration in the receiving water. Further, ammonia (NH_3) is potentially toxic to aquatic organisms. In combination with phosphorus (Chapter 5.3) nitrogen is responsible for eutrophication processes in receiving waters.

Therefore, many constructed wetland systems have been developed with the objective to remove nitrogen from wastewater. There are three principal mechanisms nitrogen can be removed:

1) Microbial transformations
2) Plant uptake
3) Sediment adsorption

5.2.2 Microbial transformations (nitrification and denitrification)

Numerous studies have revealed that in most constructed wetlands microbial nitrification and denitrification are the most important nitrogen removal pathways (about 70 - 80 % of the total N removal rate), (Kadlec and Knight, 1996; Reed, 1995; Wissing, 2002; WPCF, 1990). The first step (nitrification) is the biological transformation of ammonium to nitrate which is an oxygen-consuming process.

5.2.3 Nitrification

Nitrification occurs in a two step oxidation. The first reaction is nitritation applied by strictly aerobic bacteria species, among others, *Nitrosomonas:*

1) $NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H^+ + H_2O$

The second step is the oxidation of the formed nitrite to nitrate (nitratation) by, among others, *Nitrobacter* species:

2) $NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$

Equations 1) and 2) can be comprised as follows that describes the entire nitrification process:

3) $NH_4^+ + 2\ O_2 \rightarrow NO_3^- + 2\ H^+ + H_2O$

The released energy of this biochemical oxidation is used for synthesis of biomass, e.g. formation of organic carbon compounds from carbon dioxide (CO_2). According to Vymazal (1998a), nitrification is influenced, beside many other factors, by temperature and pH value.
The nitrification process is strongly temperature and pH dependent. The optimum temperature ranges from 25 °C to 35 °C in water and from 30 °C to 40 °C in soils. Temperatures below 15 °C affect the nitrification rate more significant compared to temperatures between 15 °C and 35 °C. Minimum temperatures for growth of *Nitrosomonas* and *Nitrobacter* are 5 °C and 4 °C, respectively (Cooper, 1996; in IWA, 2000).
A further nitrification-influencing determinant is the pH value. According to Cooper (1996; in IWA, 2000), the optimum pH ranges from pH 7.5 to 8.6, however, nitrification can also occur at much lower pH values.

5.2.4 Denitrification

Denitrification is the reduction of nitrate to molecular nitrogen or nitrogen gases by denitrifiers according to the following equation:

1) $NO_3^- + 6\ H^+ + 5\ e^- \rightarrow 0.5\ N_2 + 3\ H_2O$

This reaction requires anoxic conditions where nitrate-oxygen is used as final electron acceptor instead of DO and electron-donating substrates, usually organic compounds that are available in wastewater. Denitrification is conducted by several heterotrophic bacteria species, e.g. *Pseudonomas, Arthrobacter, Acinetobacter* or *Bacillus*.
According to Cooper (1996; in IWA, 2000), the presence of dissolved oxygen suppresses the enzymatic activity required for denitrification and is a critical parameter. Similar to nitrification, the denitrification process is also temperature and pH dependent. Denitrification proceeds only very slowly at temperatures below 5 °C, the optimum pH ranges from 7 to 8. In acidic milieu, nitrogen oxides such as NO (nitrogen monoxide) or N_2O (nitrogen dioxide) can also be formed (Vymazal, 1995b).

Another critical factor influencing the denitrification activity is the availability of organic substrates. Available, biodegradable organic compounds are often the limiting factor for denitrification in constructed wetlands, and thus, can control the removal efficiency. It is estimated that 5 - 9 g of BOD are necessary to completely denitrify 1 g of NO_3^--N (Reed, 1995). The wetland plants play a major role in providing organic carbon in all wetland types as seen in the next chapter.

5.2.5 Effect of wetland plants on microbial transformations

Nitrification

Wetland plants influence the microbial activity positively as they provide a surface area and release oxygen into the root zone which creates aerobic microsites in the root zone. Thus, it may be concluded that nitrification of ammonium to nitrate should occur. However, numerous studies have showed that the root zone oxygenation rate is often low and insufficient to allow effective nitrification.
A number of horizontal subsurface flow as well as surface flow wetlands have failed in achieving acceptable nitrification rates since the amount of oxygen available to the nitrifying microorganisms in the root zone has been often overestimated. As a result of the generally low oxygenation transfer rates, the type of plant species is of less importance concerning the nitrification performance (EPA, 2000b). Higher nitrification activities can be expected in vertical flow systems due to the improved oxygen input into the soil (Chapter 3.3).

Denitrification

Wetland plants can support nitrate reduction by heterotrophic denitrifiers as they secrete root exudates that are rich in organic carbon (Brix, 1997). Also detritus (dead plant tissue), litter and harvested plant material can be utilized by denitrifying bacteria as carbon source (Wissing, 2002). However, living plant material cannot be used as food source.
The magnitude of the plants' contribution to denitrification depends on their ability to provide new biomass. Breakdown and decomposition of aboveground plant tissue (dead leaves, stalks or stems) on the wetland surface (soil or water body) provide organic biomass which can be used as carbon source. Also dead roots and rhizomes, especially in the upper layers of the wetland soil, are decayed, and thus, are available as carbon source (Bayley, 2003; Wissing, 2002).
Especially plant species that grow rapidly and have a high leaf turnover rate can produce large amounts of carbon sources, e.g. reed sweet grass (*Glyceria maxima*), cattails (*Typha sp.*) or papyrus (*Cyperus papyrus*). These plants are also capable of forming floating mats of decaying leaf litter and accumulating plant detritus on the wetland surface (van Oostrom, 1990).

5.2.6 Nitrogen plant uptake

Inorganic bonded nitrogen (especially ammonium) can be assimilated by wetland plants for incorporation into the biomass and tissue through their root system.
However, the potential nitrogen uptake capacity by plants is limited by its productivity (growth rate) and the nutrient content in the plant tissue. Although wetland plants show generally a high productivity and can incorporate considerable amounts of nitrogen into their biomass, the uptake rates are relatively insignificant compared to the total nitrogen loading charged into the constructed wetland (Brix, 1994b; IWA, 2000).

This was showed in several studies, e.g.:

- 12 - 16 % (Gersberg, 1986)
- 11 % (Hurry, 1990)
- 6 - 10 % (Tanner, 1994)
- 6 % (Nyakang'o, 1999)

(Amount of nitrogen removed with the biomass in percent of the total annual nitrogen loading)

These data clearly show that plant uptake cannot be considered as an important removal mechanism for nitrogen. Furthermore, nitrogen is only temporarily stored in the aboveground plant biomass and will return back to the wetland system as detritus or litter which will be decayed again. Regularly harvesting of the aboveground biomass can be realized in order to improve the total nitrogen removal efficiency. However, considering that nitrogen removal by plant uptake is generally insignificant, feasibility and benefit should be balanced to each other.

5.2.7 Sediment adsorption

Removal of nitrogen through matrix adsorption (fixation of nitrogen at soil particles) accounts for the third pathway nitrogen can be removed from wastewater. Ammonium is adsorbed in sediments, and converted into humus substances and high-molecular nitrogen-containing compounds. This process amounts to about another 10 % of the total nitrogen removal rate and can be considered as insignificant (Wissing, 2002).

5.3 Phosphorus removal in constructed wetlands

5.3.1 Phosphorus in wastewater

Phosphorus (P) in wastewater is typically present as orthophosphate, dehydrated orthophosphate (polyphosphate) and organic phosphorus compounds (Vymazal, 1998a). It is highly mobile and present in solution, in particles and detritus, or in the cells of aquatic organisms. Like nitrogen, phosphorus is an essential macronutrient for the growth of plants and other organisms and is, besides other factors, responsible for eutrophication processes.

According to Metcalf & Eddy Inc. (1991) the following phosphorus concentrations are typical for domestic raw wastewater:

Total phosphorus (TP):

- Low strength wastewater: 4 mg/L
- Medium strength wastewater: 7 mg/L
- High strength wastewater: 12 mg/L

Inorganic phosphorus:

- Low strength wastewater: 3 mg/L
- Medium strength wastewater: 5 mg/L
- High strength wastewater: 10 mg/L

Many constructed wetland systems and concepts have been developed in order to remove significant amounts of phosphorus. However, the phosphorus removal efficiency shows a high range of variation strongly depending on the wetland type and composition of the soil layer. Beside other removal mechanisms such as microbial uptake, the following two pathways can be considered as the main removal mechanisms in constructed wetlands (Vymazal, 2001a):

- Soil adsorption and precipitation
- Plant uptake

5.3.2 Soil adsorption and precipitation

The main mechanisms for phosphorus removal in subsurface flow systems are chemical and physical adsorption, and precipitation in the soil matrix. The adsorption capacity depends primarily on the soil type and chemical composition, and further, surrounding conditions such as pH value or redox-potential. Metal-additives such as Fe, Al or Ca enhance the phosphorus-fixation capacity of the soil (Wissing, 2002).
Cohesive, clayey and finer-textured soils tend to have a greater ability to adsorb phosphorus than non-cohesive, coarser-textured soils (gravel beds). This belongs to the Kickuth' theory (1977) that wetlands designed according to his root zone concept, show a better phosphorus-fixation than gravel beds (Wissing, 2002).

5.3.3 Plant uptake

Like nitrogen, phosphorus is taken up through the root system and incorporated into the biomass, particularly at the beginning of the growing season (in temperate regions during the early spring). However, the wetland vegetation acts only as a temporary storage, thus, phosphorus removal through plants is limited to seasonal uptake during the vegetation period. Senescent and mature plants have lesser uptake rates (EPA, 2000b).

Phosphorus removal by plant uptake is only minor compared to the total phosphorus loading of municipal wastewater charged into the constructed wetland (Brix, 1994b) as seen in the following examples:

- 7 % (Hurry, 1990)
- 6 - 13 % (Tanner, 1994)
- 2 % (Nyakang'o, 1999)

(Amount of phosphorus removed with the biomass in percent of the total annual phosphorus loading)

Although phosphorus uptake can be significant for a short period, the percentage indications above show that the amount of phosphorus removed by emergent plants forms only a small fraction of the total phosphorus removed in constructed wetlands.
The uptake capacity of phosphorus in macrophytes is significantly lower compared to nitrogen since the phosphorus content in the plant tissue is much lower than nitrogen (Brix, 1994b). This is a consequence of the Redfield ratio that quantifies the molar ratio of elements as follows: C / N / P = 106 / 16 / 1. However, this ratio is valid for

marine plankton under non-limiting conditions, and thus, it should not be considered as commonly valid.
Phosphorus is released back to the wetland system again through leaching and mineralization processes after the plant decays, particularly in autumn and winter during the dormancy period (in temperate regions).

The major processes in phosphorus removal both in subsurface flow and surface flow systems are adsorption and precipitation. However, due to the limited contact possibilities between water body and soil layer in surface flow systems, phosphorus removal by plant uptake is usually of higher importance in these systems compared to subsurface flow systems (Brix, 1994b; Brix, 1999; Vymazal, 1998a).
Plant uptake of phosphorus (and also nitrogen) can be significant in low-loaded constructed wetlands, especially in free-water-surface systems that are often designed for tertiary treatment and nutrient polishing. However, such systems show relatively low biomass production rates and are generally not harvested to utilize the biomass. As a result, the large amounts of nitrogen and phosphorus taken up by the plants are released back to the water by subsequent decomposition of plant detritus, and thus, are not removed from the system (Brix, 1999; Reed, 1995).

5.4 Other wastewater constituents

Many other wastewater constituents can be removed in constructed wetlands such as heavy metals, hydrocarbons and trace organics; substances that are mainly found in industrial wastewaters, landfill leachate, etc. Apart from heavy metals briefly discussed in the next chapter, they will not be discussed here because this thesis primarily concerns with constructed wetlands for treatment of municipal or domestic wastewaters.

5.4.1 Heavy metals

Heavy metals at trace-level concentrations can be found in all types of wastewaters including domestic and municipal effluents. However, the major sources are industrial and commercial activities (Reed, 1995). The most important heavy metals are copper (Cu), nickel (Ni), lead (Pb), zinc (Zn) and cadmium (Cd).
The mechanisms for removal of heavy metals in constructed wetlands include, among others, adsorption, complexation, precipitation and plant uptake. Constructed wetlands can be very effective in removing heavy metals; both subsurface flow and surface flow systems are similar in their removal capability (Reed, 1995).
However, the main mechanisms are precipitation and adsorption processes in interactions with the organic sediment. Plant uptake is only of minor significance (less than 1 % of the total metals removed by the wetland system), and further the highest metal accumulations can be found in the belowground plant parts (roots and rhizomes). Thus, harvesting of aboveground biomass for metal removal can be neglected (Reed, 1995; Vymazal, 1995b).
Some plant species have developed tolerances to certain metals and can accumulate significantly higher amounts of them, e.g. *Typha latifolia* for Pb, Zn and Cu or *Cyperus malaccensis* for Cu (in: Wissing, 2002).

5.4.2 Boron: occurrence and distribution

Boron is a naturally occurring non-metal, but includes metallic properties, and is found in nature in form of the borates, perborates and boric acid in oceans, sedimentary rocks and clay-rich soils. Beside natural sources, boron is also released from anthropogenic sources that include, among others, industrial purposes, e.g. fibreglass production, metal and textile industry and further agricultural uses as addition for crop fertilizers and herbicides.
A significant boron source are cleaning and washing products. Boron is often used as bleaching agent in laundries (in form of sodium perborates) or as a washing aid and softener in soaps and detergents. Thus, boron releases, mainly as perborates from detergents, may be possible in municipal wastewaters (Atri, 1983; WHO, 1998). However, boron is of higher importance for industrial wastewaters that have usually higher boron concentrations than typical municipal wastewaters (Reed, 1995). No reports about possible problems with elevated or toxic boron concentrations could be found in the case studies used for this thesis (personal evaluation of existing data).

- Boron concentrations found in domestic wastewater without commercial and industrial additions: 0.1 - 0.2 mg/L B (Metcalf & Eddy Inc., 1991)

5.4.3 Boron accumulation in wetland plants

Boron is an essential micronutrient for higher plants like aquatic macrophytes and is required for normal growth and plant development. Demands and tolerance ranges vary within the different plant species.
The accumulation in plants depends on the boron concentrations in soil and water, soil conditions and climatic factors. The mobility of boron in soils depends on the soil acidity and precipitation. It shows a low persistence in light-textured and acid soils, and tends readily to leaching, particularly in areas with high rainfall. This may explain the fact that boron toxicity is more a problem in arid and hot climates than in temperate regions, and further that boron deficiency is more likely to occur in humid regions with light-textured and acidic soils (WHO, 1998).

Boron moves into the plant tissue via non-metabolic adsorption mainly in form of boric acid. Once in the plant, boron moves readily through the xylem in the transpiration pathway. As a result, highest accumulations are found in the upper, stomatal parts of the plants, e.g. leaf tips due to transpiration effects (water losses), but also in the storage organs such as roots or rhizomes. The main symptoms of an excess uptake of boron in toxic concentrations are decreased or inhibited growth and photosynthesis rate, and therefore, yield reductions. Further, the root development is inhibited and yellowing of the leaves can be typically observed (Gupta, 1985).

The boron tolerance of plants is divided into three groups according to crop species

- Tolerant crops: tolerant up to 2 - 4 mg/L B (e.g. cotton, sugar beet)
- Semi-tolerant crops: tolerant up to 1 - 2 mg/L B (e.g. corn, barley, oats)
- Sensitive crops: tolerant up to 1 mg/L B (fruits and nuts)

(Reed, 1995)

5.4.4 Boron tolerance of macrophytes

Several studies have been conducted to investigate the effect of boron on aquatic macrophytes, especially at elevated concentrations. Most of the studies investigated submerged and floating macrophytes. In general, Maier and Knight (1991) concluded that rooted submerged macrophytes tend to be the most boron-sensitive macrophytes. According to Nobel (1983), the submerged plant waterweed *(Elodea canadensis)* showed an inhibited growth rate at a concentration of 1.0 mg/L boron. The same study reported an inhibited growth for water milfoil *(Myriophyllum alterniflorum)* when exposed to a boron concentration of 2.0 mg/L.
Concerning floating plants, most studies relate to the common duckweed *(Lemna minor)*. This species shows the highest accumulation rates of all investigated macrophytes. Boron concentrations between 10 - 20 mg/L at pH 5.0 could be tolerated without being inhibited in plant growth and development, whereas the accumulation capacity of boron in duckweed species is strongly pH dependent. At a pH of 4.0 and in the presence of 0.02 mg/L boron for 7 d, the plant accumulation amounted to 0.093 mg/g B (fresh weight). At pH 7.0, the plant accumulation amounted to 0.257 mg/g B (fresh weight), (Frick, 1985).

There are only a few studies that relate to boron tolerances of emergent macrophytes. Bergmann (1995) investigated the boron tolerance of common reed *(Phragmites australis)* in a free water body during the vegetation period. Growth characteristic, development and growth rate was determined and compared at different boron concentrations. Conclusion of this study was that *Phragmites australis* is able to tolerate relatively high concentrations ranging from 4 - 8 mg/L boron over a period of 2 - 3 months without any significant damages. Following the tolerance groups presented in the last chapter, *Phragmites australis* can be classified as a particularly boron-tolerant plant. However, long-term exposure would result in plant damages, growth and yield reductions (Bergmann, 1995).

Finally, it should be complemented that the limits between boron deficiency and toxicity are very narrow. While boron concentrations can be extremely toxic to some species, the same concentrations are at or close to the optimum for others. This fact, and the toxicity problems in arid and hot climate zones, should be considered for the choice of plant species in constructed wetlands if elevated boron concentrations are to be expected (Gupta, 1985).

Apart from common reed (*Phragmites australis*) which is a boron-tolerant species, data about boron tolerances of other emergent macrophytes could not be found.

6 Emergent macrophytes: adaptabilities and functions

6.1 Life cycle and reproduction

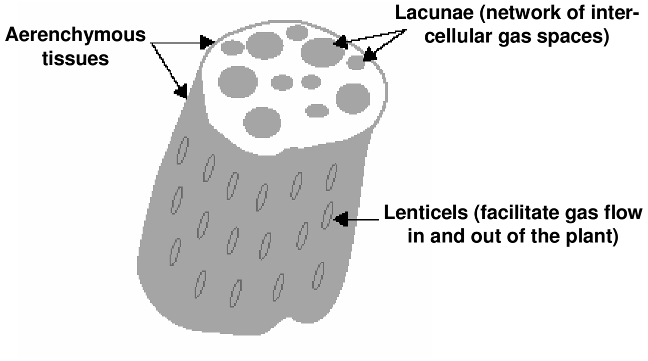
Wetland plants show several anatomical and morphological adaptations to their water-saturated and flooded habitat. Particularly, the root and rhizome system of aquatic macrophytes shows significant differences to terrestrial plants.
In general, emergent macrophytes are perennial means that the plant lives and continuous for at least three growing seasons due to its belowground portions (e.g. rhizomes, roots or tubers) that remain dormant throughout the winter season and sprout again in the next growing season. This is independent of the aboveground portion (stems and leaves) that can either remain standing through the dormant season until the beginning of the next growing season (persistent) or die back to the ground and decay (non-persistent) (Thunhorst, 1993; Wissing, 2002).
Perennial plant species can propagate both generatively by crops or seeds and vegetatively by rhizomes and stolons. Vegetative reproduction is “the process of asexual reproduction, in which the new plant develops from roots, stems and leaves of the parent plant” (clonal production), (EPA, 2000b). In contrast to the perennials are the annual plants that die entirely at the end of the growing season and can only reproduce themselves by seed production (Thunhorst, 1993).

For the most wetland plants, vegetative reproduction is more important, particularly in cold/boreal and temperate climate zones. Generative reproduction is less important and occurs only poor and sporadic due to the uncertain water supply of the seeds (Chambers, 1994a).

6.2 Adaptabilities for survival in wetland habitat

Since the soils of both natural and constructed wetlands are temporarily or permanently inundated, and thus water-saturated, they are generally anaerobic or anoxic. The macrophytes have developed physiological adaptations to survive under these hostile, flooded and oxygen-depleted conditions. The most important adaptive mechanism compared to terrestrial plants (terraphytes) is the presence of the aerenchyma or aerenchymous tissues: an aerating tissue containing large intercellular gas spaces (lacunae) that form a hollow connecting channel system from the leaves and shoots to the roots and rhizomes, and vice versa (Figure 6.1). The aerenchyma facilitates rapid oxygen movement to the root system allowing aerobic respiration in an otherwise nearly oxygen-free environment (Brix, 1994b; Wissing, 2002).

Figure 6.1: Aerenchyma in vascular wetland plants (taken from USDA, 2002; modified)



Main survival strategies of the flood-tolerant rhizomes are to maintain the internal aeration and to create oxidized zones on the surface of the rhizomes. On the one hand, oxygen releases in the rhizosphere are essential to the plants since they facilitate chemical and microbial oxidation, and detoxification of potential toxic compounds, e.g. dissolved heavy metals or hydrogen sulphides (H_2S). On the other hand, plant-internal aeration and oxygen supply has to be maintained: all wetland plants attempt to keep oxygen releases and losses from roots to the surrounding to a minimum. To achieve this, oxygen releases into the soil are limited to definite regions at the roots and rhizomes (Wissing, 2002). The highest oxygen releases are found in young roots at the root-tips, whereas oxygen releases from old roots are very low or not detectable (Brix, 1990). This is due to the increased lignification and suberization processes occuring with increasing tissue age that reduce the gas permeability of the root walls (Brix, 1997). The oxygen release rates from roots into the soil depend on the following factors (Brix, 1994b):

- Oxygen concentration within the plant species
  → Maintenance of internal pressurizations
- Oxygen demand of the surrounding medium
  → Consumption processes in the root zone
- Anatomical characteristic of the roots
  → Extension, length, diameter, root wall development and permeability

There are two mechanisms for the internal oxygen transportations in wetland plants: (1) either by passive molecular diffusion due to concentration gradients within the aerenchyma or (2) additionally, by convective flow of air through the intercellular gas spaces. The latter is physically driven by differences in temperature and water vapour pressure between the internal gas vessels of the plant and the surrounding atmosphere (Brix, 1994b).
Oxygen transportation by convective flow allows the wetland plant to achieve higher oxygen concentrations in the roots and rhizome than by passive diffusion alone. These plants have the potential to release more oxygen into the root zone than plants without convective flow (Armstrong, 1990; Brix, 1994b; IWA, 2000). Species that have a convective flow through their rhizomes are e.g. common reed (*Phragmites australis*), cattails (*Typha sp.*), tall spike sedge (*Eleocharis sphacelata*), but also soft stem bulrush (*Scirpus validus*), jointed twig-rush (*Baumea articulata*) and giant rush (*Juncus ingens*), (Brix, 1992). Such plant species may be preferably used in constructed wetlands.

6.3 Functions of macrophytes in constructed wetlands

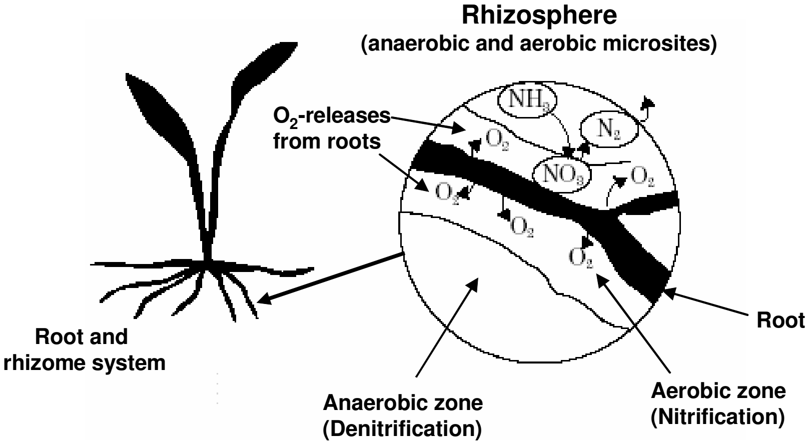
The macrophytes can either directly or indirectly contribute to treatment processes in constructed wetlands. The major effect is based on their physical presence in the wetland system that creates conditions that are beneficial for wastewater purification such as filtration effects or providing a surface area for microorganisms. The plants can contribute to nutrient transformation both directly through plant uptake and indirectly as they support physical, chemical and microbial processes. Here, the functions are briefly summarized and subsequently they are described more detailed (Brix, 1994b).

- Release of oxygen and root exudates into the soil
  → Mainly important for horizontal subsurface flow wetlands
- Effects of root penetration
  → Mainly important for vertical subsurface flow wetlands
- Effect of emergent and submerged biomass and litter fall
  → Affects all wetland systems
- Plant uptake of nutrients and other wastewater constituents
  → Can affect all systems, but mainly important for surface flow wetlands
- Surface area for attached microorganisms
  → Mainly important for surface flow wetlands
- Biological and aesthetic functions
  → Affects all wetland systems

6.4 Release of oxygen and root exudates into the soil

As it was described in Chapter 6.2 aquatic macrophytes have developed the biologically unique capability to take up oxygen and other gases from the atmosphere through their emergent leaves, shoots and stems and transport them to the roots and rhizomes. Consequently, the region which is directly adjacent to the aerated roots and rhizomes can be aerobic (aerobic microsites), while otherwise water-saturated, anaerobic or anoxic conditions are prevailing in the soil (Brix, 1997). The zone which is influenced by plant roots is known to be the habitat for attached microorganisms and is defined as the rhizosphere. Oxygen releases into the rhizosphere can support microbial, aerobic degradation of carbon (organic compounds) and nitrification.

Figure 6.2: Oxygen releases within the rhizosphere (taken from: USDA, 2002; modified)



It should be considered that many plant species are sensitive to extremely high organic or hypereutrophic loadings (and thus high oxygen demands). For example, common reed *(Phragmites australis)* is susceptible to oxygen demands in the rhizosphere that exceed the oxygen releases from the roots significantly for longer periods. This can be caused by high strength or over-loaded concentrations of organic matter and highly eutrophic conditions being a considerable stress factor for the plant roots. Consequences are callus-formations and abnormal lignification processes that block the internal aeration and vascular transport pathways in the root's aerenchyma. Therefore, oxygen releases into the rhizosphere are severely reduced and phytotoxic concentrations can increase leading to reduction or even die-back of reed stands (Armstrong, 1996).

Beside oxygen, the roots release also a wide variety of organic substances into the rhizosphere (Seidel, 1966). These root exudates comprise supplementary substrates for microorganisms such as carbon sources for denitrification as well as antibiotic substances.
Seidel showed in some of her earlier studies that the total microbial content in the effluent passing through a gravel bed planted with common bulrush *(Scirpus lacustris)* was reduced to 2 - 5 order of magnitude; strongly depending on the HRT. She proved that bulrushes release substances that appear to have an antibiotic effect on pathogen microorganisms (mainly enteric bacteria and coliforms).
However, the practical magnitude of antibiotic substances to bacterial removal in constructed wetlands is still unclear as there are many other physical and chemical processes such as sedimentation, filtration and adsorption that can decrease the microbial loading, too (Wissing, 2002).

6.5 Effects of root penetration

Horizontal subsurface flow wetlands

The roots, rhizomes and stems penetrate physically the soil layer in subsurface flow wetlands. The water flow is conducted through channels that are formed by living and dead roots, rhizomes and soil pores (Brix, 1994b). However, the effect on the hydraulic conductivity has been controversial for a long time. Based on initial studies in Europe during the 1980's, some researchers proposed that the presence of plant roots allow more effective fluid movement, prevent channelling, and increase and maintain the hydraulic conductivity of the soil (Kickuth, 1981). According to his root zone theory, Kickuth claimed that growing roots would loosen any soil and after their death they would leave behind a macrospore-system consisting of tubular pores and channels. A hydraulic conductivity, once developed, would gradually stabilize and maintain itself in any soil (Kickuth, 1981).
However, several studies of soil-based root zone wetland systems in Austria, Denmark and the UK showed no improvement in the hydraulic conductivity for developed root zone systems (Schierup, 1990). Most common problems in these systems were soil-clogging and surface runoff means that the wastewater flow occurs to a large extent aboveground.

Vertical subsurface flow wetlands

In vertical flow systems, the roots have been reported to improve the hydraulic regime of the system, water-root contact and soil oxygenation if the wastewater is charged intermittently at the bed surface and percolates vertically through the soil layer. The roots and stems of the vegetation stands prevent clogging of the soil medium through permanent, wind-induced movements and steadily growth that keeps the infiltration area at the surface open (Brix, 1997; Wissing, 2002).
Another positive effect of the root penetration that concerns all wetland types is the physical stabilization of the soil surface. The dense and intertwine root system, together with the aboveground canopy, lessens the risk of erosion caused by wind, rainfall, etc. (Brix, 1997).

6.6 Effect of emergent and submerged biomass and litter fall

Effect of emergent and submerged plant biomass

The functions of the emergent plant parts are most obvious in the surface flow wetlands. Here, the aboveground vegetation cover serves as a shading canopy which limits penetration of sunlight, and thus, algal growth on the water surface is prevented or lessened. Algal biomass could become a problem as it potentially increases the effluent TSS, and further BOD concentration due to the extra-cellular products excreted by algae (Brix, 1994b; WPCF, 1990).
Furthermore, dense vegetation stands reduce wind-induced turbulences and slow down current wind velocities near the water surface. As a result, there are better conditions for sedimentation processes leading to an improved TSS removal efficiency, and further increased contact times between wastewater and surface areas of the submerged plant portions (Brix, 1997). However, a drawback is the decreased re-aeration capacity near the water surface and the limited oxygen supply of the water body. This can be significant for surface flow wetlands since surface re-aeration is the major oxygen source in these systems (WPCF, 1990).

In cold/boreal and temperate climate zones, there is another important effect of the vegetation, especially during the winter season under freezing conditions. Long-persisting freezing temperatures can result in formation of significant ice layers covering the wetland system. The presence of standing (persistent) plant biomass including plant litter provides a natural, thermal insulation of the wetland that helps to protect the soil free of frost. This effect concerns all wetland types, but particularly surface flow systems (Brix, 1994b; Brix, 1997; Wissing, 2002).

Effect of litter fall

The effects of litter fall in surface flow wetland systems are diversified. In temperate climate zones litter falls onto the water surface usually at the end of the growing season. An accumulating litter layer on the water surface can interfere with the hydraulic regime of the wetland system and cause short circuiting-flows and dead zones. Regular harvesting and removal of accumulated plant litter is necessary to maintain the treatment performance and to avoid the interfering streams.
In subsurface flow systems, the accumulation of plant litter on the ground surface does not considerably impair the belowground flow of wastewater (WPCF, 1990).

Furthermore, litter removal and harvesting can help to prevent the development of mosquito populations and other insects since local anaerobic zones caused by anaerobic decomposition of plant litter are removed (Reed, 1995). However, in subsurface flow wetlands, it is also possible that the litter layer as well as the vegetation canopy can limit the development of nuisance insects by adsorbing the wastewater that has gathered on the ground surface into the litter mass. (Many insects require open water zones for their development), (Wood, 1995).
Finally, plant litter, together with plant vegetation, can act as a natural odour biofilter. Odour nuisances caused by anaerobic degradation processes can be kept within the wetland system (Wood, 1995).

6.7 Plant uptake and harvesting

Plant uptake

The contribution of aquatic macrophytes to nutrient removal via plant uptake was discussed in the Chapters 5.2.6 and 5.3.3, and was considered as insignificant compared to the total nutrient removal efficiency. In the first place, the emergent macrophytes take up nutrients through their root system from the sediment. A minor uptake occurs through submerged plant portions such as stems, stalks or leaves (Denny, 1987).

The potential nutrient uptake and storage rate of a plant species depends essentially on three parameters (Reddy and De Busk, 1987b):

- Plant productivity (growth rate)
  → Affects uptake capacity
- Biomass accumulation (standing crop: biomass yield per unit area)
  → Affects storage capacity
- Plant tissue nutrient content
  → Affects uptake and storage capacity

Rapid growth rates, high biomass yields and also high tissue nutrient contents affect the nutrient assimilation and storage positively.
Generally, the productivity (growth rate) of wetland plants increases with an increasing availability of nutrients. Reddy and De Busk (1987b) found a direct relation between nutrient supply and biomass yield, and nutrient accumulation: increased concentrations of nutrients result in higher biomass yields, and as consequence, in increased nutrient accumulation rates.
The nutrient uptake capacity of emergent macrophytes depends on many parameters, among others, plant species, wastewater composition, loading rate, management practises such as harvesting and climate (Reddy and De Busk, 1987b). Particularly, in tropical and subtropical regions where seasonal dormant periods are reduced or completely absent, plants can rapidly grow throughout the year under optimum climatic conditions, and thus, can be highly productive. Consequences are high biomass yields with large nutrient accumulations (Denny, 1987). Such high productive species are e.g. cattails (*Typha sp.*), papyrus *(Cyperus papyrus),* vetiver grass *(Vetiveria zizanioides*) and giant reed *(Arundo donax)*.
The primary benefit of using high productive plants in constructed wetlands is the potential utilization of their biomass. Such species have the capability to attain high harvestable biomass yields that can provide a basis for many economically valuable products (see Chapter 7.4).

Harvesting

If the wetland is not harvested, the major part of the nutrients that were accumulated by the plant will be recycled to the water (or soil) again (IWA, 2000). As the plants remove only a minor portion of the total nutrient removal performed by the constructed wetland, the pros and cons have to be studied if harvesting only for this purpose (nutrient removal) is economically useful and feasible (Reed, 1995).

Especially in tropical environments, the frequency, and thus, the costs of harvesting should be considered: the use of rapidly growing plant species in the tropics requires frequent and regular harvesting. This leads to costs that can negatively offset the advantageously economical utilization of the harvested biomass.
In cold/boreal and temperate climates, frequent harvesting is usually not necessary in order to achieve maximum nutrient removal. However, harvesting can be undertaken once a year at the end of the vegetation period to improve the total nutrient removal efficiency (Reddy and De Busk, 1987a; Vymazal, 2001a).
Harvesting during the growing season (and maximum standing crop) is not recommended for some species because this can lead to plant stress, death of stems and considerable delay in re-growth in the next growing season (EPA, 2000b).

6.8 Surface area for attached microorganisms

The major contribution to removal of organic matter and nitrogen is attributed to microbial transformations. The submerged plant portions in surface flow wetlands (stems, stalks and leaves) as well as the buried parts in subsurface flow wetlands (roots and rhizomes) serve as a large surface area for dense and diversified populations of attached microorganisms like bacteria, protozoa and certain algae species. Litter, fallen plant material and detritus provide additional surface areas and attachment sites for microbial growth (Brix, 1994b; Tanner, 2001). Both submerged and buried plant tissues provide a habitat for a vast diversity of microbial communities due to diversified and complex conditions that include anaerobic, aerobic and anoxic microsites, oxygen releases and root exudates (Wissing, 2002).
In surface flow wetlands, only the submerged plant parts can provide a surface medium for attached microbial population. Wetland systems including a substrate provide additional surface areas for treatment contact, and as consequence, the treatment effectiveness per unit area is higher (Brix, 1994b; ITRC, 2003; Chapter 3.2.1).

6.9 Biological and aesthetic functions

These are functions that do neither directly nor indirectly contribute to wastewater treatment. Emergent macrophytes can provide a suitable habitat for wildlife. Particularly, large wetland systems consisting of extensive vegetation stands and open water areas can provide a habitat for diverse wildlife that includes mammal species, reptiles and numerous bird species. Wide-area constructed wetlands used for advanced treatment of secondary treated effluents (polishing) have been constructed in the USA (Chapter 3.2.2). These systems are similar to natural wetlands and resemble floodplains and wet meadows including a high biodiversity (Brix, 1997; Gopal, 1999; Wissing, 2002). (It should be considered that wildlife species can also damage the plants in constructed wetlands.)

Furthermore, macrophytes can enhance the aesthetic value of constructed wetland systems. Flowering plants can give the treatment wetland an aesthetic and decorative appearance in particular when nice-looking species such as the yellow or blue flag (*Iris pseudacorus; Iris versicolor*) or calla lily (*Zantedeschia aethiopica*) are chosen. The visual aspect is more interesting in small treatment systems, e.g. for hotels or single houses (Brix, 1997), (see pictures of some plant species in Appendix A).

7 Criteria for the choice of plants in different climate zones

Several criteria are required to facilitate the choice of plant species that are suitable for use in constructed wetlands under different climatic conditions. Among the numerous possible criteria that could affect the plant choice, definite criteria were considered as the most important ones. They form the basis for the selection of plants in different climatic regions. This chapter presents these selected criteria and investigates some general aspects for the plant choice.

7.1 Plant-specific properties and adaptabilities

- Tolerance to flooded and water-saturated conditions (hydroperiod)
- Adaptability to anaerobic and anoxic conditions (root zone oxygenation)
- Propagation (vegetative by rhizomes and generative by seeds)
- Life cycle (perennial and annual)
- Growth characteristic (persistence and non-persistence)
- Salinity tolerance (high, moderate and low)
- Light demand (full sun, semi-shade and shade)
- pH conditions (Acidity and Alkalinity)

The first three factors have been discussed detailed in the Chapters 4.1 and 6.2.

The most emergent macrophytes are perennials; these plants are generally to be preferred to annual plants in constructed wetlands because they continue to grow in the same area for more than one year and there is no concern about seeds that could be washed or carried away.
Persistent species are generally to be preferred to non-persistent (or semi-persistent) plants because the standing biomass can provide shelter and thermal insulation during the winter season (Chapter 6.6). This factor is of high importance in cold/boreal and temperate climate zones (Thunhorst, 1993).

The last three factors (salinity tolerance, light demand and pH conditions) are plant- and site-specific factors not being discussed at this point. Data and tolerance ranges are provided in the corresponding table for the plant species (Chapters 8 - 11).

7.2 Availability in different climate zones

The climatic classification in this thesis is based on the Climate Classification System according to Koeppen (1900, 1936; e.g. in: Strahler, 1984) that is still in use today (see Appendix B: Koeppen's climate classification). However, this classification is very complex, and thus, a simplification was necessary.

Two of the most important factors that determine the climate in a certain area are air temperature and precipitation (rainfall). Other factors such as evapotranspiration, humidity, solar radiation (sunlight) or freezing are an indirect consequence of these two parameters (Benders-Hyde, 2005). The global climatic regions can be specified by the latitude ranges.

1. High-latitude climate: 50° - 70° N and S

- Cold/boreal climate

  - Northern Europe (Scandinavia)
  - Northern parts of North America (especially Canada)
  - Northern Asia (Siberia, partially arctic climate)

  Climate characteristic:
  - Long, very cold winters and short, cool summers
  - Very high annual temperature range
  - Small annual precipitation

2. Mid-latitude climate: 30° - 55° N and S (Europe: 45° - 60° N)

- Temperate climate

  - Central and Eastern Europe including Ukraine
  - North America (USA and Southern Canada)
  - Asia: Russia, North China, Korea, Japan
  - New Zealand and South Eastern Australia
    (More warm/temperate and oceanic climate)
  - Southern South America
    (More warm/temperate climate)
  - South Africa
    (Temperate to warm/Mediterranean climate)

  Climate characteristic:
  - Large seasonal changes between summer and winter
  - High annual temperature range
  - Abundant precipitation throughout the year

- Warm/Mediterranean climate (30° - 45° N and S)

  - Mediterranean region (Southern Europe and North Africa)
  - Eastern North America (California, USA)

  Climate characteristic:
  - Seasonal changes between hot dry summers and mild wet winters
  - Small annual temperature range (but frost danger during winter)
  - Small annual precipitation (occurs in winter season)

3. Low-latitude climate: 0° - 30° N and S

- Arid and hot climate (10° - 30° N and S)

  - North Africa (Sahara) and Arabia
  - Central Australia

Climate characteristic:
- Extremely dry and hot desert climate throughout the year
- Large diurnal temperature range
- Very small annual precipitation throughout the year

- Subtropical climate (10° - 30° N and S)

    - South Florida (USA)
    - South Asia (India, Sri Lanka, partially Nepal)
    - Southeast Asia (e.g. Burma, South China, Taiwan, Thailand)
    - Central and Southern Africa
    - Northern Australia (Queensland)

    Climate characteristic:
    - Seasonal changes between a very wet, hot and a dry, cooler period
    - High, tropical temperatures during the wet season
    - High precipitation during the wet season

- Tropical climate (10° S - 25° N)

    - Malay Archipelago (e.g. Indonesia, The Philippines, Malaysia)
    - Equatorial Africa (Congo basin)
    - Amazon basin (mainly Brazil)

    Climate characteristic:
    - No significant seasonal changes in temperature and precipitation
    - High, tropical temperatures throughout the year
    - High precipitation and humidity throughout the year

The availability of a certain plant species in a definite climate zone provides the basis for this thesis. The climate of a region determines which plant species can survive and grow in that region. It determines also the length of the growing season and dormant period. The plants are adapted to the local climate, soil conditions, but also the surrounding plant and animal communities.
As a result, local and native wetland plant species that are widely distributed in the given area should be selected for constructed wetlands. This may increase the likelihood of plant survival and also the acceptance by local officials. Exotic (introduced) species should be avoided as they are often difficult to control, especially when they are invasive or aggressive and crowd out species that are native to the local region (Kadlec and Knight, 1996; Thunhorst, 1993).

For example, species in the genera *Phragmites* and *Arundo* are highly invasive species and are declared as noxious weeds in South Western Australia where they are naturally absent, although they are suitable for constructed wetlands and would be able to grow in this region (Chambers, 1994a).

7.3 Pollutant removal capacity and tolerance ranges

- Direct pollutant removal capacity (nutrient assimilation and storage)
- Indirect pollutant removal capacity (enhancement of microbial transformations)
- Tolerance to high organic loadings (BOD, COD)
- Tolerance to eutrophic and hypereutrophic conditions (N, P)
  (In particular, elevated ammonium concentrations)
- Tolerance to toxic constituents (e.g. heavy metals and trace organics)
- Tolerance to strongly fluctuating pollutant concentrations

High pollutant removal capacities and tolerance ranges are basic requirements for the suitability of plant species in constructed treatment wetlands. A lot of plants that occur in natural wetlands have the potential for purification of waters. However, constructed wetlands receive a permanent wastewater inflow including high organic and nutrient concentrations. Plants that cannot tolerate these conditions will not survive.

7.4 Plant productivity and biomass utilization options

Beside the climatic availability and the pollutant removal capacity, this is the third selection criterion of this thesis. Many aquatic plants show a higher efficiency in usage of the solar energy for photosynthetic purposes than terrestrial plants. A high photosynthetic activity results in increased plant productivity, and thus, high biomass yields that could be harvested (Chapter 6.7). The potential utilization of the harvested biomass as an alternative resource base can, at least partially, offset the costs of the overall treatment system (Reddy and De Busk, 1987a; Wissing, 2002).

There are numerous options the harvested biomass can be utilized. The following list provides an overview about possible biomass utilizations options.

- Energy production (renewable fuel source):
  - Anaerobic digestion: biogas (mainly methane) production
  - Thermal conversion processes, esp. direct combustion (heating material)
    → Aquatic species show a high productivity and have energy contents (calorific values) often comparable to conventional fuel sources (e.g. coal or wood).
- Agricultural purposes:
  - Composting purposes and organic soil conditioner
  - Production of fertilizer
  - Soil amendment
- Use as forage plant:
  - Animal or cattle feed, livestock forage
    → Aquatic plants growing in nutrient-enriched wastewaters are often high in crude protein and digestible organic matter and serve as valuable animal feed.
- Industrial purposes and product developments:
  - Pulp and paper production
    → Some aquatic macrophytes can be a good source of pulp for paper due to the high fibre and cellulose content in their stems and leaves
  - Packing material
  - Construction purposes (building, insulation and thatching material, fibre boards)
  - Diverse handicrafts (weaving material, basketry, etc.)

- Other utilization options, e.g.:
  - Medicinal and pharmaceutical uses
  - Feedstock for chemicals

(Lakshman, 1987; Little, 1979; Stephenson, 1980; Wissing, 2002)

7.5 Cost comparison of plant seeds

At the beginning of this thesis, a forth criterion was considered as significant for the choice of plant species: costs of purchasing the plant propagules, primarily seeds and seedlings. However, extensive investigations and researches within the scope of this thesis have revealed that the cost differences of plant propagules between the different species are marginal, and thus, cannot be considered as a significant selection criterion. Subsequently, three examples are showed to prove this conclusion:

Table 7.1: Environmental Concern Inc., St. Michaels, Maryland, USA

Species	**Costs** (for one plug)
Iris versicolor	0.80 USD $
Juncus effusus	0.70 USD $
Scirpus cyperinus	0.70 USD $
Scirpus pungens	0.80 USD $
Scirpus validus	0.70 USD $
Typha angustifolia	0.70 USD $
Typha latifolia	0.70 USD $

Source: Environmental Concern Inc., 2006, Wholesale Price List (Environmental Concern, 2006; modified)

Table 7.2: Watergarden Paradise Aquatic Nursery, Sydney, NSW, Australia

Species	**Costs** (for one bare-root plant)
Baumea articulata	5.50 AUD $
Cyperus alternifolius	5.50 AUD $
Eleocharis sphacelata	5.50 AUD $
Juncus ingens	9.90 AUD $
Lepironia articulata	5.50 AUD $
Scirpus validus	5.50 AUD $
Typha domingensis	5.50 AUD $
Typha orientalis	5.50 AUD $

Source: Watergarden Paradise Aquatic Nursery**,** 2006 (Watergarden Paradise, 2006; modified)

Table 7.3: Koanga Gardens Ltd, Maungaturoto, New Zealand

Species	**Costs** (for < 100 seeds)
Baumea articulata	1.80 NZD $
Eleocharis sphacelata	2.00 NZD $
Juncus effusus	1.80 NZD $
Scirpus validus	1.60 NZD $
Typha orientalis	2.00 NZD $

Source: Koanga Gardens Ltd., Wetland Planting Guide, 2005 (Koanga Gardens, 2005; modified)

The examples depict that cost differences of plant propagules within a nursery are normally not existent of marginal. However, exceptions such as the species *Juncus ingens* in example two may be possible. Many other nurseries, especially in Australia and the USA, could be found in the Internet; this shows similar conclusions concerning the cost differences of the different wetland plants.

7.6 Summary: basic criteria for the choice of plant species

1. Availability in climate zone (Chapter 7.2)
2. Pollutant removal capacity and tolerance ranges (Chapter 7.3)
3. Plant productivity and biomass utilizations (Chapter 7.4)

The plant species presented in the Chapters 8 - 11 were selected and investigated according to these three criteria. Plant-specific properties and adaptabilities (Chapter 7.1) were not taken into account as actual criteria as they are prerequisites making the use of these plants for wastewater treatment in constructed wetlands possible.

7.7 Division of the selected plant species

The plants selected for this thesis are divided into four different groups. The first one (Chapter 8) includes species that are cosmopolitan or widely distributed throughout the world. The two species most commonly used in constructed wetlands worldwide belong to this group: common reed (*Phragmites australis*) and broad-leaved cattail (*Typha latifolia*).
The second group (Chapter 9) includes species that were considered as standard plants for constructed wetlands typically and commonly used in high-latitude (cold/boreal) and mid-latitude (temperate) climates worldwide. The two climate areas could be summarized in one chapter since many plants growing in temperate regions are also naturally distributed in cold/boreal climates due to their good cold tolerance. However, subtropical and tropical species are usually not or only slightly frost tolerant. Thus, these plants were listed in the third group (Chapter 10) consisting of standard plants for low-latitude climates.
Eventually, this thesis presents species that were considered as possible alternatives also suitable for use in constructed wetlands (Chapter 11). In the most cases, their suitability was proved in only a few experimental or small-scale studies that showed good and promising results. It should be considered that these species are often widely distributed and show high productivities, e.g. *Lolium perenne* or *Pennisetum purpureum*, however, their application in constructed treatment wetlands is relatively new and unconventional.

In order to get a faster access to a definite plant species they are arranged in alphabetical order within their group.

8 Cosmopolitan and widely distributed standard plants

8.1 Plant species recommended for constructed wetlands

- *Juncus effusus* (soft rush)
- *Phragmites australis* (common reed)
- *Scirpus lacustris* (common bulrush)
- *Scirpus maritimus* (alkali bulrush)
- *Typha angustifolia* (narrow-leaved cattail)
- *Typha domingensis* (southern cattail)
- *Typha latifolia* (broad-leaved cattail)

8.2 *Juncus effusus* (soft rush)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: Europe and North America

1. Plant species	
Common name	Soft rush, common rush
Scientific name (genus / species)	*Juncus effusus*
Family	*Juncaceae*
2. Availability in climate zone	
Climatic range	Cold/boreal to temperate, but also subtropical
Geographic range	Native to Europe and North America; distributed throughout the cold and temperate zones of both hemispheres, but also East and South Africa, and Australasia (Wendelberger, 1986; PFAF, 2004)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous (Thunhorst, 1993), grows in clumps or tussocks (Floridata, 2006), persistent and green year-round in warm/temperate climates with mild winters (Tanner, 1996).
Growth height	Up to 1.5 m (PFAF, 2004)
Growth rate and period	Slow to moderate (Thunhorst, 1993; USDA-NRCS, 2006)
Reproduction	Vegetative and generative
Root and rhizome growth and development	Dense and fibrous root system with short, finely divided rhizomes (USDA-NRCS, 2002).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater to brackish marshes, swamp, wet meadows, lake and river margins (Floridata, 2006; USDA-NRCS, 2002)
Light demand, shade tolerance	Full sun (Thunhorst, 1993) to semi-shade (PFAF, 2004)
pH optimum and tolerances	Prefers acidic conditions (Wendelberger, 1986), according to USDA-NRCS (2002): 4.0 - 6.0
Salinity tolerance	Moderate to high, according to USDA-NRCS (2002): up to 14 ppt
Habitat dominance	The competitiveness of *Juncus effusus* is relatively low: according to a study conducted by Coleman (2001), this species showed, planted together with *Typha latifolia* and *Scirpus validus*, a significantly poorer growth rate than as single plant in monospecific stands.
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated regularly to permanently up to 0.3 m (Thunhorst, 1993), withstands drought periods (Tanner, 1997); generally shows a high tolerance to wet or dry conditions (Schueler, 1992). According to Tanner (1997) a water depth of 0.1 m can be tolerated in constructed wetlands treating dairy farm wastewaters.
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	

General aspects	*Juncus effusus* is, among other species, typically used in the second stage (horizontal flow bed) in the Krefeld Process and Haider/Rausch Process (Haider, 1987; Seidel, 1966). *Juncus effusus* shows a low competitiveness in mixed plantings with other wetland species, e.g. *Phragmites australis* or *Typha sp.*, in constructed wetlands and a relatively low stature and productivity: → More suitable for stabilizing of wetland margins and embankments (Tanner, 1997) and specific applications such as small systems serving single houses or hotels (Tanner, 1996).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Although this species usually is not used as the main species in constructed wetlands, the removal efficiency was proved in several studies. In an experimental study conducted by Coleman (2001) for treatment of primary wastewaters (BOD mean influent conc.: 137.2 mg/L), the removal rate amounted to > 65 %. Removal efficiency of *Juncus effusus* planted in a small-scale gravel bed for treatment of dairy farm wastewater according to a study conducted by Tanner (1996) in New Zealand under warm/temperate conditions: BOD reduction: > 77 % (mean BOD influent conc.: 87.6 mg/L) TSS reduction: > 76 % (mean TSS influent conc.: 95.7 mg/L)
Nitrogen and phosphorus compounds: evaluation of existing case studies	Capable of growing in ammonium-enriched organic wastewaters, e.g. dairy or animal wastewaters (Tanner, 1996). Inhibited and reduced growth rate at ammonium concentrations of above 200 mg/L after a period of weeks. However, shorter periods of evaluated ammonium conc. did not appear to affect growth. → High ammonium tolerance (Clarke, 2002) In an experimental study conducted by Wolverton (1983), *Juncus effusus* was proved to be very effective in removal of ammonium with results comparable to *Typha latifolia* (the same study): removal rate: 93 % (influent conc.: 16.7 mg/L NH_4^+-N).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Relatively low productive species (Tanner, 1996)
Biomass production, growth rates and yields	Range of annual biomass production found by Vymazal (1995b; in: IWA, 2000) for *Juncus sp.* in general: 7.96 - 53.3 t/(ha*yr) dry wt
Biomass utilization options	Stems (PFAF, 2004): - can be used for basket making and as weaving material, - building material (thatching), - the fibres can be used for paper making.
8. Nutrients: uptake and storage capacities	
General aspects	Generally, *Juncus effusus* shows relatively high aboveground tissue nutrient concentrations. However, due to the low biomass production and productivity, the total nutrient uptake capacities are low (Tanner, 1996).
Nitrogen: uptake and assimilation rates	Harvestable nitrogen uptake capacity (growth rate) for *Juncus sp.* in general: 800 kg/(ha*yr), (Vymazal, 1995b; in: IWA, 2000)
Phosphorus: uptake and assimilation rates	Harvestable phosphorus uptake capacity (growth rate) for *Juncus sp.* in general: 110 kg/(ha*yr), (Vymazal, 1995b; in: IWA, 2000)
9. Further remarks and comparisons with other plant species (if possible)	- Tolerates strong winds (PFAF, 2004), - robust and stress-tolerant species (Tanner, 1996), - high tolerance to low pH and elevated metal concentrations (USDA-NRCS, 2002).

8.3 *Phragmites australis* (common reed)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: Europe, North America and Asia (also Russian Arctic)
- Temperate climate zones of: Europe, North America and South Africa, China and Japan
- Warm/Mediterranean climate zones of: North Africa (coastal regions, e.g. Morocco)

1. Plant species	
Common name	Common reed (grass)
Scientific name (genus / species)	*Phragmites australis*, syn.: *Phragmites communis*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Nearly cosmopolitan, apart from polar climates (up to 70 °N), less common in tropical areas
Geographic range	Nearly cosmopolitan: native to Eurasia and Africa, not in polar/arctic regions, Iceland and some certain tropical areas (Amazon basin, Indonesia)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent in temperate and warmer climates (Kadlec and Knight, 1996; Thunhorst, 1993)
Growth height	Up to 4 m, occasionally up to 6 m (NewCROP, 2005)
Growth rate and period	Rapid, if once established (Thunhorst, 1993), shows often a strong dieback and seasonal senescence of aboveground plant parts during winter in temperate climates (Adcock, 1994; Surrency, 1993).
Reproduction	Vigorously vegetative reproduction by an extensive root system, low generative reproduction rate.
Root and rhizome growth and development	Extensive, strongly branched, vertically and horizontally growing root and rhizome system; deep penetration into the soil: up to 1.5 m possible (Bahlo, 1995). However, in gravel reed bed systems the rooting depth is mostly shallower: ≈ 0.6 m (Gersberg, 1986), > 90 % of belowground biomass in the upper 0.25 m of the soil layer (Adcock, 1994), > 70 % in the upper 0.2 m of the soil layer (Parr, 1990).
4. Habitat conditions and behaviour	
Natural Habitat	Brackish to freshwater marshes and swamps, lake and ponds margins and wet wastelands (ISSG, 2005; Thunhorst, 1993)
Light demand, shade tolerance	Semi-shade to full sun (Ellenberg, 1991)
pH optimum and tolerances	Tolerates highly acidic, but also alkaline conditions: pH tolerance range according to Reed (1995): 2.0 - 8.5, pH tolerance range according to Schueler (1992): 3.7 - 8.0
Salinity tolerance	High, up to 20 ppt (brackish waters), tolerates maritime exposure (PFAF, 2004; Thunhorst, 1993), Reed (1995) reported a pH tolerance of up to 45 ppt.
Habitat dominance	Highly invasive and dominant species, aggressive colonizer, typically forms dense monospecific stands (EPA, 2000a; ISSG, 2005).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated seasonally and permanently from 0.6 m (Thunhorst, 1993) up to 1 m (Reed, 1995), tolerates longer drought periods, high drought resistance; withstands also largely fluctuating water levels (Reed, 1995).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Common reed *(Phragmites australis)* is the most commonly used plant species for constructed wetlands worldwide and is the dominating wetland plant in Europe (Kadlec and Knight, 1996). Due to the deep root and rhizome system, *Phragmites australis* is the preferred plant species in CWs with vertical flow (Cooper, 1996). *Phragmites australis* is also the most commonly used wetland plant for constructed wetlands in Japan (Nakamaura, 2002) and is also used in China (Yan, 1994). Further, *Phragmites australis* is also a commonly used wetland plant species in warm/temperate South Africa (Batchelor, 1990).

Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Tolerant to high organic loadings; however, an increased organic matter content in the soil due to eutrophication can be an important stress factor for the root system leading to diminished oxygen transport rates, and thus, reduction of *Phragmites* stands (Armstrong, 1996). The high treatment efficiency of *Phragmites australis* was proved in numerous investigations and studies in temperate Europe, e.g. Denmark (Schierup, 1990), the Czech Republic (Vymazal 1995a, 2001b) and Austria (Haberl, 1998), but also in cold/boreal Europe, e.g. Estonia (Mander, 1997), Norway (Jenssen, 1993; Maehlum, 1995, 1999) and Sweden (Sundblad, 1998). A study conducted by Mandi (1998) in Morocco (≈ 31 °N) for treatment of domestic raw wastewater showed that *Phragmites australis* is also well-suitable in CWs for arid/Mediterranean climates. The BOD and TSS removal efficiencies of a pilot multistage constructed wetland system near Murmansk in the Russian Arctic (sub-arctic climate, ≈ 68 °N) planted with *Typha latifolia*, *Carex aquatilis* and *Phragmites australis* were more than 81 % (Vasilevskaya, 2004).
Nitrogen and phosphorus compounds: evaluation of existing case studies	Normally tolerant to eutrophic conditions, nitrophil. However, prolonged hypereutrophic (highly eutrophic) conditions can lead to a dieback of *Phragmites australis* stands due to extremely anaerobic conditions (insufficient detoxification capacity of the rhizosphere), (Hofmann, 1992).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Compared to the three other wetland species (*Typha latifolia*, *Glyceria maxima*, *Iris pseudacorus*), *Phragmites australis* showed the highest oxygen releases from roots into the rhizosphere (Brix, 1990; Fruergaard, 1987).
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species, strongly responding to nutrient supply.
Biomass production, growth rates and yields	- Range of annual biomass production in warm/temperate climates: 40 - 63 t/(ha*yr) dry wt (NewCROP, 2005), - range of annual biomass production found by Vymazal (1995b; in: IWA, 2000): 1.83 - 60 t/(ha*yr) dry wt (wide range, depending on nutrient supply, site and climate), - aboveground biomass yield according to Tanner (1996) in New Zealand (warm/temperate climate): 18 t/ha (dry wt). According to a field study by Ennabili (1998) in Northwest Morocco (warm/Mediterranean climate, ≈ 35 °N), *Phragmites australis* showed, together with *Typha angustifolia,* the highest aboveground biomass yields amounting to 23.0 t/ha dry wt.
Biomass utilization options	*Phragmites australis* shows highly versatile utilization options: - building material (fencing, thatching, roof materials), - the leaves can be used as weaving material, e.g. for bags, baskets, mats, etc., - fuel source (direct combustion) due to the high energy content: caloric value: 20,930 - 27,214 kJ/kg (in: Wissing, 2002), comparable to conventional fuel sources, - stems: raw material for paper making and textile industry due to the high cellulose content of 50 % and more, - according to Chivu (1968; in: Little, 1979), *Phragmites* australis can provide a high-quality pulp used for paper making, - only the young and growing plants can serve as forage for cattle and horses, after maturity common reed becomes unpalatable, - agricultural purposes, e.g. fertilizer production. (Hurter, 1988; Little, 1979; NewCROP, 2005; USDA-FS, 2006)
8. Nutrients: uptake and storage capacities	
General aspects	Several studies showed that *Phragmites australis* is efficient in nitrogen uptake and storage, but has relatively low phosphorus uptake capacities due to the generally low phosphorus content in the tissues (Burgoon, 1991b; Greenway, 1999; Tanner, 1996).
Nitrogen: uptake and assimilation rates	Uptake capacity in a temperate climate: 2,313 kg/(ha*yr), (Rogers 1985; in Wood, 1995)

	→ Significantly higher compared to *Cyperus papyrus* (1,220 kg/ha*yr) and *Typha latifolia* (1,164 kg/ha*yr). Harvestable range of nitrogen uptake capacity (growth rate): 750 - 2,450 kg/(ha*yr) (Vymazal, 1995b; in: IWA, 2000).
Phosphorus: uptake and assimilation rates	Uptake capacity in a temperate climate: 162 kg/(ha*yr), (Rogers 1985; in Wood, 1995) → Similar to *Typha latifolia* (179 kg/ha*yr), much higher than *Cyperus papyrus* (80 kg/ha*yr). Harvestable range of phosphorus uptake capacity (growth rate): 25 - 199 kg/(ha*yr) (Vymazal, 1995b; in: IWA, 2000).
9. Further remarks and comparisons with other plant species (if possible)	- High frost tolerance (PFAF, 2004), - very robust species, - high tolerance to diverse environmental conditions, e.g. droughts, fluctuating water levels or salinity, - high tolerance to elevated boron concentrations (Bergmann, 1995; see Chapter 5.4.4), - due to the deeply growing root and rhizome system *Phragmites australis* is the most commonly used emergent plant for sludge dewatering systems in Europe (Wissing, 2002), - the use of *Phragmites australis* in constructed wetlands should be avoided where it is not native, e.g. in New Zealand, Australia and some parts of the USA due to its invasive character (Tanner, 1996), - despite the high productivity and competitiveness: often relatively poor establishment and initial growth in CWs (Parr, 1990), - low food value: not subjected to damages by some mammal species possibly occuring in CWs (Reed, 1995), - one of the most sensitive species to harvest in summer and autumn (can cause severe damages to established reed stands): harvesting should only be done in the dormant period (Vymazal, 2001b).

8.4 *Scirpus lacustris* (common bulrush)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: Europe and South Africa

1. Plant species	
Common name	Common bulrush
Scientific name (genus / species)	*Scirpus lacustris*, syn.: *Schoenoplectus lacustris*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Nearly cosmopolitan: cold/boreal to (sub)tropical
Geographic range	Nearly cosmopolitan: Europe, Africa, Asia, North and Central America, Polynesia (PFAF, 2004)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial, persistent during winter season, the stems decay in the beginning of the next growing season (Wissing, 2002).
Growth height	Up to 2.5 - 3 m (Wendelberger, 1986)
Growth rate and period	Moderate to fast, rapid establishment (Batchelor, 1990)
Reproduction	Mainly vegetative, low generative reproduction rate
Root and rhizome growth and development	Shallow, dense root and rhizome system that extends near the surface (Wissing, 2002).
4. Habitat conditions and behaviour	
Natural Habitat	Shallow waters, pond margins, rivers and lakes (PFAF, 2004)
Light demand, shade tolerance	Full sun, but tolerates semi-shade (Ellenberg, 1991)
pH optimum and tolerances	Prefers slightly acid to slightly alkaline soils (Ellenberg, 1991)
Salinity tolerance	Low (freshwater species), < 1 ppt (Ellenberg, 1991)
Habitat dominance	Often dominant (Ellenberg, 1991)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated permanently up to 0.3 - 0.4 m and is sensitive to prolonged drought periods (de Jong, 1982), tolerant to

	strongly fluctuating water levels and temporarily inundations up to 0.8 m without a reduced biomass production (Coops, 1996).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	*Scirpus lacustris* is, among other species, typically used in the second stage (horizontal flow bed) in the Krefeld Process and Haider/Rausch Process (Haider, 1987; Seidel, 1966). Beside the use in Europe, especially in the German-speaking countries, e.g. Germany (Börner, 1998) and Austria (Haberl, 1998), *Scirpus lacustris* is also commonly used in the temperate climate of South Africa where it naturally occurs (Batchelor, 1990). *Scirpus lacustris* shows a high adaptability to various wastewater conditions (Seidel, 1966; Wissing, 2002).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Tolerant to organic loadings up to about 3,000 mg/L COD (Wissing, 2002). The treatment efficiency of *Scirpus lacustris* was proved in many studies, e.g. by Wood (1989) in South Africa who found a COD removal rate of > 93 % (COD influent conc.: 332 mg/L, temperate climate).
Nitrogen and phosphorus compounds: evaluation of existing case studies	Nitrophil, tolerant to high nutrient loadings (Wissing, 2002).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	The study conducted by Wood (1989) found an ammonia removal efficiency of 96 % for an influent conc. of 20.7 mg/L NH_4^+-N. It was concluded that *Scirpus lacustris* appears to have a well-developed root zone oxygenation capacity.
7. Productivity, utilization options and economic potential	
Potential productivity	Productive species with a high economical value
Biomass production, growth rates and yields	Range of annual biomass production found by Vymazal (1995b; in: IWA, 2000) for *Scirpus sp.* in general: 7.85 - 46 t/(ha*yr) dry wt
Biomass utilization options	Stems: - can be used as weaving material (mats, chair bottoms, etc.), - building material (thatching), - paper making (PFAF, 2004), - packing material (Aichele, 1981). - Energy source (fuel) for direct combustion (Wissing, 2002), - agricultural purposes: was proved to be a good source for composting (Aichele, 1981), - can also be used as forage plant (Wissing, 2002).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No sufficient data available
Phosphorus: uptake and assimilation rates	No sufficient data available
9. Further remarks and comparisons with other plant species (if possible)	- Frost tolerant species (up to - 25 °C), (PFAF, 2004), - according to Wood (1989), strong wind and heavy rainfall can cause damages to the stems due to their low weight, and thus, relatively low stability, - according to Seidel (1967), capable to metabolize complex compounds such as phenols and cyanides without apparent damages: phenol was decomposed into CO_2 by 80 % at a concentration of 900 mg/L; the cyanides (conc.: 200 mg/l) were decomposed nearly completely within 14 d (> 99 %), - very closely related to the soft stem bulrush *(Scirpus validus).*

8.5 *Scirpus maritimus* (alkali bulrush)

Suitable and recommended for constructed wetlands in:
- Temperate climate zone of: North America
- Warm/Mediterranean climate zones of: Southern Europe and North Africa (coastal regions)

1. Plant species	
Common name	Alkali bulrush, maritime bulrush, sea bulrush
Scientific name (genus / species)	*Scirpus maritimus*, syn.: *Bolboschoenus maritimus*, *Schoeneplectus maritimus*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Nearly cosmopolitan, but apart from polar climates
Geographic range	Nearly cosmopolitan, but apart from the Artic region; mainly in the Northern Hemisphere from cold/boreal to warm regions, e.g. North America, Mexico and the Mediterranean region (Browning, 1995; PFAF, 2004)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous (Hoag, 1998b)
Growth height	Up to 1.5 m (Hoag, 1998b)
Growth rate and period	Rapid growth under favourable environmental conditions, responds fairly strong to nutrient supply, but not as strong as other common wetland species such as *Phragmites australis, Glyceria maxima* or *Typha sp.* (Dykyjova, 1986).
Reproduction	Mainly vegetative, but also low generative reproduction rate (Hoag, 1998b)
Root and rhizome growth and development	Extensive root and system (Hoag, 1998b); maximum depth: 0.6 m, the belowground root and rhizome biomass is mainly located in the upper 0.2 m of the soil layer (Fiala, 1968).
4. Habitat conditions and behaviour	
Natural Habitat	Along seashores, salt and brackish marshes, pond margins, shallow waters of tidal rivers (PFAF, 2004)
Light demand, shade tolerance	Full sun (PFAF, 2004)
pH optimum and tolerances	Tolerates alkaline conditions up to pH 9.0 (Hoag, 1998b); pH range according to Karagatzides (1991): 5.2 - 8.9
Salinity tolerance	Moderate tolerance to saline conditions (Hoag, 1998b)
Habitat dominance	Can form dense monospecific vegetation stands (Hoag, 1998b).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Tolerates temporarily inundations up to 1 m as well as drought periods (Hoag, 1998b).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	According to the study conducted by Ennabili (1998) in Northwest Morocco, *Scirpus maritimus* is potentially a well-suitable species for use in constructed wetlands for wastewater treatment, especially in the Mediterranean region (South Europe and North Africa). Although this species is said to be well-suitable for use in constructed treatment wetlands (Ennabili, 1998; Hoag, 1998b; Mandel, 1992), no appropriate investigation that proved the effectiveness of *Scirpus maritimus* was available for this thesis.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	No appropriate study available
Nitrogen and phosphorus compounds: evaluation of existing case studies	No appropriate study available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Potentially a productive species under nutrient-enriched and favourable conditions (Dykyjova, 1986)

Biomass production, growth rates and yields	No appropriate data available
Biomass utilization options	- The leaves can serve as raw material for weaving and basket making (PFAF, 2004), - raw material for paper making (Zafar, 1976).
8. Nutrients: uptake and storage capacities	
General aspects	Generally, *Scirpus maritimus* shows lower nutrient uptake capacities than many other species commonly used in CWs such as *Phragmites australis, Glyceria maxima* and *Typha sp.* (Dykyjova 1986). This was also observed in the study by Ennabili (1998) where *Scirpus maritimus* showed, in contrast to *Typha angustifolia* and *Phragmites australis*, relatively low aboveground biomass yields as well as low nutrient uptake and storage rates in the polluted wetland.
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Similar to *Scirpus lacustris, Scirpus maritimus* was proved to remove phenols from industrial wastewaters (Zafar, 1976), - according to Seidel (1971), *Scirpus maritimus* was, similar to *Scirpus lacustris*, very effective in removal of fecal pathogens from sewage effluents.

8.6 *Typha angustifolia* (narrow-leaved cattail)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: Europe and North America
- Warm/Mediterranean climate zones of: Southern Europe and North Africa
- Subtropical climate zone of: Central America
- Subtropical and tropical climate zones of: Southeast Asia

1. Plant species	
Common name	Narrow-leaved cattail
Scientific name (genus / species)	*Typha angustifolia*
Family	*Typhaceae*
2. Availability in climate zone	
Climatic range	Temperate to tropical
Geographic range	Native to North America (USA) and Central America (Mexico), Europe, North Africa (e.g. Morocco) and Southeast Asia (e.g. Indonesia, Malaysia, The Philippines, Thailand); does not extend so far as north to cold/boreal climates as *Typha latifolia*.
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent (Thunhorst, 1993)
Growth height	Up to 3 m (Sim, 2003)
Growth rate and period	Very fast (Thunhorst, 1993) with a rapid establishment (similar to *Typha latifolia*)
Reproduction	Spreads rapidly through vegetative reproduction, but also readily through generative reproduction (similar to *Typha latifolia).*
Root and rhizome growth and development	Relatively shallow root penetration, up to 0.3 m into the depth in gravel-bed systems (similar to *Typha latifolia*), (Reed, 1995).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater and brackish salt marshes, pond edges, disturbed wetlands (TNC, 2005; Thunhorst, 1993), can grow in deeper waters than *Typha latifolia* (TNC, 2005).
Light demand, shade tolerance	Full sun (Thunhorst, 1993)
pH optimum and tolerances	pH tolerance range according to Schueler (1992): 3.7 - 8.5, pH tolerance range according to Reed (1995): 4 - 10
Salinity tolerance	High, up to 15 ppt (tolerates brackish waters), (Thunhorst, 1993) → Higher salinity tolerance compared to *Typha latifolia.*
Habitat dominance	Highly invasive and dominant species, aggressive colonizer, commonly forms dense monoculture stands (similar to *Typha latifolia*).

5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated irregularly to permanently up to 0.3 m (Thunhorst, 1993), tolerates fluctuating water levels, but also short drought periods (USDA-NRCS, 2006).
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	Typical plant species for surface flow as well as subsurface wetlands in the USA (Brown, 1994; Reed, 1995). The suitability of this species for CWs in subtropical and tropical Southeast Asia was proved in several studies, particularly in Thailand (Kantawanichkul 2003b; Klomjek, 2005; Koottatep, 1997, 2005), but also in Malaysia (Sim, 2003).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Tolerant to high organic loadings (similar to *Typha latifolia).* In an investigation conducted by Kantawanichkul (2003b) in Thailand where *Typha angustifolia* was planted in a combined wetland system (first stage: horizontal subsurface flow CW, second stage: vertical flow CW), the following results were achieved: - COD removal: 94 - 98 % (influent conc.: ≈ 680 mg/L; corresponds to high strength municipal wastewater). → High efficiency, however, plants grew better in the horizontal flow bed due to the higher water level and moisture content (*Typha sp.* show generally a relatively low drought tolerance).
Nitrogen and phosphorus compounds: evaluation of existing case studies	High tolerance to eutrophic conditions (similar to *Typha latifolia).* Nitrogen removal performance according to the investigation by Kantawanichkul (2003b): - TKN removal: 79 - 98 % (influent conc.: ≈ 230 mg/L, much higher compared to municipal wastewater) → High efficiency, mainly due to microbial transformations. However, plant growth near the inlet zone of the horizontal bed was retarded due to the high ammonia concentrations.
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Can be supposed to be similar to *Typha latifolia*
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species (similar to the other types of *Typha sp.*), high potential as a renewable biomass source.
Biomass production, growth rates and yields	According to the field study conducted by Ennabili (1998) in Northwest Morocco (Mediterranean climate, ≈ 35 °N), *Typha angustifolia* showed together with *Phragmites australis* the highest aboveground biomass yields amounting to 21.6 t/ha (dry wt). Range of harvestable (aboveground) biomass yield (standing stock) found by Koottatep (2005) in the tropical climate of Thailand: 30 - 54 t/ha (dry wt). (In this study *Typha angustifolia* was planted in a vertical flow CW receiving medium to high strength septage effluents).
Biomass utilization options	Highly versatile utilization options (similar to the other types of *Typha sp.* (see *Typha latifolia* in Chapter 8.8): Stems and leaves: - can be used as weaving material, e.g. mats, baskets, etc., - building material (thatching, roof materials), - paper making, - additional material for composting purposes. High potential as a renewable biomass source (similar to *Typha latifolia*), e.g.: - fuel source (direct combustion) due to the high energy content comparable to conventional fuel sources.
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	Harvestable nitrogen uptake capacity according to the study of

	Ennabili (1998) in Northwest Morocco: 420 kg/ha
Phosphorus: uptake and assimilation rates	Harvestable phosphorus uptake capacity according to the study of Ennabili (1998) in Northwest Morocco: 36.7 kg/ha
9. Further remarks and comparisons with other plant species (if possible)	- Very closely related to *Typha domingensis,* - capable of forming floating mats of rhizomes, roots and accumulating plant litter on shallow open water sites (IWA, 2000), - high tolerance to certain heavy metals, esp. lead, zinc and copper (similar to *Typha latifolia*).

8.7 *Typha domingensis* (southern cattail)

Suitable and recommended for constructed wetlands in:
- Warm/Mediterranean climate zones of: Southern Europe
- Warm and subtropical climate zones of: Southern North America and Central America
- Subtropical climate zones of: North-Eastern Australia

1. Plant species	
Common name	Southern cattail, (in Australia: narrow-leaved cumbungi)
Scientific name (genus / species)	*Typha domingensis*, syn.: *Typha angustata*
Family	*Typhaceae*
2. Availability in climate zone	
Climatic range	Warm/temperate to tropical
Geographic range	Nearly cosmopolitan in the warm and tropical regions worldwide (Smith, 1987): Southern Europe (Mediterranean region), Asia (especially India), Southern North America to South America, Central America and Caribbean region, north-eastern parts of Australia (Queensland and the Northern Territory) (Gopal, 1982; Moerkerk, 2001; PFAF, 2004; TNC, 2005)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent, year-round growth in warm and subtropical climates without severe and prolonged winter seasons (Gopal, 1982).
Growth height	Up to 3 (PFAF, 2004) - 4 m (Stevens, 2000b)
Growth rate and period	Very fast, rapid establishment (similar to *Typha latifolia*)
Reproduction	Spreads rapidly by vegetative reproduction, but also readily generative reproduction (similar to *Typha latifolia).*
Root and rhizome growth and development	Shallow root penetration (up to 0.3 m), close to the ground surface (Gopal, 1982)
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater to brackish and nutrient-enriched marshes, pond margins and shallow water sites, coastal marshes (PFAF, 2004; Stevens, 2000b)
Light demand, shade tolerance	Full sun (similar to *Typha latifolia*)
pH optimum and tolerances	No data found, presumably similar to *Typha latifolia*
Salinity tolerance	High, greater than *Typha latifolia;* according to CAPRT (2004) higher than *Typha angustifolia*; can be found more in saline habitats than *Typha latifolia* (TNC, 2005).
Habitat dominance	Highly invasive and dominant species, aggressive colonizer, commonly forms dense monoculture stands (PFAF, 2004).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated irregularly to permanently; according to Kadlec and Knight (1996) up to 0.75 m. Tolerates temporarily inundations up to 1 m, but sensitive to droughts of a few weeks, (Gopal, 1982).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	*Typha domingensis* was used in divers constructed wetland systems in the Mediterranean region, e.g. Turkey (Kücük, 2003) for treatment of tannery effluents, Crete (Manios, 2002) for treatment of domestic wastewater and Spain (Cerezo, 2001).
Organic constituents (BOD and COD) and sus-	In the study conducted by Cerezo (2001) in Mojacar, Almeria,

pended solids (TSS): evaluation of existing case studies	Southeast Spain (semi-arid/Mediterranean climate), *Typha domingensis* was planted, together with *Phragmites australis*, in a multistage horizontal subsurface low wetland and tested under different HRTs, hydraulic loadings and area sizes: → High removal efficiencies: TSS: 90 - 96 %; COD: 78 - 87 %; BOD: ≈ 90 % (influent: pre-treated wastewater from an anaerobic stabilization pond)
Nitrogen and phosphorus compounds: evaluation of existing case studies	No sufficient data available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Can be supposed to be similar to *Typha latifolia.*
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species, high potential as a renewable biomass source (similar to the other types of *Typha sp.*)
Biomass production, growth rates and yields	Harvestable (aboveground) biomass production according to Greenway (2001) in a constructed wetland for polishing of secondary treated municipal effluent in Queensland, Australia under subtropical conditions: 22.64 t/(ha*yr). Mean aboveground biomass yields of *Typha domingensis* growing in secondary lagoon effluent in Okeechobee, Florida, USA (subtropical climate, ≈ 27.2 °N): - 20 t/ha under nutrient-enriched conditions, - 9 t/ha without nutrient additions (control effluent) (De Busk, 1995)
Biomass utilization options	Biomass utilization options are as versatile and similar as the other types of *Typha sp.* (see *Typha latifolia* in Chapter 8.8): - High potential as a biomass source for renewable energy, e.g. source of fuel (direct combustion). Stems and leaves: - can serve as raw material for thatching, paper making, weaving, basket making, addition for composting purposes and insulation material
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	Harvestable uptake capacity in low-loaded secondary wastewater: 306 kg/(ha*yr), (Greenway, 2001)
Phosphorus: uptake and assimilation rates	Harvestable uptake capacity in low-loaded secondary wastewater: 87.2 kg/(ha*yr), (Greenway, 2001)
9. Further remarks and comparisons with other plant species (if possible)	- Closely related to *Typha latifolia,* and especially *Typha angustifolia,* - wider range of geographic distribution than *Typha orientalis,* - not in cold/boreal climates compared to *Typha latifolia,* - capable of forming floating mats of rhizomes, roots and accumulating plant litter on shallow open water sites (IWA, 2000), - like the other types of *Typha sp.*, high tolerance to certain heavy metals, esp. lead, zinc, copper (Wissing, 2002).

8.8 *Typha latifolia* (broad-leaved cattail)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: Europe, North America and Asia (also Russian Arctic)
- Temperate climate zones of: Europe and North America

1. Plant species	
Common name	Broad-leaved cattail, common cattail
Scientific name (genus / species)	*Typha latifolia*
Family	*Typhaceae*
2. Availability in climate zone	
Climatic range	Nearly cosmopolitan, cold/boreal to (sub)tropical

Geographic range	Nearly cosmopolitan: from the Arctic to latitude 30° S (Europe and West Asia, North America, Central America, North Africa, New Zealand, Australia and Japan), (PFAF, 2004; Rook, 2004)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent (Thunhorst, 1993)
Growth height	2.5 - 3 m (PFAF, 2004)
Growth rate and period	Very fast and rapid establishment (Thunhorst, 1993), can produce dense vegetation stands within three months after planting (EPA, 1988), shows markedly aboveground senescence in autumn (Chambers, 1994a).
Reproduction	Rapidly spreading by vegetative reproduction, but also readily generative reproduction (highly invasive species), (ISSG, 2005).
Root and rhizome growth and development	Extensive horizontal rhizome system and shallow depth penetration, root biomass largely confined to the upper 0.3 m of the soil layer (Gersberg, 1986).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater wetlands, lake and pond margins and wet ditches, generally: shallow water sites, prefers soils rich in organic matter (Rook, 2004).
Light demand, shade tolerance	Full sun (Thunhorst, 1993; Ellenberg, 1991)
pH optimum and tolerances	pH tolerance range according to Reed (1995): 4 - 10, pH tolerance range according to Schueler (1992): 3.5 - 8.0
Salinity tolerance	Low (freshwater species), < 0.5 ppt (Thunhorst, 1993)
Habitat dominance	Highly invasive and dominant species, aggressive colonizer, commonly forms dense monoculture stands (ISSG, 2005).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated irregularly to permanently up to 0.3 m (Thunhorst, 1993), tolerates only short drought periods (Floridata, 2006), temporarily inundations up to 1 m can be tolerated according to Reed (1995).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Typical plant species for surface flow as well as subsurface wetlands in the USA (Brown, 1994; Reed, 1995) and for gravel bed treatment systems in Canada (Lakshman, 1994) Typically used in the horizontal flow stage of the Krefeld Process or Haider/Rausch Process, not recommended in vertical flow wetlands due to the shallow root system.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Tolerant to high organic loadings (Brändle, 1996), shows a good performance in cold/boreal climates. Mean BOD removal efficiency of a vertical flow wetland in Estonia (cold/boreal climate, ≈ 58 °N): 82 % (influent conc.: 27 - 460 mg/L BOD, domestic wastewater), (Mander, 1997). The BOD and TSS removal efficiencies of a pilot multistage constructed wetland system near Murmansk in the Russian Arctic (sub-arctic climate, ≈ 68 °N) planted with *Typha latifolia*, *Carex aquatilis* and *Phragmites australis* were more than 81 % (Vasilevskaya, 2004). The BOD treatment performance of several multistage systems in Norway (cold/boreal climate, ≈ 60 °N) planted with *Typha latifolia* amounts up to > 80 % (BOD influent conc.: about 200 mg/L), (Jenssen, 1993; Maehlum 1995, 1999).
Nitrogen and phosphorus compounds: evaluation of existing case studies	High tolerance to eutrophic conditions (Brändle, 1996). Inhibited and reduced growth rate at ammonium concentrations of 200 mg/L and higher after a period of weeks, however, shorter periods of evaluated ammonium conc. did not appear to affect growth. → High ammonium tolerance (Clarke, 2002) The same study showed that flooded conditions (0.1 m) did not significantly increase ammonium toxicity to *Typha latifolia* compared to non-flooded conditions.

	Another study according to Surrency (1993) reported an inhibited growth at 160 - 170 mg/L ammonium concentrations.
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Compared to the three other wetland species (*Phragmites australis, Glyceria maxima, Iris pseudacorus*), *Typha latifolia* showed the lowest oxygen releases from roots into the rhizosphere (Brix, 1990; Fruergaard, 1987). However, from this laboratory study cannot be judged that *Typha latifolia* has generally poorer treatment efficiencies than the other tested species.
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species, high potential as a renewable biomass source
Biomass production, growth rates and yields	- Annual aboveground productivity according to Reed (1995): ≈ 30 t/(ha*yr) dry wt (in temperate climates), - range of annual aboveground productivity according to Lakshman (1987): 3.8 - 52.7 t/(ha*yr) dry wt. Ranges of annual biomass production (growth rates): - 8.0 - 61.0 t/(ha*yr) dry wt (Reddy and De Busk, 1987b) - 5.7 - 93.4 t/(ha*yr) dry wt (Vymazal, 1995b; in: IWA, 2000) (wide ranges, depending on nutrient supply, site and climate)
Biomass utilization options	Generally, *Typha latifolia* shows a high potential as a renewable biomass and energy source. - Can be used as fuel source (direct combustion), e.g. as heating fuel, due to the high energy content (calorific value) of the biomass, comparable to conventional fuel sources, - can be used for agricultural purposes, e.g. as additional material for composting, - can be used as feed for cattle due to the high crude protein and DOM content when growing in nutrient-enriched wastewaters. (Lakshman, 1987, 1994) Harvested leaves and stems have versatile utilization options: - building material, e.g. thatching and roof materials, - weaving material, e.g. mats, hats, chairs, etc., - raw material for paper making (source of fibre), - many other utilization options, e.g. insulation material, rayon production or packing material. (Rook, 2004; Wissing, 2002)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	Uptake capacity in a temperate climate: 1,164 kg/(ha*yr), (Rogers 1985; in Wood, 1995) → similar to *Cyperus papyrus* (1,220 kg/ha*yr) Harvestable range of nitrogen uptake capacity (growth rate): 111 - 2,630 kg/(ha*yr), (Vymazal, 1995b; in: IWA, 2000)
Phosphorus: uptake and assimilation rates	Uptake capacity in a temperate climate: 179 kg/(ha*yr), (Rogers 1985; in Wood, 1995) → similar to *Phragmites australis* (162 kg/ha*yr) Harvestable range of phosphorus uptake capacity (growth rate): 8 - 400 kg/(ha*yr), (Vymazal, 1995b; in: IWA, 2000)
9. Further remarks and comparisons with other plant species (if possible)	- High frost tolerance (Maehlum, 1995), - most commonly distributed type of *Typha sp*, similar to *Typha angustifolia,* - capable of forming floating mats of rhizomes, roots and accumulating plant litter on shallow open water sites (IWA, 2000), - high tolerance to certain heavy metals, especially lead, zinc, copper (Wissing, 2002), - in cold/boreal climates, the aboveground plant portions remain upright (persistent) and serve as shelter from freezing.

9 Standard plants for high-latitude and mid-latitude climates

9.1 Plant species recommended for constructed wetlands

- *Baumea articulata* (jointed twig-rush)
- *Carex acuta* (slender tufted sedge)
- *Carex aquatilis* (water sedge)
- *Carex rostrata* (beaked sedge)
- *Eleocharis sphacelata* (tall spike rush)
- *Glyceria maxima* (reed sweet grass)
- *Juncus ingens* (giant rush)
- *Phalaris arundinacea* (reed canary grass)
- *Scirpus acutus* (hard stem bulrush)
- *Scirpus californicus* (giant bulrush)
- *Scirpus cyperinus* (wool grass)
- *Scirpus pungens* (Olney's bulrush)
- *Scirpus validus* (soft stem bulrush)
- *Typha capensis* (common cattail)
- *Typha subulata* (cattail, totora)
- *Zizania latifolia* (Manchurian wild rice)
- *Zizaniopsis bonariensis* (Espadaña)
- *Zizaniopsis miliacea* (giant cutgrass)

9.2 *Baumea articulata* (jointed twig-rush)

Suitable and recommended for constructed wetlands in:
- Warm/temperate climate zones of: Australia and New Zealand

1. Plant species	
Common name	Jointed twig-rush
Scientific name (genus / species)	*Baumea articulate*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Warm/temperate
Geographic range	Native to Australia, New Zealand and Southwest Pacific
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, green year-round and little seasonal dieback (Tanner, 1996), also able to increase the standing biomass throughout the winter period (Adcock, 1994).
Growth height	Up to 2 - 3 m (Chambers, 1994b)
Growth rate and period	Slow to moderate, relatively slow initial growth and establishment: it takes two growing seasons to develop fully (Tanner, 1997). After establishment *Baumea articulata* forms good and stable stands in constructed wetlands (Tanner, pers. comm.).
Reproduction	Mainly vegetative, very low generative reproduction (Chambers, 1994b)
Root and rhizome growth and development	The root penetration of *Baumea articulata* in gravel bed constructed wetlands extended to depths of about 0.3 - 0.4 m (Adcock, 1994; Tanner, 1996).
4. Habitat conditions and behaviour	
Natural Habitat	Swamps, coastal lagoons, usually in standing waters up to a depth of 1 m (Leaf Liaisons, 2006).
Light demand, shade tolerance	Shade to full sun (Leaf Liaisons, 2006)
pH optimum and tolerances	No data found
Salinity tolerance	Presumably moderate salt tolerance (habitat: coastal waters)
Habitat dominance	Presumably non-invasive

5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	*Baumea articulata* tolerates a wide range of water depths with high seasonal variations (Chambers, 1994b) and can be inundated permanently up to 0.3 m (Tanner, 1997); tolerates inundations up to 0.5 m (Chambers, 1994a).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	*Baumea articulata* is a common plant for constructed wetlands in Australia and New Zealand (Tanner, pers. comm.)
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the study conducted by Heritage (1995) in NSW, Australia (warm/temperate climate, ≈ 34 °S), where *Baumea articulata* was planted in a VF wetland for treatment of primary urban sewage with relatively high fluctuating influent concentrations (134 - 575 mg/L BOD), the reduction of BOD achieved a very high efficiency: 98 - 100 % (Heritage, 1995).
Nitrogen and phosphorus compounds: evaluation of existing case studies	The study by Heritage (1995) showed removal performances for total nitrogen and total phosphorus of 79 - 97 % and 54 - 95 %, respectively, with an improved performance during the colder winter months. This was due to the high evapotranspiration rate of this plant species that is also maintained during the cold season leading to (1) an increased potential for microbial nitrogen transformations in the root zone since the water level in the vertical flow CW is lowered (2) significantly increased actual HRT. Further, the year-round growth of this species, and thus, nutrient assimilation throughout the year contributed to the increased performance during winter (Heritage, 1995). Capable to grow in relatively high strength wastewaters (Tanner, 1996). → Influent concentrations of up to about 105 mg/L NH_4^+-N were tolerated without obvious plant damages (typical concentrations found in dairy farm wastewaters, NH_4^+-N conc. in municipal wastewaters are significantly lower), (Tanner, 1996).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Low productivity compared to the high productive species, e.g. *Typha sp.* or *Phragmites sp.*
Biomass production, growth rates and yields	Harvestable biomass yield after 9 months growth of *Baumea articulata* according to Browning (2003): 21.6 t/ha → Relatively high biomass yield, however, continuous reduction after each harvesting in this study.
Biomass utilization options	According to Tanner (pers. comm.), there are no utilization options of *Baumea articulata* in Australia and New Zealand.
8. Nutrients: uptake and storage capacities	
General aspects	Due to the low biomass production and slow establishment, nutrient uptake and accumulation capacities for *Baumea articulata* are relatively low compared to other, high productive species such as *Glyceria maxima, Phragmites australis* or *Zizania latifolia* (Tanner, 1996).
Nitrogen: uptake and assimilation rates	No appropriate data available
Phosphorus: uptake and assimilation rates	No appropriate data available
9. Further remarks and comparisons with other plant species (if possible)	- Tolerant to frost periods (Tanner, 1996), - *Baumea articulata* stands show a slow regrowth rate after harvesting (Browning, 2003), - best used in mixed planting with *Scirpus validus* as nurse crop (Tanner ,1997), - it requires two or three growing seasons to get harvestable stands of *Baumea articulata* (Tanner, 1996), - unlikely to be a well-suitable forage plant for livestock due to the high fibre content (Tanner, pers. comm.).

9.3 *Carex acuta* (slender tufted sedge)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: Europe
- Temperate climate zones of: Europe

1. Plant species	
Common name	Slender tufted sedge, slender spiked sedge
Scientific name (genus / species)	*Carex acuta*, syn.: *Carex gracilis*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Cold/boreal to temperate
Geographic range	Native to Northern and Central Europe; distributed in the cold/boreal and temperate regions of the Northern Hemisphere (Aichele, 1981).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous (Thunhorst, 1993)
Growth height	Up to 1.5 m (Aichele, 1981)
Growth rate and period	No sufficient data available
Reproduction	Mainly vegetative, but also low generative reproduction (similar to the other types of *Carex sp.*)
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater marshes, along watersides, wet meadows and lake edges (Aichele, 1981; Thunhorst, 1993)
Light demand, shade tolerance	Semi-shade (Ellenberg, 1991)
pH optimum and tolerances	Prefers neutral to slightly alkaline conditions (Aichele, 1981)
Salinity tolerance	Low, < 0.5 ppt (freshwater species), (Thunhorst, 1993)
Habitat dominance	Often dominant (Ellenberg, 1991)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	This species was successfully tested in several studies conducted in Slovenia (Urbanc-Bercic 1998; Vrhovek 1996; Bulc, 2002). These studies showed that *Carex acuta* is well-suitable for the treatment of high-strength wastewaters.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In a study conducted in Gradie (Slovenia), *Carex acuta* was planted, beside *Phragmites australis*, in a two-stage horizontal subsurface flow CW system for treatment of high strength industrial wastewater (food processing). Removal efficiencies: - COD: 92 % (mean influent conc.: 3674 mg/L) - BOD: 89 % (mean influent conc.: 962 mg/L) → Very high removal performance despite the very high organic loadings, especially of COD. → *Carex acuta* was able to tolerate the high-loaded industrial influent without any damages. → This system showed also high removal efficiencies for orthophosphate (96 %), ammonium (86 %) and nitrate (65 %). (Vrhovek, 1996) In other systems in Slovenia, *Carex acuta* and *Phragmites australis* were planted in various multistage subsurface flow CWs for treatment of domestic wastewater pre-treated in a septic tank or sedimentation basin. Removal efficiencies were high concerning all typical parameters found in municipal wastewaters (Bulc, 2002).
Nitrogen and phosphorus compounds: evaluation of existing case studies	No sufficient data available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification	No plant-specific information found

and denitrification activity)	
7. Productivity, utilization options and economic potential	
Potential productivity	Low to moderate productive species
Biomass production, growth rates and yields	No data found
Biomass utilization options	- The straw and hay can be used for bedding (Aichele, 1981; PFAF, 2004).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- High adaptability to various adverse conditions (Aichele, 1981).

9.4 *Carex aquatilis* (water sedge)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: Europe, Asia (incl. Russian Arctic and Siberia) and North America (incl. Canadian Arctic and Alaska, USA)

1. Plant species	
Common name	Water sedge
Scientific name (genus / species)	*Carex aquatilis*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Cold/boreal to arctic
Geographic range	Native to Northern Europe (Scandinavia), Northern Russia and Siberia (PFAF, 2004), also in North America, especially in Alaska, USA (USDA-FS, 2006)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous
Growth height	Up to 1.5 m (PFAF, 2004)
Growth rate and period	No sufficient data available
Reproduction	Mainly vegetative, very low generative reproduction (USDA-FS, 2006)
Root and rhizome growth and development	Relatively shallow, dense root penetration: in arctic climates confined to the upper 0.2 - 0.3 m of the soil layer (USDA-FS, 2006).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater marshes, along watersides, wet meadows, pond and lake edges (USDA-FS, 2006)
Light demand, shade tolerance	Full sun to shade (PFAF, 2004)
pH optimum and tolerances	Preferred pH range: 6.2 - 7.1 (prefers slightly acidic soil conditions), (USDA-FS, 2006).
Salinity tolerance	Low, < 0.5 ppt (freshwater species), (Thunhorst, 1993)
Habitat dominance	Usually dominant or co-dominant, strong competitor (USDA-FS, 2006)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	This species was successfully tested in the Murmansk region in Russia under arctic conditions (Vasilevskaya 2004).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	The removal efficiencies of BOD and TSS in the pilot multi-stage constructed wetland system near Murmansk in Russia (sub-arctic climate, ≈ 68 °N) were more than 81 %. The wetland system was planted with *Carex aquatilis, Phragmites australis* and *Typha latifolia* (Vasilevskaya, 2004). Further data of this study were not available.
Nitrogen and phosphorus compounds: evaluation of existing case studies	No data found
Root zone effects: oxygenation capacity and ef-	No plant-specific information found

fect on microbial transformations (nitrification and denitrification activity)	
7. Productivity, utilization options and economic potential	
Potential productivity	Relatively high productivity in consideration of the adverse arctic conditions (USDA-FS, 2006)
Biomass production, growth rates and yields	No data found
Biomass utilization options	No data found
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Very frost hardy species, - occasionally capable of forming floating mats on open waters (USDA-FS, 2006).

9.5 *Carex rostrata* (beaked sedge)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: Europe (incl. Iceland)

1. Plant species	
Common name	Beaked sedge, blue sedge, also: bottle sedge
Scientific name (genus / species)	*Carex rostrata*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Cold/boreal to temperate
Geographic range	Widespread in Northern Europe (Scandinavia), Iceland and Eurasia, also from Alaska to Greenland and North America, generally north to 71 °N (Engelhardt, 2003; PFAF, 2004). *Carex rostrata* is also widespread in Siberia, Russia (Little, 1979).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, non-persistent (Thunhorst, 1993)
Growth height	Up to 1.2 m (USDA-FS, 2006)
Growth rate and period	Rapid (especially in early spring), (USDA-FS, 2006)
Reproduction	Mainly vegetative, but also low generative reproduction rate (Ogle, 2003)
Root and rhizome growth and development	Forms a dense, deeply growing, root and rhizome system (USDA-FS, 2006).
4. Habitat conditions and behaviour	
Natural Habitat	Lake margins, pond edges, freshwater wetlands and wet meadows (Rook, 2004)
Light demand, shade tolerance	Full sun, but tolerates semi-shade (Ellenberg, 1991)
pH optimum and tolerances	tolerance range according to Rook (2004): 3.0 - 7.9, tolerance range according to USDA-NRCS (2006): 4.5 - 7.0
Salinity tolerance	Low (freshwater species), < 0.5 ppt (Ellenberg, 1991; Thunhorst, 1993)
Habitat dominance	*Carex rostrata* is usually dominant or co-dominant where it occurs; forms often monoculture stands (USDA-FS, 2006).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated temporarily to permanently up to 0.25 m (Kadlec and Knight, 1996), tolerant to strong water level fluctuations and temporarily water levels up to 1 m, but also long periods without standing waters (USDA-FS, 2006), low tolerance to droughts (USDA-NRCS, 2006).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	For this thesis, no case that investigated the performance of *Carex rostrata* in constructed wetlands for treatment of municipal or domestic wastewaters study was available, although this species appears to be well-suitable for use in constructed wetlands. The information given below is mainly based on the work by

	Allen (2002) who studied the effect of low temperatures on three emergent macrophytes (*Carex rostrata, Typha latifolia* and *Scirpus acutus)* in a microcosm study.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	COD removal for *Carex rostrata* at 24 °C as well as 4 °C: was almost complete: 93 % (influent: simulated secondary domestic wastewater, COD conc.: 470 mg/L); the removal rate was more rapid at 4 °C than at 24 °C. Higher redox potential and increased root zone oxygenation rate at 4°C (Allen, 2002). In the same study the COD removal rate of *Scirpus acutus* was similar to *Carex rostrata* at both temperatures (96 % at 4 °C and 24 °C). *Typha latifolia* showed a lower performance at 4 °C (77 %), (at 24 °C: 89 %), (Allen, 2002).
Nitrogen and phosphorus compounds: evaluation of existing case studies	No sufficient data available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Due to the increased root zone oxygenation rate at low temperatures, one can expect an enhanced nitrification activity (Allen, 2002).
7. Productivity, utilization options and economic potential	
Potential productivity	Low to moderate productive species
Biomass production, growth rates and yields	No data found
Biomass utilization options	- Straw and hay can be used for bedding (PFAF, 2004), - considered as an excellent forage plant for cattle (Little, 1979).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- High frost tolerance species, - sometimes able to form floating mats on shallow open waters sites (USDA-FS, 2006), - the study by Allen (2002) revealed that *Carex rostrata* appears to have a high potential for use in constructed wetlands in cold/boreal climates, - many studies investigated the heavy metal accumulation capacity of *Carex rostrata* (e.g. Matthews, 2005; Stoltz, 2002), however, the use of this species for treatment of municipal wastewaters has been less researched yet.

9.6 *Eleocharis sphacelata* (tall spike rush)

Suitable and recommended for constructed wetlands in:
- Warm/temperate to subtropical climate zones of: Australia
- Warm/temperate climate zones of: New Zealand

1. Plant species	
Common name	Tall spike rush, tall spike sedge, bamboo spike sedge
Scientific name (genus / species)	*Eleocharis sphacelata*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Warm/temperate, but also subtropical
Geographic range	Native to Australia and New Zealand
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous
Growth height	Up to 2 -3 m (EW-NZ, 2006)
Growth rate and period	Moderate (Tanner, 1997) to fast (CSU, 2005)
Reproduction	Easily vegetative reproduction, but low germination rate by seeds (CSU, 2005)
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Swamps, lagoons and lakes, deep standing waters and fresh water rivers (Leaf Liaisons, 2006)
Light demand, shade tolerance	Semi-shade to full sun (EW-NZ, 2006)

pH optimum and tolerances	Can grow in slightly acidic waters (Greenway, pers. comm.).
Salinity tolerance	Low (freshwater species), (Greenway, pers. comm.)
Habitat dominance	Forms dense and extensive stands (CSU, 2005)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated permanently up to 0.5 m (Greenway, pers. comm.) and tolerates temporarily inundations up to a water depth of about 0.9 m (CSU, 2005).
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	The use of this species in large-scale treatment wetlands was primarily investigated in several surface flow systems in Queensland, Australia, especially in a pilot wetland constructed at Cairns (warm/subtropical climate, ≈ 16 °S). However, this system received only a low-loaded secondary effluent and further, other plant species (e.g. *Typha domingensis* and *Scirpus validus*) were also planted in this wetland system (Greenway, 1999, 2001). Thus, data about the treatment efficiency of *Eleocharis sphacelata* from these studies were insufficient in order to make conclusions for the suitability of this species. According to Tanner (1997) and Greenway (pers. comm.), this species is only suitable for use in constructed surface flow wetlands and is considered as a key plant in Australia and New Zealand.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Among five other wetland species, the treatment efficiency of *Eleocharis sphacelata* was investigated in an experimental microcosm study with gravel substrate conducted in Griffith (NSW, Australia, warm/temperate climate). → Very high treatment efficiency for COD, total nitrogen and total phosphorus at a HRT of 5 d; influent: primary settled wastewater Further data about this study were not available (Breen, 1992; in: Mitchell, 1995)
Nitrogen and phosphorus compounds: evaluation of existing case studies	No appropriate data available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Appears to have a root zone oxygenation capacity similarly high as *Phragmites australis* (Brix, 1992).
7. Productivity, utilization options and economic potential	
Potential productivity	Moderate productive species
Biomass production, growth rates and yields	Harvestable biomass production rate (growth rate) according to Greenway (2001) in a constructed wetland for polishing of secondary treated municipal effluent in Queensland, Australia (subtropical climate): 9.2 t/(ha*yr).
Biomass utilization options	- Stems can be used as weaving material (Tanner, 1997), - due to the high wet weight biomass, *Eleocharis sphacelata* is fairly succulent: may be valuable as a forage plant for cattle (Greenway, pers. comm.).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	Harvestable uptake capacity according to Greenway (2001) in low-loaded secondary wastewater: 138 kg/(ha*yr)
Phosphorus: uptake and assimilation rates	Harvestable uptake capacity according to Greenway (2001) in low-loaded secondary wastewater: 38.6 kg/(ha*yr)
9. Further remarks and comparisons with other plant species (if possible)	- Frost tolerant and very robust species (EW-NZ, 2006), - *Eleocharis sphacelata* responds well to harvesting and shows high regrowth rates after the shoots were harvested (Greenway, 1999).

9.7 *Glyceria maxima* (reed sweet grass)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: Europe
- Temperate climate zones of: Europe and Asia

1. Plant species	
Common name	Reed sweet grass, giant manna grass
Scientific name (genus / species)	*Glyceria maxima*, syn.: *Glyceria aquatica*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Cold/boreal to warm/temperate
Geographic range	Native to Europe and temperate Asia, introduced to temperate (Southern) Australia and New Zealand (ISSG, 2005)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, green year-round in warm and temperate climates (Tanner, 1996).
Growth height	1 - 2.5 m (FAO, 2006)
Growth rate and period	Rapid growth, long vegetation period in temperate climates (Tanner, 1996).
Reproduction	Mainly vegetative, but also low generative propagation (ISSG, 2005)
Root and rhizome growth and development	Shallow root system, no deep penetration (Wissing, 2002)
4. Habitat conditions and behaviour	
Natural Habitat	Lakes, freshwater wetlands and shallow water sites, preferred at nutrient-rich sites (ISSG, 2005)
Light demand, shade tolerance	Full sun (Ellenberg, 1991), tolerant to light shade (ISSG, 2005)
pH optimum and tolerances	Tolerates strongly acid soils (FAO, 2006)
Salinity tolerance	Low (freshwater species), (Aichele, 1981)
Habitat dominance	Often dominant in wetlands and littorals, forms monocultures stands (ISSG, 2005; Wittgren, 1987)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated permanently up to a water depth of 0.3 m, tolerates also longer drought periods (Kadlec and Knight, 1996), tolerant to strongly fluctuating water levels (Wissing, 2002). According to Tanner (1997) a water depth of 0.4 m can be tolerated in constructed wetlands treating dairy farm wastewaters.
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Typical and commonly used plant species for horizontal subsurface flow systems in Central and Northern Europe (Gumbricht, 1993), e.g. in the Czech Republic (Vymazal, 1995a). Generally, *Glyceria maxima* shows high BOD and TSS removal efficiencies similar to other standard plant species used in CWs such as *Phragmites australis, Typha sp.* or *Scirpus sp.*
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Removal efficiency of *Glyceria maxima* planted in a small-scale gravel bed for treatment of dairy farm wastewater according to the study conducted by Tanner (1996) in warm/temperate New Zealand: BOD reduction: > 77 % (mean BOD influent conc.: 87.6 mg/L) TSS reduction: > 76 % (mean TSS influent conc.: 95.7 mg/L) In a study conducted in Sweden (cold/boreal climate), a constructed subsurface wetland system planted with *Glyceria* maxima achieved a high BOD removal efficiency (mean BOD influent conc.: 130 mg/L), (Sundblad, 1989; Wittgren, 1987).
Nitrogen and phosphorus compounds: evaluation of existing case studies	High tolerance to eutrophic conditions and relatively high strength wastewaters (Brändle, 1996; Tanner, 1996). → influent concentrations of about 105 mg/L NH_4^+-N were tolerated without obvious plant damages (typical concentrations found in dairy farm wastewaters, NH_4^+-N conc. in municipal wastewaters are significantly lower), (Tanner, 1996).

Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	As shown in a study conducted by Both (1990), the presence of *Glyceria maxima* can significantly stimulate the nitrification activity due to relatively high root zone oxygen releases compared to other wetland species, e.g. *Typha sp.* (Fruergaard, 1987). Due to the high leaf turnover rate and the long vegetation period, *Glyceria maxima* can also stimulate the denitrification activity positively by providing high amounts of biomass that serve as the required organic carbon source for denitrifiers (Halicki, 2004). → Ideal species for treatment of nitrified wastewaters. The stimulating effect can be enhanced by formation of floating mats in surface flow systems (high organic carbon supply and anaerobic sites).
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species (Wittgren, 1987) with a high potential as renewable biomass.
Biomass production, growth rates and yields	- Range of annual biomass production according to Vymazal (1995b; in: IWA, 2000): 9 - 28.6 t/(ha*yr) (dry wt), - aboveground biomass stock according to Westlake (1966) in a cold/boreal climate: 6 - 26 t/ha (dry wt), - total annual biomass yield according to Sundblad (1989) in Sweden (cold/boreal climate): 8.7 - 11.65 t/(ha*yr) (dry wt), - aboveground biomass yield according to Tanner (1996) in New Zealand (warm/temperate climate): 33 t/ha (dry wt)
Biomass utilization options	Generally, *Glyceria maxima* is a high-yielding species with a high nutritional value: - shows a significant potential for forage production (Sundblad, 1989): → High-quality food plant for cattle with a high nutritional value (however, possible cyanide toxicity in young growing shoots should be avoided), (Sundblad, 1989). High potential as a renewable energy source, e.g. for biogas (methane) production), (Wittgren, 1987).
8. Nutrients: uptake and storage capacities	
General aspects	Due to its high productivity, *Glyceria maxima can* assimilate large amounts of nutrients.
Nitrogen: uptake and assimilation rates	- Harvestable range of nitrogen uptake capacity (growth rate): 75 - 1,500 kg/(ha*yr) (Vymazal, 1995b; in: IWA, 2000), - harvestable annual uptake in a cold/boreal climate (Sweden): 321 kg/(ha*yr), (Sundblad, 1989), - harvestable annual uptake in a warm/temperate climate(NZ): ≈ 700 kg/(ha*yr), (Tanner, 1996).
Phosphorus: uptake and assimilation rates	- Harvestable range of phosphorus uptake capacity (growth rate): 50 - 425 kg/(ha*yr) (Vymazal, 1995b; in: IWA, 2000), - harvestable annual uptake in a cold/boreal climate (Sweden): 48 kg/(ha*yr), (Sundblad, 1989), - harvestable annual uptake in a warm/temperate climate (NZ): ≈ 92 kg/(ha*yr), (Tanner, 1996).
9. Further remarks and comparisons with other plant species (if possible)	- Can form intertwined floating mats of decaying leaf litter over shallow waters (thickness: about 0.2 m and more), (van Oostrom, 1990). → Particularly in surface flow systems, this effect can stimulate denitrification as it provides the required carbon source. - Maintains a year-round vegetation cover in warm/temperate climates without strong diebacks during the cold season, - in cold/boreal climates, the aboveground plant portions remain upright (persistent) and serve as shelter from freezing. (Tanner, 1996) Together with *Zizania latifolia* and *Phragmites australis, Glyceria maxima* showed the highest aboveground biomass production rates in the comparative study conducted by Tanner (1996) in New Zealand.

9.8 *Juncus ingens* (giant rush)

Suitable and recommended for constructed wetlands in:
- Warm/temperate climate zones of: Australia

1. Plant species	
Common name	Giant rush
Scientific name (genus / species)	*Juncus ingens*
Family	*Juncaceae*
2. Availability in climate zone	
Climatic range	Warm/temperate
Geographic range	Native to Australia (mainly Southern Australia, NSW)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, green year-round in warmer climates including mild winters (CPBR, 2005)
Growth height	Up to 5 m (CPBR, 2005)
Growth rate and period	Rapid (CPBR, 2005)
Reproduction	Mainly vegetative, but also low generative reproduction (CPBR, 2005)
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Shallow water sites, lake margins and periodically flooded areas (CPBR, 2005)
Light demand, shade tolerance	Semi shade to full sun (CPBR, 2005)
pH optimum and tolerances	No data found
Salinity tolerance	No data found
Habitat dominance	Often forms dense, extensive monoculture stands (normally untypical for *Juncus sp.*), (CPBR, 2005).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be permanently inundated, tolerant to a wide range of wet, flooded and dry conditions (CPBR, 2005).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Among five other wetland species, the treatment efficiency of *Juncus ingens* was investigated in an experimental microcosm study with gravel substrate conducted in Griffith (NSW, Australia, warm/temperate climate). → Very high treatment efficiency for COD, total nitrogen and total phosphorus at a HRT of 5 d; influent: primary settled wastewater Further data about this study were not available (Breen, 1992; in: Mitchell, 1995) In a further study in Victoria, Australia (warm/temperate climate), *Juncus ingens* was planted, together with *Scirpus validus*, in a pilot subsurface flow constructed wetland system with gravel substrate (Thomas, 1995). Influent: Secondary treated sewage effluent from a treatment facility, HLR: 3.9 cm/d Removal efficiencies: - BOD: 75 % (influent conc.: 86 mg/L, range: 25 - 164 mg/L) - COD: 68 % (influent conc.: 229 mg/L, range: 159 - 327 mg/L) → Good removal performance; no significant differences between *Juncus ingens* and *Scirpus validus.*
Nitrogen and phosphorus compounds: evaluation of existing case studies	Reduction of ammonia and total phosphorus in the study conducted by Thomas (1995) was very poor with no significant differences between the two plant species tested (*Juncus ingens* and *Scirpus validus*).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Compared to other species tested in this study, e.g. *Phragmites australis, Typha sp.* or *Eleocharis sphacelata*, *Juncus ingens* appears to have a relatively low root zone oxygenation capacity (Brix, 1992).
7. Productivity, utilization options and economic potential	
Potential productivity	High productive species; potentially suitable as a renewable

	energy source, but no sufficient data available
Biomass production, growth rates and yields	No data found
Biomass utilization options	No utilization options found
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Appears to be the largest *Juncus sp.* worldwide (CPBR, 2005), - very robust species (CPBR, 2005).

9.9 *Phalaris arundinacea* (reed canary grass)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: Europe
- Temperate climate zones of: Europe and West Asia (Eurasia)

1. Plant species	
Common name	Reed canary grass
Scientific name (genus / species)	*Phalaris arundinacea*, syn.: *Typhoides arundinacea*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Cold/boreal to temperate
Geographic range	Northern Hemisphere: native to Europe (not Mediterranean area), also in West and North Asia, North America and North Africa (PFAF, 2004; Wendelberger, 1986)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent
Growth height	Up to 2 m (Wendelberger, 1986)
Growth rate and period	Very fast, begins rapidly to grow very early in spring after frost (NewCROP, 2005), strongly responds to nutrient supply (Stannard, 2002).
Reproduction	Mainly vegetative, usually low generative reproduction rate (Stannard, 2002).
Root and rhizome growth and development	Shallower root depth than *Phragmites australis* the rhizomes can form dense mats within one year and quickly dominate the soil (Stannard, 2002; Wissing, 2002).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater marshes and shallow water sites, pond and lake margins, mainly at nutrient-enriched sites (ISSG, 2005).
Light demand, shade tolerance	Semi-shade to full sun, not shade tolerant (USDA-FS, 2006)
pH optimum and tolerances	pH tolerance range: 4.5 - 8.2 (NewCROP, 2005); according to ISSG (2005): up to pH 8.8
Salinity tolerance	Low (freshwater species), (NewCROP, 2005)
Habitat dominance	Aggressive colonizer and competitor, invasive species (Stannard, 2002)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated temporarily to permanently up to 0.3 m (Kadlec and Knight, 1996), high tolerance to temporary and frequent inundations (Wendelberger, 1986), moderately tolerant to droughts (NewCROP, 2005).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Often used for irrigation purposes with sewage effluents from municipal and industrial sources (NewCROP, 2005). After *Phragmites australis*, *Phalaris arundinacea* is the plant species most commonly used in constructed wetland systems in the Czech Republic (Vymazal, 1995a, 2001b), either planted together with *Phragmites australis* or as single species.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	The treatment efficiency of *Phalaris arundinacea,* either alone or together with *Phragmites australis,* was successfully proved in many subsurface flow wetland systems (Urbanc-Bercic, 1998; Vymazal, 1999, 2001).

	The high treatment performance of *Phalaris arundinacea* in cold/boreal climates was proved, among other studies, in a subsurface flow wetland in Norway: BOD removal rate: > 77 % (BOD conc. in raw wastewater: 140 mg/L), (Maehlum, 1998)
Nitrogen and phosphorus compounds: evaluation of existing case studies	High tolerance to eutrophic conditions (Brändle, 1996).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species (one of the highest yielding perennial grasses in temperate regions). Under optimum conditions, *Phalaris arundinacea* can be harvested 2 - 3 times a year (Wendelberger, 1986).
Biomass production, growth rates and yields	- Range of annual biomass production according to Vymazal, (1995b; in: IWA, 2000): 8.0 - 35 t/(ha*yr) dry wt, - range of annual aboveground yields in temperate climates for natural stands: 8 - 20 t/ha (NewCROP, 2005), - maximum aboveground biomass yield in a constructed wetland in North Yorkshire, UK (temperate climate) receiving secondary municipal effluent: 25 t/ha (Hurry, 1990).
Biomass utilization options	- High-quality and productive forage plant (Hurry, 1990), - can be used as pasture grass and for production of silage and hay (high nutritional and palatable value), (NewCROP, 2005). High potential as a renewable source of biomass fuel and energy crop (Hurry, 1990): → In Northern Europe (Scandinavia), *Phalaris arundinacea* is cultivated as a source of renewable biomass fuel (about 4,000 ha are in production in Sweden (Kätterer, 1998).
8. Nutrients: uptake and storage capacities	
General aspects	Generally, *Phalaris arundinacea has the* ability to assimilate enormous amounts of nitrogen, especially from wastewaters with high nitrogen loadings (e.g. dairy farm or food processing effluents), (Ogle, 2003).
Nitrogen: uptake and assimilation rates	- Harvestable range of nitrogen uptake capacity (growth rate): 80 - 1,200 kg/(ha*yr), (Vymazal, 1995b; in: IWA, 2000), - harvestable nitrogen accumulation in aboveground plant tissue according to Hurry (1990) in a temperate climate: 494 kg/ha (11 % of the annual nitrogen loading), - harvestable annual range of nitrogen uptake in a cold/boreal climate (Alberta, Canada): 200 - 434 kg/(ha*yr), (Bole, 1985, in Wittgren, 1997).
Phosphorus: uptake and assimilation rates	- Harvestable range of phosphorus uptake capacity (growth rate): 23 - 140 kg/(ha*yr), (Vymazal, 1995b; in: IWA, 2000), - harvestable phosphorus accumulation in aboveground plant tissue according to Hurry (1990): 109 kg/ha (11 % of the annual phosphorus loading).
9. Further remarks and comparisons with other plant species (if possible)	- Very robust and frost tolerant species (up to - 20 °C), (PFAF, 2004), - Compared to *Phragmites australis, Phalaris arundinacea* is able to establish and grow much faster after planting; the maximum biomass is achieved during the next growing season (*Phragmites australis* grows more slowly, but more steadily, maximum biomass is achieved after about three growing seasons), (Vymazal, 1998b), - very easy to establish in CWs (Stannard ,2002).

9.10 *Scirpus acutus* (hard stem bulrush)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: North America
- Warm/Mediterranean climate zones of: North America (California, USA)

1. Plant species	
Common name	Hard stem bulrush
Scientific name (genus / species)	*Scirpus acutus*, syn.: *Schoenoplectus acutus*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Cold/boreal to warm/Mediterranean (California, USA)
Geographic range	Native to North America: from Canada to Southern USA (PFAF, 2004)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent (Thunhorst, 1993) and deciduous (shoots senesce in winter), (Stevens, 2003a).
Growth height	Up to 2 - 3 m, occasionally up to 5 m (USDA-FS, 2006)
Growth rate and period	Rapid (Hoag, 1998a)
Reproduction	Mainly vegetative, but also low generative reproduction (Ogle, 2003)
Root and rhizome growth and development	Dense, horizontally growing, root and rhizome system
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater to brackish marshes (Thunhorst, 1993), lake and pond margins, floodplains (PFAF, 2004)
Light demand, shade tolerance	Full sun (Thunhorst, 1993)
pH optimum and tolerances	pH tolerance according to USDA-NRCS (2006): 5.2 - 8.5; tolerates calcareous (alkaline) conditions (Hoag, 1998a).
Salinity tolerance	Moderate, tolerates saline and brackish waters (Hoag, 1998a).
Habitat dominance	Aggressive colonizer and dominant species, forms often monocultures (USDA-FS, 2006).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated regularly to permanently up to 0.9 m (Thunhorst, 1993); fairly high tolerance to droughts and tolerates temporarily, but not too long, inundations up to 1.5 m (Hoag, 1998a).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	*Scirpus acutus* is often used in CWs for treatment of agricultural wastewaters (USDA-FS, 2006), e.g. animal wastewaters (Hill, 1997). Since municipal or domestic wastewaters usually have lower BOD and ammonium concentrations than agricultural wastewaters (Kadlec and Knight, 1996), *Scirpus acutus* appears to be also well-suitable for treatment of municipal wastewaters.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	According to the study conducted by Allen (2002), the COD removal for *Scirpus acutus* at 24 °C as well as 4 °C was almost complete: 96 % (influent: simulated secondary domestic wastewater with a COD conc. of: 470 mg/L). The Removal rate is more rapid at 4 °C than at 24 °C. → Higher redox potential and increased root zone oxygenation rate at 4°C (Allen, 2002). In a batch-loaded experimental constructed wetland system for the treatment of synthetic domestic wastewater (mean COD influent conc.: 200 mg/L), a removal efficiency of 91.3 % was achieved (Stein, 2005). The study was conducted in Bozeman, Montana, USA (warm/temperate climate, ≈ 45.4 °N).
Nitrogen and phosphorus compounds: evaluation of existing case studies	In the same study, the ammonia removal rate (mean NH_4^+-N influent conc.: 40 mg/L) amounted to 59.5 % (Stein, 2005).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Due to the good root zone oxygenation capacities both at higher and lower temperatures, a stimulating effect on nitrification can be expected resulting in an enhanced ammonium reduction (Allen, 2002).
7. Productivity, utilization options and economic potential	

Potential productivity	Moderate to high productive species
Biomass production, growth rates and yields	Typical annual biomass production rates (growth rates) for *Scirpus sp.* in general: 7.85 - 46 t/(ha*yr) dry wt (Vymazal, 1995b; in: IWA, 2000).
Biomass utilization options	Stems: - can be used for basket making, - the fibres of the stems can be used for paper making, - building material (thatching, roof material). Stems and leaves: - can be used as weaving material (bags, mats, mattresses, etc.), - can be used for bedding. (PFAF, 2004; Stevens, 2003a)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Low forage value due to the low protein content (USDA-FS, 2006), - very similar to *Scirpus validus* (Stevens, 2003a).

9.11 *Scirpus californicus* (giant bulrush)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: North America and South America (southern parts)
- Warm/Mediterranean climate zones of: North America (California, USA)

1. Plant species	
Common name	Giant bulrush, California bulrush, tule
Scientific name (genus / species)	*Scirpus californicus*, syn.: *Schoenoplectus californicus*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Warm/Mediterranean to temperate
Geographic range	Native to Southern USA and California (USA), Central America and temperate South America (Argentina, Bolivia, Chile and Southern Brazil); introduced to and naturalized in the North Island of New Zealand (Giovaninni, 1999; Stevens, 2003b; de Lange, 1998)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial, rhizomatous and persistent, evergreen and year-round growth in warm/temperate climates, less winter dieback and senescence compared to *Scirpus validus* (de Lange, 1998).
Growth height	Up to about 3 m (de Lange, 1998), occasionally up to 4 m with increasing water levels (Giovaninni, 1999)
Growth rate and period	Rapid (Busnardo, 1992)
Reproduction	Mainly vegetative, usually low generative reproduction (de Lange, 1998)
Root and rhizome growth and development	Thick, long and dense root and rhizome system (Stevens, 2003b)
4. Habitat conditions and behaviour	
Natural Habitat	Brackish (coastal) to freshwater marshes, shores (Stevens, 2003b)
Light demand, shade tolerance	Semi-shade to full sun (USDA-NRCS, 2006)
pH optimum and tolerances	pH tolerance according to USDA-NRCS (2006): 4.0 - 9.0
Salinity tolerance	Moderate (similar to *Scirpus validus*)
Habitat dominance	Often dominant in habitat and forms dense monospecific stands, can out-compete other species by the dense rhizomatous root system (Stevens, 2003b).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be permanently inundated up to 0.4 m in constructed wetlands treating dairy farm wastewaters (Tanner, 1997), low drought tolerance (USDA-NRCS, 2006).
6. Removal efficiencies, tolerance to waste-	

water constituents and root zone effects	
General aspects	*Scirpus californicus* appears to be a well-suitable species for use in constructed wetlands for treatment of agricultural, non-point source pollutions and municipal wastewaters (Surrency, 1993).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	No appropriate study available
Nitrogen and phosphorus compounds: evaluation of existing case studies	The study conducted by Surrency (1993) revealed no growth inhibition at mean ammonium concentrations of 160 - 170 mg/L. Higher tolerance to ammonia-enriched organic wastewaters than *Scirpus validus* (de Lange, 1998).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	High productive species (Busnardo, 1992)
Biomass production, growth rates and yields	Mean aboveground biomass production of *Scirpus californicus* under higher nutrient conditions (dairy farm wastewaters) in constructed wetlands under warm/temperate conditions in News Zealand: 54.4 t/ha (in: de Lange, 1998)
Biomass utilization options	Utilization options are similar to *Scirpus acutus*: - Can be used as weaving material, e.g. mats, baskets, etc., - building material, e.g. thatching and roof materials (the stems have been used for tule houses in California, USA, due to their insulating and water-proof property), - can be used for bedding. (Stevens, 2003b)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Very similar to *Scirpus validus,* but taller and more robust (de Lange, 1998), - in a study conducted by Campagna (2001) in Southern Brazil (subtropical climate) *Scirpus californicus* was, beside other wetland species, subjected to an effluent from an oil and petroleum refinery without any limitations in survival and permanence. Compared to *Scirpus validus, Scirpus californicus* usually achieves higher aboveground biomass production rates, especially under nutrient-enriched conditions in CWs (de Lange, 1998).

9.12 *Scirpus cyperinus* (wool grass)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: North America

1. Plant species	
Common name	Wool grass, wool grass bulrush
Scientific name (genus / species)	*Scirpus cyperinus*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Cold/boreal to temperate
Geographic range	Native to Eastern North America (USA, Canada): natural range: from Newfoundland to Florida (PFAF, 2004)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent (Thunhorst, 1993)
Growth height	Up to 2 m (Silberhorn, 1995)
Growth rate and period	Moderate (Thunhorst, 1993)
Reproduction	Vegetative and generative

Root and rhizome growth and development	Shallow root penetration
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater marshes, wet meadows, ponds and swamps (Thunhorst, 1993)
Light demand, shade tolerance	Full sun (Thunhorst, 1993), but tolerates semi-shade (USDA-NRCS, 2006)
pH optimum and tolerances	pH tolerance range: 4.8 - 7.2 (USDA-NRCS, 2006)
Salinity tolerance	Low (freshwater species), < 0.5 ppt (Thunhorst, 1993)
Habitat dominance	No sufficient data available
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated irregularly to seasonally (Thunhorst, 1993), low tolerance to droughts (USDA-NRCS, 2006).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	This species is, beside *Scirpus validus*, commonly used, particularly, in surface flow treatment wetlands in Canada (Crolla, 2004). However, no case study for the treatment of municipal or domestic wastewater in the cold/boreal climate of North America was available. Only studies that use this species for the treatment of animal wastewaters (e.g. Hunt, 2003) or stormwater runoffs (Shaw, 2003) were available.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	No data found
Nitrogen and phosphorus compounds: evaluation of existing case studies	No data found
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Moderate
Biomass production, growth rates and yields	No data found
Biomass utilization options	- Stems can be used as weaving material (PFAF, 2004)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Frost tolerant species (USDA-NRCS, 2006)

9.13 *Scirpus pungens* (Olney's bulrush)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: North America
- Warm/Mediterranean climate zones of: North America (California, USA)

1. Plant species	
Common name	Olney's bulrush, three-square bulrush, American bulrush
Scientific name (genus / species)	*Scirpus pungens*, syn.: *Scirpus americanus*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Temperate to warm/Mediterranean
Geographic range	Native to throughout North America
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, semi-persistent (Thunhorst, 1993)
Growth height	Up to 1.5 m (USDA-FS, 2006)
Growth rate and period	Rapid (Thunhorst, 1993)
Reproduction	Mainly vegetative, usually low generative reproduction (USDA-FS, 2006)
Root and rhizome growth and development	Relatively shallow rhizome system, up to about 0.15 m into the depth (USDA-FS, 2006)

4. Habitat conditions and behaviour	
Natural Habitat	Brackish and alkaline marshes (Thunhorst, 1993), but also in freshwater marshes (USDA-FS, 2006)
Light demand, shade tolerance	Full sun (Thunhorst, 1993)
pH optimum and tolerances	pH range according to USDA-NRCS, 2006): 3.7 - 7.5. However, alkaline conditions are also tolerated (Hoag, 1998c): according to Mandel (1992): up to pH 8.9.
Salinity tolerance	High, up to 15 ppt (brackish waters), (Thunhorst, 1993)
Habitat dominance	Forms nearly monospecific stands, especially in brackish or saline marshes (USDA-FS, 2006).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated regularly to permanently up to 0.3 m (Thunhorst, 1993); tolerates temporarily inundations up to 0.45 m as well as seasonal drought periods (Hoag, 1998c).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	The BOD and TSS removal performance of *Scirpus pungens* was proved in a study conducted by De Busk (1990) in Central Florida, USA, in a subsurface flow gravel bed receiving primary domestic effluent. Removal efficiencies: - BOD: 89.8 % (mean BOD influent conc.: 177 mg/L) - TSS: 92.0 % (mean TSS influent conc.: 50 mg/L) → During the winter season, only a slight decrease in the treatment performance was observed (De Busk, 1990). A study conducted by Burgoon (1991a) revealed that *Scirpus pungens*, planted in a subsurface horizontal flow gravel bed, is as well as effective in BOD removal than *Phragmites australis* and *Typha latifolia* (BOD removal rate*: 93.2* %, mean influent conc.: 120 mg/L).
Nitrogen and phosphorus compounds: evaluation of existing case studies	No appropriate data available; a further study also conducted by Burgoon (1991b) showed nitrogen removal rates of *Scirpus pungens*, planted in a subsurface flow bed with gravel substrate, similarly high as *Phragmites australis.*
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Moderate productive species
Biomass production, growth rates and yields	No appropriate data available
Biomass utilization options	- The leaves can be used as weaving material (Stevens, 2000a), - the stems can serve as thatching material (Stevens, 2000a).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No appropriate data available
Phosphorus: uptake and assimilation rates	No appropriate data available
9. Further remarks and comparisons with other plant species (if possible)	- *Scirpus pungens* shows a markedly metal accumulation capacity (Schueler, 1992), - a poor regrowth after harvesting: reduced biomass yields after each harvest was observed by Burgoon (1991b).

9.14 *Scirpus validus* (soft stem bulrush)

Suitable and recommended for constructed wetlands in:
- Cold/boreal climate zones of: North America
- Temperate climate zones of: North America and New Zealand

1. Plant species	
Common name	Soft stem bulrush, river club rush
Scientific name (genus / species)	*Scirpus validus*, syn.: *Scirpus tabernaemontani,*

	Schoenoplectus validus, Schoenoplectus tabernaemontani
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Cold/boreal to warm/temperate
Geographic range	Throughout North America (all areas, except for the extreme north), (PFAF 2004).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous; persistent, but shows a strongly dieback and marked senescence of the aboveground biomass in winter season (Tanner, 1996, 1997).
Growth height	Up to 2 - 3 m (Chambers, 1994b)
Growth rate and period	Rapid (Thunhorst, 1993)
Reproduction	Vegetative and generative
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater and brackish marshes, pond and lake margins, shallow water sites (CAPRT, 2004; Thunhorst, 1993)
Light demand, shade tolerance	Full sun (Thunhorst, 1993)
pH optimum and tolerances	pH range according to Schueler (1992): 6.5 - 8.5)
Salinity tolerance	Moderate, up to 5 ppt (tolerates slightly brackish waters), (Thunhorst, 1993); appears to grow better under saline conditions than in freshwaters (USDA-FS, 2006).
Habitat dominance	Aggressive colonizer, often dominant (Schueler, 1992); however, reduced growth in competition with *Typha latifolia* (Coleman, 2001).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Tolerant to regular to permanent inundations from 0.3 m (Thunhorst, 1993) to 0.6 m (Blanch, 1994), tolerates periodical inundations up to 1.3 m, but no strongly fluctuating water levels (Chambers, 1994b).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	*Scirpus validus* is, beside *Scirpus cyperinus*, commonly used in constructed wetlands in Canada, particularly in surface flow systems (Crolla, 2004). According to Tanner (1997), probably the most common plant species in constructed wetlands in New Zealand. Generally, *Scirpus validus* shows a high pollutant removal performance.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	The high efficiency of *Scirpus validus* in BOD removal was proved in several studies in the USA, e.g. Coleman (2001) and Gersberg (1986) with mean reductions of > 70 % and 96 %, respectively. *Scirpus validus* stands remained also healthy when exposed to primary (raw) wastewater with the following concentrations: BOD: 118.3 mg/L, TSS: 57.3 mg/L and NH_4^+-N: 24.7 mg/L (Gersberg, 1986). In a study conducted by Heritage (1995) in NSW, Australia (warm/temperate climate, ≈ 34 °S), where *Scirpus validus* was planted in a VF wetland for treatment of primary urban sewage with relatively high fluctuating influent concentrations (134 - 575 mg/L BOD), the reduction of BOD achieved 92 % and more (Heritage, 1995).
Nitrogen and phosphorus compounds: evaluation of existing case studies	Inhibited and reduced growth rate at ammonia concentrations of above 100 mg/L after a period of weeks; however, shorter periods of evaluated ammonia conc. did not appear to affect growth → High ammonia tolerance (Clarke, 2002). The same study showed that flooded conditions (0.1 m) did not significantly increase ammonia toxicity to *Scirpus validus* compared with non-flooded conditions. However, another study reported no growth inhibition at 160 - 170 mg/L ammonium concentrations (Surrency, 1993). Compared to other wetland species (*Baumea articulata* and *Cyperus involucratus*), the removal performance for nitrogen

	and phosphorus declined markedly into autumn due to the seasonal physiological response (strong dieback in winter) of this species (Heritage, 1995).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	The study by Gersberg (1986) showed an ammonium removal efficiency of 94 % in a bed planted with *Scirpus validus* (mean influent conc.: 24.7 mg/L NH_4^+-N) compared to *Phragmites australis* (78 %) and *Typha latifolia* (28 %). The high removal efficiency in this study was largely explained by the deep root penetration of the bulrushes (≈ 0.76 m) that increased oxidized conditions in the rhizosphere stimulating the nitrification activity.
7. Productivity, utilization options and economic potential	
Potential productivity	Moderate to high productive species
Biomass production, growth rates and yields	- Aboveground biomass yield according to Tanner (1996) in New Zealand (warm/temperate climate): 16.5 t/ha (dry wt).
Biomass utilization options	Biomass utilization options are supposed to be similarly versatile as *Scirpus lacustris*, e.g.: - Stems can be used as weaving material (e.g. mats, etc.) and basket making (PFAF, 2004). However, further information could not be found.
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	- Harvestable range of nitrogen uptake capacity (growth rate) for *Scirpus sp.* in general: 125 - 775 kg/(ha*yr) (Vymazal, 1995b; in: IWA, 2000), - harvestable annual uptake in a warm/temperate climate (NZ): ≈ 400 kg/(ha*yr), (Tanner, 1996).
Phosphorus: uptake and assimilation rates	- Harvestable range of phosphorus uptake capacity (growth rate) for *Scirpus sp.* in general: 18 - 150 kg/(ha*yr) (Vymazal, 1995b; in: IWA, 2000), - harvestable annual uptake in a warm/temperate climate (NZ): ≈ 55 kg/(ha*yr), (Tanner, 1996).
9. Further remarks and comparisons with other plant species (if possible)	- Frost tolerant species, not affected through low temperatures up to about - 19 °C (Surrency, 1993), - quick to establish in constructed wetlands (compared to e.g. *Phragmites australis*), - very closely related to *Scirpus lacustris.* Together with *Baumea articulata* and *Cyperus involucratus, Scirpus validus* showed a moderate aboveground biomass production in the comparative study in conducted by Tanner (1996) in New Zealand.

9.15 *Typha capensis* (common cattail)

Suitable and recommended for constructed wetlands in:
- Warm/temperate climate zones of: South Africa

1. Plant species	
Common name	Common cattail
Scientific name (genus / species)	*Typha Capensis*, syn.: *Typha latifolia ssp. capensis*
Family	*Typhaceae*
2. Availability in climate zone	
Climatic range	Warm/temperate
Geographic range	Native to Southern Africa (e.g. South Africa, Zimbabwe)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent (similar to *T. latifolia* and *T. angustifolia*)
Growth height	Up to 2.5 - 3 m (similar to *T. latifolia* and *T. angustifolia*)
Growth rate and period	Very fast, rapid establishment (Wood, 1989)
Reproduction	Rapidly spreading by vegetative reproduction, but also readily generative reproduction (similar to *T. latifolia* and *T. angustifolia*).

Root and rhizome growth and development	Shallow, horizontal growing, root and rhizome system (similar to *T. latifolia* and *T. angustifolia*).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater marshes, swamps and lake margins
Light demand, shade tolerance	Full sun (similar to *T. latifolia* and *T. angustifolia*)
pH optimum and tolerances	No sufficient data available
Salinity tolerance	No sufficient data available
Habitat dominance	Highly invasive and dominant species, aggressive colonizer; commonly forms dense monoculture stands (similar to *T. latifolia* and *T. angustifolia*).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Presumably similar to *Typha latifolia* and *Typha angustifolia*
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Due to the very high phenological and morphological similarity to *Typha latifolia* and *Typha angustifolia,* one can expect that *Typha capensis* is not less suitable in constructed wetlands than the more common types of *Typha sp.* The most studies investigating the performance of this species were undertaken in South Africa, primarily by Wood (1989).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In one pilot study conducted in South Africa, a high COD removal performance (94 %) was achieved. Influent: settled sewage from a septic tank with a mean COD conc. of 332 mg/L; soil substrate: waste ash (Wood, 1989) → The removal efficiency of *Typha capensis* was similar to the other species tested in this study (for example *Scirpus lacustris* or *Phragmites australis*).
Nitrogen and phosphorus compounds: evaluation of existing case studies	The same study achieved also very high ammonium nitrogen (94 %, mean influent conc.: 20.7 mg/L NH_4^+-N) and phosphate (92 %, mean influent conc.: 8 mg/L PO_4^--P) removal efficiencies with no significant differences compared to the other species (Wood, 1989).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found, presumably similar to the other types of *Typha sp.*
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species (similar to *T. latifolia* and *T. angustifolia*)
Biomass production, growth rates and yields	No plant-specific data found
Biomass utilization options	No specific data available; however, utilization options for *Typha capensis* can be supposed to be similarly versatile as the more common types of *Typha sp.* (see *Typha latifolia* in Chapter 8.8)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Taxonomically intermediate between *Typha latifolia* and *Typha angustifolia:* very similar to the hybrid of *Typha latifolia* and *Typha angustifolia* (*Typha x glauca*). However, *Typha capensis* is considered as a single species, - the geographic distribution is confined to Southern Africa (Smith, 1987), - capable of forming floating mats of rhizomes, roots and accumulating plant litter on shallow open water sites (IWA, 2000).

9.16 *Typha subulata* (cattail, totora)

Suitable and recommended for constructed wetlands in:
- Warm/temperate to subtropical climate zones of: South America (southern parts)

1. Plant species	
Common name	Cattail; common name in South America: totora
Scientific name (genus / species)	*Typha subulata*
Family	*Typhaceae*
2. Availability in climate zone	
Climatic range	Warm/temperate to subtropical
Geographic range	Warm/temperate and subtropical Southern South America (e.g. Argentina, Southern Brazil, Uruguay), (Giovaninni, 1999)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent (similar to *Typha domingensis*)
Growth height	Up to 2.5 - 3 m (similar to *Typha domingensis*)
Growth rate and period	Rapid, rapid establishment (similar to *Typha domingensis*)
Reproduction	Spreads rapidly by vegetative reproduction, but also readily generative reproduction (similar to *Typha domingensis)*
Root and rhizome growth and development	Shallow root penetration (similar to *Typha domingensis*)
4. Habitat conditions and behaviour	
Natural Habitat	No sufficient data available
Light demand, shade tolerance	Presumably full sun (similar to *Typha domingensis*)
pH optimum and tolerances	No sufficient data available
Salinity tolerance	No sufficient data available; however, *Typha subulata* appears to have a higher salt tolerance than *Typha latifolia*, similar to *Typha domingensis* and *Typha angustifolia.*
Habitat dominance	Highly invasive and dominant (similar to *Typha domingensis)*
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated irregularly to permanently; according to Kadlec and Knight (1996): up to 0.75 m. According to the study conducted by Giovaninni (1999), *Typha subulata* appears to grow best under permanently flooded conditions (about 0.1 m) rather than at fluctuating water levels.
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	Due to the very high similarity to the more common types of *Typha sp.,* especially *Typha domingensis* and *Typha angusti-folia*, one can expect that *Typha subulata* shows similar re-moval efficiencies. However, no appropriate operational case study or investigation was available.
Organic constituents (BOD and COD) and sus-pended solids (TSS): evaluation of existing case studies	No appropriate data available
Nitrogen and phosphorus compounds: evaluation of existing case studies	No appropriate data available
Root zone effects: oxygenation capacity and ef-fect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found, presumably similar to the other types of *Typha sp.*
7. Productivity, utilization options and eco-nomic potential	
Potential productivity	Highly productive species (da Motta Marques, 2001), similar biomass production rates compared to the more common types of *Typha sp.* can be supposed.
Biomass production, growth rates and yields	No sufficient data available
Biomass utilization options	High potential as a source of biomass for renewable energy and versatile utilization options (very similar to the more com-mon types of *Typha sp.* (see *Typha latifolia* in Chapter 8.8).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Very closely related to *Typha angustifolia* and especially to *Typha domingensis* (Smith, 1987),

	- in a study conducted by Campagna (2001) in Southern Brazil (subtropical climate), *Typha subulata* was, beside other species, subjected to an effluent from an oil and petroleum refinery without any limitations in growth, survival and permanence.

9.17 *Zizania latifolia* (Manchurian wild rice)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: East Asia and restricted parts of New Zealand

1. Plant species	
Common name	Manchurian wild rice, water bamboo
Scientific name (genus / species)	*Zizania latifolia*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Warm/temperate to subtropical
Geographic range	Native to East Asia (North and South China, Japan, Korea, Vietnam, Taiwan) and Southern Russia; according to Tanner (1997), introduced to restricted areas of New Zealand, but considered as a weed in Northern New Zealand (Tanner, pers. comm.)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent, no significant dieback during the winter season (Tanner, 1996).
Growth height	Up to 3.5 - 4 m (ISSG, 2005)
Growth rate and period	Very fast, growth throughout the year (Tanner, 1996)
Reproduction	Vegetative and generative
Root and rhizome growth and development	Strong and deep root rhizome (Tanner, 1996)
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater and brackish swamps, marshes, slow moving or stagnant shallow waters (PFAF, 2004)
Light demand, shade tolerance	Semi-shade to full sun (PFAF, 2004)
pH optimum and tolerances	pH range for best growth: 5.5 - 6.0 (slightly acidic conditions); tolerated soil pH range: 4.5 - 7.0 (NewCROP, 2005).
Salinity tolerance	Tolerant to saline (brackish) waters (EW-NZ, 2006)
Habitat dominance	Highly invasive, forms dense stands that can out-compete almost any native plant species (ISSG, 2005).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Tolerates prolonged inundated conditions up to a water depth of 1 m (Kadlec and Knight, 1996) → Can grow in deeper waters than *Phragmites australis* (Yamasaki, 1981).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Although this species appears to be well-suitable for use in constructed wetlands and shows a very high productivity, only one study (Tanner, 1996) that investigated the performance in constructed wetland systems was available for this thesis.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Removal efficiency of *Zizania latifolia* planted in a small-scale gravel bed for treatment of dairy farm wastewater according to the study conducted by Tanner (1996) in the warm/temperate conditions of New Zealand: BOD reduction: > 77 % (mean BOD influent conc.: 87.6 mg/L) TSS reduction: > 76 % (mean TSS influent conc.: 95.7 mg/L)
Nitrogen and phosphorus compounds: evaluation of existing case studies	An influent concentration of up to about 105 mg/L NH_4^+-N was tolerated without obvious plant damages (typical concentrations found in dairy farm wastewaters, the NH_4^+-N conc. in municipal wastewaters are significantly lower), (Tanner, 1996).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Appears to have a higher root zone oxygenation capacity than *Phragmites australis* (Yamasaki 1987).
7. Productivity, utilization options and economic potential	
Potential productivity	High productive species (Tanner, 1996); appears to have a

	high potential as renewable biomass source.
Biomass production, growth rates and yields	In the study conducted by Tanner (1996) in New Zealand (warm/temperate climate, ≈ 37 °S), *Zizania latifolia* showed, together with *Glyceria maxima,* the highest aboveground biomass yields of the plant species tested in this study: 38 t/ha.
Biomass utilization options	- The leaves can be used as weaving material, e.g. for mats, etc. (PFAF, 2004), - is used for making of handmade paper in New Zealand (ZPP, 2006), - in China, *Zizania latifolia* is used as raw material for building purposes and as fuel source (Yan, 1994).
8. Nutrients: uptake and storage capacities	
General aspects	Generally, the nutrient tissue concentrations in *Zizania latifolia* are relatively low. However, due to the high productivity nitrogen and phosphorus uptake capacities can be very high (*Zizania latifolia* showed the highest nutrient uptake capacities in the study conducted by Tanner (1996).
Nitrogen: uptake and assimilation rates	Harvestable annual uptake rate under warm/temperate conditions in New Zealand: ≈ 760 kg/(ha*yr), (Tanner, 1996)
Phosphorus: uptake and assimilation rates	Harvestable annual uptake rate under warm/temperate conditions in New Zealand: ≈ 95 kg/(ha*yr), (Tanner, 1996)
9. Further remarks and comparisons with other plant species (if possible)	- Tolerates light frosts with winter temperatures up to -4 °C (PFAF, 2004), - can be a serious weed risk in areas where it is not naturally present (ISSG, 2005), - robust and stress tolerant species, similar to *Phragmites australis* (Tanner, 1996).

9.18 *Zizaniopsis bonariensis* (Espadaña)

Suitable and recommended for constructed wetlands in:
- Warm/temperate and subtropical climate zones of: South America (southern parts)

1. Plant species	
Common name	Espadaña, cut-grass
Scientific name (genus / species)	*Zizaniopsis bonariensis*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Warm/temperate to subtropical
Geographic range	Warm/temperate and subtropical Southern South America (e.g. Argentina, Southern Brazil, Uruguay), (Giovaninni, 1999)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial
Growth height	Up to 4 m possible, the height correlates positively with increasing water level (Giovaninni, 1999).
Growth rate and period	Rapid (da Motta Marques, 2001), responds strongly to nutrient supply (Campagna, 2001).
Reproduction	Mainly vegetative
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Presumably freshwater wetlands and swamps
Light demand, shade tolerance	No sufficient data available
pH optimum and tolerances	No sufficient data available
Salinity tolerance	No sufficient data available
Habitat dominance	Forms large monospecific stands in the Southern Brazilian wetlands (da Motta Marques, 2001).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Tolerates a wide range of water levels; however, according to the study conducted by Giovaninni (1999), *Zizaniopsis bonariensis* appears to grow best under permanently flooded conditions (about 0.1 m) rather than at fluctuating water levels.
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	This species showed a high potential to be used in constructed

	wetlands with removal performances only slightly lower than *Typha sp*. (da Motta Marques, 2001).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	*Zizaniopsis bonariensis* was investigated in a wetland system consisting of a septic tank followed by a root zone in Florianopolis-SC, Brazil (warm/temperate climate, ≈ 27.1 °S) treating relatively high strength domestic and industrial effluents. Removal efficiencies (including pre-treatment): - BOD: 69 % (raw sewage, mean influent conc.: 449 mg/L) - COD: 71 % (raw sewage, mean influent conc.: 1045 mg/L) (Philippi, 1999).
Nitrogen and phosphorus compounds: evaluation of existing case studies	In terms of nutrient removal (N and P), the removal efficacies were 78 % for TN (mean influent conc.: 224 mg/L) and 72 % for TP (mean influent conc.: 47 mg/L), (Philippi, 1999).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	High productive species with a high potential as a renewable biomass source.
Biomass production, growth rates and yields	No data found
Biomass utilization options	No utilization options found
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- In a study conducted by Campagna (2001) in Southern Brazil (subtropical climate), *Zizaniopsis bonariensis* was, beside other wetland species, subjected to an effluent from an oil and petroleum refinery without any limitations in growth, survival and permanence.

9.19 *Zizaniopsis miliacea* (giant cutgrass)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: North America (mainly southern parts)

1. Plant species	
Common name	Giant cutgrass, southern wild rice
Scientific name (genus / species)	*Zizaniopsis miliacea*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Temperate to warm
Geographic range	Native to USA, mainly south-eastern states (CAPRT, 2004)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous
Growth height	Up to 3 m (CAPRT, 2004)
Growth rate and period	Rapid with a quick establishment, long vegetation period: grows into the winter months when many other plants have already become dormant (USDA-SCS, 1993).
Reproduction	Mainly vegetative, less generative reproduction (USDA-SCS, 1993)
Root and rhizome growth and development	Extensive, creeping rhizome and root system (USDA-SCS, 1993)
4. Habitat conditions and behaviour	
Natural Habitat	Shallow fresh to brackish water sites of marshes and swamps, shorelines of lakes and ponds (CAPRT, 2004)
Light demand, shade tolerance	Full sun (USDA-NRCS, 2006)
pH optimum and tolerances	pH tolerance according to USDA-NRCS (2006): 5.6 - 6.8
Salinity tolerance	Freshwater species, but tolerant up to 10 ppt (USDA-SCS, 1993).
Habitat dominance	Aggressive and invasive plant species (Surrency, 1993); grows in dense and almost impenetrable stands (CAPRT, 2004).

5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Plant growth and survival was not affected by water levels of up to 0.3 m (Surrency, 1993), sensitive to dry conditions (USDA-NRCS, 2006), according to Kadlec and Knight (1996) this species can be inundated permanently up to 1 m.
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	*Zizaniopsis miliacea* appears to be a well-suitable species for use in constructed wetlands for treatment of agricultural, non-point source pollutions and municipal wastewaters.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In a constructed wetland system planted with giant cutgrass in South Georgia, USA (temperate climate, ≈ 30.4 °N) for treatment of municipal wastewater, the BOD concentration was significantly reduced (data about influent and effluent concentrations were not available), (Surrency, 1993).
Nitrogen and phosphorus compounds: evaluation of existing case studies	According to USDA-SCS (1993) *Zizaniopsis miliacea* appears to be tolerant to ammonium concentrations of higher than 100 mg/L for extended periods.
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Appears to be a high productive species with a great potential. However, data about biomass production rates and utilization options were not available.
Biomass production, growth rates and yields	No data found
Biomass utilization options	No utilization options found
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Usually a warm season grass; however, *Zizaniopsis miliacea* shows a high frost tolerance (up to - 19 °C), (Surrency, 1993).

10 Standard plants for low-latitude climates

10.1 Plant species recommended for constructed wetlands

- *Arundo donax* (giant reed)
- *Canna flaccida* (canna lily)
- *Canna indica* (Indian shot)
- *Cyperus involucratus* (umbrella sedge)
- *Cyperus papyrus* (papyrus)
- *Pennisetum clandestinum* (Kikuyu grass)
- *Phragmites karka* (tall reed)
- *Phragmites mauritianus* (Lowveld reed)
- *Scirpus grossus* (greater club rush)
- *Typha orientalis* (broad-leaved cumbungi)
- *Vetiveria zizanioides* (vetiver grass)

10.2 *Arundo donax* (giant reed)

Suitable and recommended for constructed wetlands in:
- Warm/Mediterranean climate zones of: Southern Europe
- Subtropical climate zones of: South Asia (India, Sri Lanka, etc.)

1. Plant species	
Common name	Giant reed, bamboo reed
Scientific name (genus / species)	*Arundo donax*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Warm/Mediterranean to (sub)tropical
Geographic range	Native to the Mediterranean region, India and Sri Lanka; introduced to many subtropical and warm/temperate regions worldwide (NewCROP, 2005).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial, persistent and green year-round in frost free climates, dies down to the ground in frosty areas (Floridata, 2006)
Growth height	Up to 6 - 8 m and higher (NewCROP, 2005; Wissing, 2002)
Growth rate and period	Very fast, strongly correlating with nutrient supply; a free water surface wetland in southern Crete with a total surface area of 5,700 m^2 was completely covered within two years (Manios, 2002).
Reproduction	Mainly vegetative, generative only in indigenous regions (ISSG, 2005)
Root and rhizome growth and development	Shallow, branched, horizontally growing root and rhizome system; poor depth penetration (up to 0.3 m) compared to *Phragmites sp.* (ISSG, 2005; Wood, 1989). The roots usually lie close to the soil surface (0.05 - 0.15 m deep), (Sharma, 1998).
4. Habitat conditions and behaviour	
Natural Habitat	Ditches, riversides and (coastal) marshlands (ISSG, 2005)
Light demand, shade tolerance	Full sun (Faucon, 2005)
pH optimum and tolerances	pH tolerance range according to USDA-FS (2006): 5.0 - 8.7; pH tolerance range according to PFAF(2004): 5.5 - 8.3
Salinity tolerance	Tolerates weakly saline conditions (NewCROP, 2005).
Habitat dominance	Highly invasive and aggressive species; forms dense homogeneous vegetation stands and out-competes most other species, even species invasive such as *Typha domingensis* can be out-competed as observed in the study conducted by Manios (2002) on Crete.
5. Water regime	

Hydroperiod: tolerance to inundations, droughts and water levels	According to Manios (2002), *Arundo donax* can, used in a free water surface system for treatment of domestic wastewater, tolerate water levels of 0.3 - 0.4 m. However, in the study conducted by Surrency (1993), *Arundo donax* could not tolerate a water depth of 0.15 m in a CW for treatment of swine wastewater. Once established, *Arundo donax* stands show a relatively high drought tolerance (USDA-FS, 2006).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	The removal efficiency of *Arundo donax* was proved in a free water constructed wetland system in Southern Crete (Mediterranean climate, ≈ 35 °N) treating primary domestic wastewater (Manios, 2002): - BOD removal rate: 90 % (mean influent conc.: 50 mg/L) - TSS removal rate: 95 % (mean influent conc.:100 mg/L) In another study conducted by Wood (1989) in South Africa, a moderate COD removal of 65 % (mean influent conc.: 271 mg/L) was achieved. This relatively poor removal performance was explained by the shallow root penetration (Wood, 1989; Batchelor, 1990).
Nitrogen and phosphorus compounds: evaluation of existing case studies	Ammonium removal rates in the studies of Manios (21 %, mean influent conc.: 19 mg/L NH_4^+-N) as well as Wood (18 %, mean influent conc.: 42.8 mg/L NH_4^+-N) were low: also explained by the poor root penetration and reduced conditions around the rhizomes (Manios, 2002; Wood, 1989).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Since *Arundo donax* is not a true wetland plant, it does not possess a convective flow system (Brix, 1992). → Can only grow in very shallow water and shows a poor root zone oxygenation capacity.
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species with an enormous potential as a renewable source of biomass.
Biomass production, growth rates and yields	Annual productivity ranges according to Westlake (1963) in natural stands: - 57 - 59 t/(ha*yr), (Merinotti, 1941, in: Westlake, 1963), - 40 - 75 t/(ha*yr), (estimation for warm/temperate and tropical regions) Aboveground annual net primary production of a natural *Arundo donax* stand in an Indian wetland (Jaipur, Rajasthan, India, ≈ 26 °N) under subtropical conditions: - 20.8 t/ha (stems were not harvested) - 66.52 t/ha (stand were harvested once a year) - 73.19 t/ha (stand were harvested twice a year) → The highest aboveground productivity was achieved when the stands were harvested twice a year. However, the growth of the belowground plant organs were adversely affected, and thus, annual harvesting was recommended (Sharma, 1998).
Biomass utilization options	*Arundo donax* has highly versatile utilization options. Stems: - support for vines and similar climbing plants (trellises), - measurement rods, musical instruments, baskets and mats, - fibres: paper making due to the high cellulose content, - other industrial purposes (e.g. fishing poles, in Italy: rayon), - the leaves of young plants can be used as forage. (Hurter, 1988; NewCROP, 2005) - Building material (thatching, roof materials), - particle board production (Niklas, 1990), - basket making (especially in South Europe), - the leaves can be used as weaving material, e.g. mats, etc. (PFAF, 2004) - High potential as a renewable source of biomass for energy,

	- in the Mediterranean region, *Arundo donax* can be used as a renewable biomass source for fibre production and as heating material (Wissing, 2002), - high biomass yields are obtained also in natural wetlands.
8. Nutrients: uptake and storage capacities	
General aspects	Sufficient data for nutrient uptake capacities and accumulation rates of this plant species are still not available until today. It can be supposed that the uptake capacities are relatively high due to the high biomass production (Manios, 2002).
Nitrogen: uptake and assimilation rates	No sufficient data available
Phosphorus: uptake and assimilation rates	No sufficient data available
9. Further remarks and comparisons with other plant species (if possible)	- Very similar to *Phragmites australis,* - the stems can be harvested at any time of the year (New CROP, 2005), - high evapotranspiration rates (ISSG, 2005).

10.3 *Canna flaccida* (canna lily)

Suitable and recommended for constructed wetlands in:
- Subtropical climate zones of: North America (Florida, USA)
- Subtropical climate zones of: Central America (Caribbean region, Mexico, etc.)

1. Plant species	
Common name	Canna lily, golden canna
Scientific name (genus / species)	*Canna flaccida*
Family	*Cannaceae*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native to Southern North America (e.g. Florida, Louisiana) and Central America (e.g. Mexico, Caribbean region)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous (Floridata, 2006)
Growth height	Up to 1.5 m (Gilman, 1999)
Growth rate and period	Rapid (Gilman, 1999)
Reproduction	Mainly vegetative, but also low generative reproduction (Gilman, 1999)
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater wetlands, pond and lake margins (Floridata, 2006)
Light demand, shade tolerance	Full sun, but also tolerates partial shade (Floridata, 2006)
pH optimum and tolerances	Tolerates acidic to slightly alkaline soil conditions (Floridata, 2006)
Salinity tolerance	Low (Gilman, 1999)
Habitat dominance	Not known to be invasive (Gilman, 1999)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated regularly to permanently up to 0.25 m (Kadlec and Knight, 1996), shows a moderate drought tolerance (Floridata, 2006).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Although Wolverton (1989) reported that *Canna flaccida*, planted in a rock/gravel filter bed, is able to treat effluents from a septic tank, only one study that investigated the high potential of this species in constructed wetlands was available. This study was conducted by Belmont in 2004 and showed that *Canna flaccida* performed as well as *Typha sp* for treatment of domestic wastewater. However, according to Kantawanichkul (pers. comm.), the influent concentrations should not be high- or over-loaded. Since *Canna sp.* can only grow in very shallow waters or on wet soils, they are not suitable for surface flow wetlands (Brix, 1992).

Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	The study of Belmont (2004) was undertaken in Santa Maria Nativitas, Central Mexico (warm/subtropical climate, ≈ 19.2 °N). In this multistage system for treatment of domestic wastewaters, *Canna flaccida* was planted (together with *Zantedeschia aethiopica*) in a subsurface flow bed and was compared to *Typha angustifolia*, also planted in a subsurface flow bed connected in parallel to the *Canna* bed. - Mean COD removal (whole treatment system): 84.9 % - Mean COD removal (*Canna* bed): 79.8 % - Mean COD removal (*Typha* bed): 77.0 % (mean influent conc.: 643.1 mg/L COD) → No significant differences between these two plant species concerning COD removal. → Similar conclusions were made for TSS reduction.
Nitrogen and phosphorus compounds: evaluation of existing case studies	Comparison of the total nitrogen (TN) removal efficiencies (Belmont, 2004): - Mean TN removal (whole treatment system): 71.7 % - Mean TN removal (*Canna* bed): 58.3 % - Mean TN removal (*Typha* bed): 54.7 % (influent conc.: 70.0 mg/L TN) → The TN removal performance was low for both species, however, no significant difference between these two plant species. → Similar conclusions were made for ammonia reduction.
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	*Canna flaccida* shows a relatively poor root zone oxygenation capacity (Brix, 1992).
7. Productivity, utilization options and economic potential	
Potential productivity	Appears to be a high productive species; according to the study by De Busk (1995), *Canna flaccida* showed the highest biomass yields under nutrient-enriched conditions compared to nine other emergent wetland species (among others: *Juncus effusus,. Phragmites australis* and *Typha domingensis*).
Biomass production, growth rates and yields	Mean aboveground biomass yields of *Canna flaccida* growing in a secondary lagoon effluent in Okeechobee, Florida, USA (subtropical climate, ≈ 27.2 °N): - 38 t/ha, under nutrient-enriched conditions, - 14 t/ha, without nutrient additions (control effluent) (De Busk, 1995)
Biomass utilization options	- The flowers can be sold for decoration purposes or for gardening, however, not for a big market (Kantawanichkul, pers. comm.)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No appropriate data available
Phosphorus: uptake and assimilation rates	No appropriate data available
9. Further remarks and comparisons with other plant species (if possible)	- Relatively hardy plant species (Belmont, 2004), - however, *Canna flaccida* was killed by the first heavy frost (up to - 19 °C) during the winter season in North Eastern Alabama, USA (temperate climate), (Surrency, 1993).

10.4 *Canna indica* (Indian shot)

Suitable and recommended for constructed wetlands in:
- Subtropical to tropical climate zones of: Central and South America (northern parts)
- Subtropical climate zone of: South Asia (India) and Southeast Asia (e.g. South China)

1. Plant species	
Common name	Indian shot
Scientific name (genus / species)	*Canna indica*
Family	*Cannaceae*
2. Availability in climate zone	

Climatic range	Subtropical to tropical
Geographic range	Native to tropical Central and South America (Floridata, 2006); naturalized in many subtropical and tropical regions worldwide, e.g. in India and South China (PFAF, 2004).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous
Growth height	Up to 1.5 - 2 m (PFAF, 2004; USDA-IPIF, 2005)
Growth rate and period	Rapid (Floridata, 2006)
Reproduction	Vegetative and generative
Root and rhizome growth and development	Thick and branched rhizome system (ISSG, 2005)
4. Habitat conditions and behaviour	
Natural Habitat	Disturbed and moderately polluted areas, riparian zones and water courses (ISSG, 2005)
Light demand, shade tolerance	Prefers full sun, but also tolerates partial shade (Floridata, 2006).
pH optimum and tolerances	No data found
Salinity tolerance	No data found
Habitat dominance	Potentially invasive (USDA-IPIF, 2005), may out-compete other species (ISSG, 2005).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	According to Kantawanichkul (pers. comm.), the influent concentrations should not be too high or over-loaded. Since *Canna sp.* can only grow in very shallow waters or on wet soils, they are not suitable for surface flow wetlands (Brix, 1992).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Three subspecies of *Canna indica* (yellow, orange and red flower canna) were planted, among other species, in the second stage of the multistage constructed wetland system according to the investigation by Lei (2004) in Shenzhen, South China (see Chapter 11.9 for further descriptions and removal results). → Generally, the *Canna* species showed a good growth year-round; however, the red flower canna was eliminated due to its poor growth. → Most parts of the *Canna* leaves became yellow and withered during the cold winter season in the windward side. → A direct comparison with the other species (*Miscanthus sacchariflorus, Phragmites australis, Scirpus validus* and *Thalia dealbata*) concerning removal performance was not possible. In another study (Yue, 2004), *Canna indica* was planted, together with *Lolium perenne,* in a medium-scale pilot system (vertical/reverse-vertical flow CW) for treatment of domestic wastewater in Ningbo, Zhejiang Province, China (subtropical climate, ≈ 30 °N). → High mean removal efficiencies for COD (≈ 91 %) and BOD (≈ 95 %), the influent corresponded to a low strength municipal wastewater and showed mean influent conc. of about 250 mg/L COD and 150 mg/L BOD. This species was also used in Bombay, India, under subtropical conditions where it was planted, together with *Cyperus sp.*, in a horizontal subsurface flow wetland for treatment of pre-treated municipal wastewater (Tayade, 2005). → High removal efficiency
Nitrogen and phosphorus compounds: evaluation of existing case studies	See Chapter 11.9: (*Miscanthus sacchariflorus*) Removal efficiencies according to the study by Yue (2004): - TN: average removal rate: ≈ 76 % (influent: ≈ 64 mg/L), - NH_4^+-N: average removal rate: ≈ 87 % (influent: ≈ 50 mg/L) - TP: average removal rate: ≈ 72 % (influent: ≈ 5.4 mg/L) → Very high efficiencies without clear seasonal variations

	(subtropical climate)
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	*Canna indica* shows a relatively poor root zone oxygenation capacity (Brix, 1992).
7. Productivity, utilization options and economic potential	
Potential productivity	Appears to be a high productive species
Biomass production, growth rates and yields	No data found
Biomass utilization options	- The leave fibres can be used for paper making, - a dye can be obtained from seeds. (PFAF, 2004) - The flowers can be sold for decoration purposes or for gardening, however, no for a big market (Kantawanichkul, pers. comm.)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Frost tender, vulnerable to cold temperatures (Lei, 2004; PFAF, 2004), - relatively sensitive to windy conditions (Lei, 2004).

10.5 *Cyperus Involucratus* (umbrella sedge)

Suitable and recommended for constructed wetlands in:
- Tropical climate zones of: Southern Africa
- Subtropical climate zones of: Southeast Asia
- Subtropical climate zones of: Northern Australia

1. Plant species	
Common name	Umbrella sedge, umbrella plant, umbrella grass, dwarf palm
Scientific name (genus / species)	*Cyperus involucratus*, syn.: *Cyperus flabelliformis, Cyperus alternifolius ssp. flabelliformis*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Subtropical to tropical, but also warm/temperate
Geographic range	Native to tropical and Southern Africa; naturalized throughout the tropical and subtropical regions of Southeast Asia (e.g. South China, Thailand,), warm/subtropical Australia (Queensland, New South Wales) and New Zealand.
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous; green year-round in warm/temperate climates and no dieback in winter (Hocking, 1985; Tanner, 1996)
Growth height	Up to 1.8 m (Tanner, 1997)
Growth rate and period	Rapid, year-round growth in warmer regions
Reproduction	Vegetative and generative
Root and rhizome growth and development	Strong, thick and densely branched root and rhizome system (Tanner, 1997)
4. Habitat conditions and behaviour	
Natural Habitat	Wet places, marshy areas and swamplands (Liao, 2003; USDA-IPIF, 2005)
Light demand, shade tolerance	Full sun, but also tolerates shady conditions (Floridata, 2006)
pH optimum and tolerances	No sufficient data available; appears to prefer slightly acid soil conditions (USDA-IPIF, 2005).
Salinity tolerance	Moderate (Hocking, 1985)
Habitat dominance	Can be invasive in warm climates (Floridata, 2006); however, not as aggressive as *Phragmites sp.* or *Typha sp.* (Hocking, 1985).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Tolerates relatively dry soil conditions (Tanner, 1997), tolerant to a wide range of water level fluctuations and soil moisture

	conditions (Tanner, 1996).
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	An evaluation of the studies available for this thesis showed that this species is particularly suitable for use in gravel-bed constructed wetlands and vertical flow systems.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the study conducted by Heritage (1995) in NSW, Australia (warm/temperate climate, ≈ 34 °S), where *Cyperus involucratus* was planted in a VF wetland for treatment of primary urban sewage with relatively high fluctuating influent concentrations (134 - 575 mg/L BOD), the reduction of BOD achieved 97 - 99 % (Heritage, 1995). The high tolerance to high-loaded organic wastewaters was proved in several studies, e.g. in South China by Liao (2003) and in Thailand. In a combined wetland system, *Cyperus involucratus* was planted in a vertical flow bed as the first treatment stage and exposed to a COD influent conc. ranging from 1,725 - 3,210 mg/L (averaged conc.: 2,800 mg/L) without any damages or limited growth rates (removal efficiency: 97 %), (Kantawanichkul, 2001).
Nitrogen and phosphorus compounds: evaluation of existing case studies	Tolerant to hyper-eutrophic conditions, capable to grow in high-strength wastewaters (Hocking, 1985; Tanner, 1996). This was showed by Kantawanichkul (2001) in Thailand treating settled high-strength pig farm wastewater: TKN reduction: 97 % (mean influent conc.: 240 mg/L) NH_3-N reduction: > 98 % (mean influent conc.: 168 mg/L) The study by Heritage (1995) showed removal performances for total nitrogen and total phosphorus of 81 - 91 % and 55 - 71 %, respectively, without a significant decrease during the colder winter months. → This was due to the high evapotranspiration rates (leads to an increased potential for microbial nitrogen transformations in the root zone since the water level in the vertical flow CW is lowered) and the year-round growth (nutrient assimilation throughout the year) of this species (Heritage, 1995).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	*Cyperus involucratus* shows a relatively low root zone oxygenation capacity compared to e.g. *Phragmites australis, Eleocharis sphacelata* or *Typha sp.* that can limit the potential for nitrification activity, especially in ammonium-enriched wastewaters (Brix, 1992).
7. Productivity, utilization options and economic potential	
Potential productivity	Relatively high productive species
Biomass production, growth rates and yields	Evaluated harvestable biomass yield (productivity) according to Hocking (1985) in a warm/temperate climate: 22 t/ha dry wt In the study conducted by Kantawanichkul (2001) under subtropical conditions, a biomass yield of 27.9 t/ha was achieved.
Biomass utilization options	*Cyperus involucratus* shows versatile utilization options: - fencing, - paper making, - divers handicrafts, e.g. making of mats, baskets, etc. (Liao, 2003) - The aboveground biomass can be used as composting agent or as medium for plant/crop nursing, - the plant biomass appears to have a great potential for biogas (methane) production. (Liao, pers. comm.) - Raw material for fertilizer and mulch (Kantawanichkul, 1999)
8. Nutrients: uptake and storage capacities	
General aspects	The study conducted by Hocking (1985) showed that most of

	the accumulated N and P are stored in the harvestable parts of the plant (over 60 % of the total N and P taken up).
Nitrogen: uptake and assimilation rates	No appropriate data available
Phosphorus: uptake and assimilation rates	No appropriate data available
9. Further remarks and comparisons with other plant species (if possible)	- Usually frost tender, but can withstand moderate frost periods (Tanner, 1996), - robust species, tolerates adverse environmental conditions (Kantawanichkul, 1999), - closely related to *Cyperus papyrus* (Floridata, 2006), - well-suitable for gravel bed CW systems (Tanner, 1997), - relatively high ET rates throughout the year (Heritage, 1995).

10.6 *Cyperus papyrus* (papyrus)

Suitable and recommended for constructed wetlands in:
- Tropical climate zones of: Africa

1. Plant species	
Common name	Papyrus, Egyptian papyrus
Scientific name (genus / species)	*Cyperus papyrus*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Tropical and Northern Africa (e.g. Egypt, Kenya, Madagascar, Sudan, Uganda), (Floridata, 2006; NewCROP, 2005)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial, green year-round (Floridata, 2006)
Growth height	Up to 4 m (Floridata, 2006), under ideal conditions: 5 m (Cook, 1974; SANBI, 2005)
Growth rate and period	Very fast, strongly responding to nutrient supply (Kansiime, 2003).
Reproduction	Mainly vegetative, insignificant generative reproduction (New-CROP, 2005)
Root and rhizome growth and development	Horizontally growing root and rhizome system; forms loose and open floating root mats (about 0.5 m thick) over waters allowing vertical penetration of wastewater into the mat (Kansiime, 2001). The increased interactions between wastewater and the loose papyrus root mat result in enhanced nutrient exchange capacities (Kansiime, 2003).
4. Habitat conditions and behaviour	
Natural Habitat	Swamps, shallow lakes and river banks, typical plant in the swamps in Central Africa: “Papyrus Swamps” (NewCROP, 2005)
Light demand, shade tolerance	Prefers full sun, but also tolerates semi-shade (Floridata, 2006)
pH optimum and tolerances	pH tolerance according to NewCROP (2005): 6.0 - 8.5
Salinity tolerance	Low (freshwater species), (Hammer, 1986)
Habitat dominance	Forms typical monoculture stands (papyrus swamps) that outcompetes other species (Kansiime, 2003).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can grow in standing water as well as in wet soils, but sensitive to dry conditions (SANBI, 2005).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	The removal performance of *Cyperus papyrus* was investigated in several studies in Kenya (Nyakang’O, 1999), but particularly in Uganda (e.g. Okurut, 1999; Kansiime, 2003; Kyambadde, 2004).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In a study conducted by Okurut (1999) in Kampala, Uganda (tropical climate, ≈ 1 °N), the removal performance of *Cyperus papyrus,* planted together with *Phragmites mauritianus* in a surface flow CW, was investigated. The removal rates were as follows:

	- COD: 63.3 % (mean influent conc.: 155.2 mg/L) - BOD: 68.0 % (mean influent conc.: 48.4 mg/L) → Very low-loaded influent concentration → Compared to *Phragmites mauritianus*, the effluent conc. of the Cyp*erus papyrus* system were slightly, but not significantly better. → The BOD and COD removal rates increased with time: this was explained by the higher plant density and increased root zone oxygen releases available for microbial decompositions of organic matter (Okurut, 1999).
Nitrogen and phosphorus compounds: evaluation of existing case studies	The ammonium reduction (39 %, mean influent conc.: 54.1 mg/L NH_4^+) in the study conducted by Okurut (1999) was low: this was mainly explained due to the inhibited oxygen transfer into the system caused by the dense plant canopy (shading effect) and insufficient oxygenation capacity. However, another comparative study (*Cyperus papyrus* and *Miscanthidium violaceum*) in Kampala, Uganda showed a significantly higher ammonium removal (75.3 %) and also a good phosphorus reduction (83.2 %). Here, it was explained through the high nutrient uptake and assimilation capacity in plant tissues (N and P) as a result of the high productivity, and further, the good nitrification activity in the papyrus root mats (increased contact possibilities between plant tissue and wastewater due to the loose root mat structure), (Kyambadde, 2004).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	According to Okurut (1999), *Cyperus papyrus* has a relatively low root zone oxygenation capacity that would lead to a reduced nitrification activity. However, this can be outweighed through high nutrient uptake rates and the phenologically favourable root mat structure (Kyambadde, 2004).
7. Productivity, utilization options and economic potential	
Potential productivity	Extremely productive plant species; productivity strongly responds to nutrient supply (Kansiime, 2003).
Biomass production, growth rates and yields	- Aboveground annual biomass production according to NewCROP (2005) for natural papyrus stands: 30 - 50 t/(ha*yr), - aboveground annual productivity according to Westlake (1963): 70 t/(ha*yr) → theoretical evaluation under ideal environmental conditions, - biomass yield in a constructed wetland in Nairobi, Kenya (tropical climate, ≈ 1.3 °S) for the treatment of domestic wastewater according to Nyakang'o, (1999): 62.5 t/ha dry wt, - comparison of aboveground biomass yields with and without wastewater discharge in the Nakivubo wetland, Kampala, Uganda according to Kansiime (2003): - 13.84 - 49.55 t/ha (without wastewater discharge) - 35.29 - 58.44 t/ha (with wastewater discharge)
Biomass utilization options	*Cyperus papyrus* shows highly versatile utilization options: - high potential as a renewable source of biomass for energy (similar to other highly productive species such as *Arundo donax, Typha sp.* or *Phragmites sp.*). - The stems can be used as building material (e.g. as done in Southern Africa), (SANBI, 2005), - can be used as weaving material, e.g. making of mats and baskets in Uganda, - can be compressed into fuel briquettes with a high calorific content (Rwanda), (Kabii, 1997), - the stems can be used for paper making (high cellulose content), (Hurter, 1988).
8. Nutrients: uptake and storage capacities	
General aspects	Uptake and assimilation of nitrogen and phosphorus can be significant during the early growing stage when the plant biomass increases rapidly (Okurut, 2001).

Nitrogen: uptake and assimilation rates	Uptake capacity in a tropical climate: 1,220 kg/(ha*yr), (Rogers 1985; in Wood, 1995) → similar to *Typha latifolia* (1,164 kg/ha*yr)
Phosphorus: uptake and assimilation rates	Uptake capacity in a tropical climate: 80 kg/(ha*yr), (Rogers 1985; in Wood, 1995) → lower than *Typha latifolia* and *Phragmites australis* (179 and 162 kg/ha*yr, respectively)
9. Further remarks and comparisons with other plant species (if possible)	- Frost tender species (Floridata, 2006), - closely related to *Cyperus involucratus,* - capable of forming floating mats in constructed surface flow wetlands (IWA, 2000).

10.7 *Pennisetum clandestinum* (Kikuyu grass)

Suitable and recommended for constructed wetlands in:
- Warm/temperate climate zones of: Southern Africa
- Tropical climate zones of: East Africa

1. Plant species	
Common name	Kikuyu grass
Scientific name (genus / species)	*Pennisetum clandestinum*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Warm/temperate to tropical
Geographic range	Native to tropical East Africa; introduced to many warm and (sub)tropical areas worldwide, e.g. Southern Africa, Australasia, China, Indonesia, The Philippines; Southern North America, Central America and South America; usually found between 35 °N and 37 °S (FAO, 2006; ISSG, 2005).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial, rhizomatous and stoloniferous (Cook, 2005)
Growth height	Up to 1.2 m (USDA-IPIF, 2005)
Growth rate and period	Low to rapid, strongly responding to nutrient supply (FAO, 2006).
Reproduction	Rapidly spreading by vegetative reproduction, but also readily generative reproduction (FAO, 2006).
Root and rhizome growth and development	Extensively creeping, relatively deep rhizome system, 90 % of the total root weight is usually found in the upper layer up to 0.6 m (FAO, 2006). However, other studies in South Africa showed that the root and rhizome development in subsurface flow beds is less prolific which may limit the root zone oxygenation capacity (Wood, 1989).
4. Habitat conditions and behaviour	
Natural Habitat	Coastal areas, wetlands, grasslands and forest margins (ISSG, 2005)
Light demand, shade tolerance	Full sun to light shade, not shade tolerant (FAO, 2006)
pH optimum and tolerances	Tolerates low pH up to 4.5 (Cook, 2005)
Salinity tolerance	Moderate, tolerates saline conditions (Cook, 2005)
Habitat dominance	Invasive species; usually forms monospecific stands (FAO, 2006).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Good tolerance to inundations, relatively high drought tolerance due to the deep root and rhizome system (FAO, 2006).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	The performance of this species in constructed treatment wetlands was primarily investigated in South Africa (Batchelor, 1990; Wood, 1989).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In one pilot study in South Africa, the treatment bed planted with *Pennisetum clandestinum* achieved a very high COD removal efficiency of 95 %. Influent: settled sewage from a septic tank with a mean COD conc. of 332 mg/L; soil substrate: waste ash (Wood, 1989).

	→ Similar to other, more commonly used species (e.g. *Scirpus lacustris* or *Phragmites australis*).
Nitrogen and phosphorus compounds: evaluation of existing case studies	The same study showed very high ammonia-nitrogen (97 %, mean influent: conc.: 20.7 mg/L NH_4^+-N) and good phosphate (83 %, mean influent conc.: 8 mg/L PO_4^--P) removal efficiencies. → No significant differences compared to the other species (Wood, 1989). In another study, the capability of *Pennisetum clandestinum* to form dense floating mats on open waters was used in a hydroponic system for removal of ammonia and nitrate from a low-loaded pond effluent. Within one month after planting this species formed a dense stand with an extensive root and rhizome system penetrating the water layer. → Significantly improved water quality of the pond effluent (Batchelor, 1990).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Potentially a high productive species, strongly depending on nutrient supply (especially nitrogen fertilizers).
Biomass production, growth rates and yields	Data about growth rates or biomass yields for *Pennisetum clandestinum* growing in CWs under tropical or subtropical conditions were not available. In Northern New South Wales, Australia, a maximum biomass yield of 30 t/(ha*yr) dry wt was obtained by use of nitrogen fertilizers (Cook, 2005). In domestic or municipal wastewaters that are usually characterized by evaluated concentrations of nitrogen and phosphorus compounds, an enhanced growth rate can be supposed.
Biomass utilization options	Mainly agricultural utilization options: - Generally, *Pennisetum clandestinum* is a highly digestible, palatable and valuable pasture grass which can be used as grazing for domestic animals (e.g. cows, sheep), - high quality forage plant due to the high crude protein (normally > 12 % of dry wt) and low fibre content of the leaves, - animal production: valuable pasture grass for dairy (milk) production and cattle finishing in tropical and subtropical areas, - can also be used as hay or silage, (Cook, 2005; FAO, 2006)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Tolerates occasional and light frost periods, but no prolonged and severe frosts (moderately frost tolerant), (ISSG, 2005), - markedly declined growth at temperatures below 7 °C and high temperatures (Cook, 2005), - can form floating mats on open waters (ISSG, 2005), - tolerant to high Al and Mn concentrations (Cook, 2005), - studies in South Africa showed that *Pennisetum clandestinum* responds well to frequent harvesting (Batchelor, 1990).

10.8 *Phragmites karka* (tall reed)

Suitable and recommended for constructed wetlands in:
- Subtropical climate zones of: South Asia (India, Burma, etc.)
- Tropical climate zones of: Southeast Asia

1. Plant species	
Common name	Tall reed, tropical reed, common reed
Scientific name (genus / species)	*Phragmites karka*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native to India, Burma, Nepal, tropical Asia (e.g. Indonesia, Malaysia, New Guinea, The Philippines), Northern Australia and tropical East Africa
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent
Growth height	Up to 4 m (Sim, 2004)
Growth rate and period	Fast, rapid establishment (Juwarkar, 1995)
Reproduction	Mainly vegetative, but also low generative reproduction (Sim, 2003)
Root and rhizome growth and development	Vertically growing root and rhizome system, up to 1.0 m into the depth (similar to *Phragmites australis*), (Sharma, 1998).
4. Habitat conditions and behaviour	
Natural Habitat	Swamps, both freshwater and brackish marshes, pond and lake edges, along riversides (Sim, 2003)
Light demand, shade tolerance	Semi-shade to full sun
pH optimum and tolerances	Preferred pH range according to FAO (2006): 4.5 - 7.5
Salinity tolerance	High (brackish waters), presumably similar to *Phragmites australis*
Habitat dominance	Highly invasive, usually forms monocultures (Sharma, 1998; Sim, 2003)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Tolerant to permanent and temporary inundations (similar to *Phragmites australis*), (FAO, 2006).
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	Although *Phragmites australis* is the species most commonly used and investigated in constructed wetland systems in Europe, USA and other temperate regions, the use of the very closely related *Phragmites karka* has been far less studied. The most studies available for this thesis were conducted in India (Juwarkar, 1995; Billore, 1999), Nepal (Laber, 1999; Shrestha 2001a/b), but also in Indonesia (Kurdinadie, 2000). This species is further used in the Philippines (Parco, 2005) and Malaysia (Sim, 2003).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In Dhulikhel, Nepal (≈ 27 °N), a two-staged CW (horizontal flow bed followed by a vertical flow bed) was constructed to treat primary wastewater from a hospital; both beds were planted with *Phragmites karka.* Removal efficiencies: - COD: 94 - 97 % (strongly fluctuating influent conc.: 62.55 - 1048 mg/L, mean conc.: 324.5 mg/L) → High treatment efficiency (similar results were achieved for TSS and BOD (Laber, 1999; Shrestha, 2001a). In other projects in Kathmandu, Nepal, *Phragmites karka*, planted in vertical flow beds, was successfully used to treat greywater for reuse purposes and a septic tank effluent, both with a high BOD, COD and TSS removal efficiency (Shrestha, 2001a/b). In Central India (Ujjain, Madhya Pradesh, subtropical climate, ≈ 23 °N), *Phragmites karka* was planted in a horizontal subsurface flow gravel bed for treatment of primary municipal waste-

	water. - TSS removal: 78 % (mean influent conc.: 701 mg/L) - BOD removal: 65 % (mean influent conc.: 79 mg/L) → TSS concentrations corresponded to extremely high strength municipal wastewaters. A further study was conducted in Bandung, Indonesia (tropical climate, ≈ 6.5 °S) where *Phragmites karka* was planted in a vertical flow wetland for the treatment of mechanically pre-treated sewage from a private household. This system showed high efficiencies in BOD and COD removal and the treated wastewater was used again for irrigation purposes, e.g. gardening (Kurniadie, 2000).
Nitrogen and phosphorus compounds: evaluation of existing case studies	The two-staged wetland system in Dhulikhel, Nepal showed also a high ammonia removal performance (mainly due to nitrification in the vertical flow bed), but the phosphorus removal rate was relatively poor. Removal efficiencies: - NH_4^+-N: 80 - 99 % (mean influent conc.: 33.3 mg/L) - PO_4^--P: 5 - 69 % (mean influent conc.: 8 mg/L) → High range in the phosphorus reduction due to decreasing absorption capacity of the soil with increasing age (Laber, 1999; Shrestha, 2001a). The CW for the treatment of greywater in Kathmandu, Nepal showed a similar performance in ammonia and phosphorus removal (Shrestha, 2001a/b).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	*Phragmites karka* appears to have a root zone oxygenation capacity as effective and high as *Phragmites australis.* This was showed by Billore (1999) who found an increasing DO concentration in the effluent of the CW (34 %) that is unusual for horizontal subsurface flow beds. This effect resulted in relatively high ammonium reductions: NH_4^+-N removal: 78.7 % (mean influent conc.: 34 mg/L).
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species with a high potential as a renewable biomass source (similar to *Phragmites australis)*
Biomass production, growth rates and yields	Total (aboveground and belowground) biomass production observed by Billore (1999) in the constructed wetland system in Central India within a period of 10 months: 121 t/ha. → Very high production due to ideal environmental conditions (warm climate, availability of unlimited nutrients in wastewater and year-round growth).
Biomass utilization options	Although no specific information for *Phragmites karka* was available, the versatile utilization options are supposed to be similar to those of *Phragmites australis,* e.g.: - High potential as a renewable fuel and energy source, - building material (thatching, roof materials), - paper making (Hurter, 1988), - raw material for making of mats and baskets, etc., - the leaves are used as fertilizer for paddy fields on the Philippines (Bodner, 1988).
8. Nutrients: uptake and storage capacities	
General aspects	Due to the high productivity of *Phragmites karka* as showed by Billore (1999), nutrient uptake and storage capacities can be significant, especially for nitrogen. However, for this thesis no data were available.
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Very similar to *Phragmites australis*, difficult to differentiate from each other.

10.9 *Phragmites mauritianus* (Lowveld reed)

Suitable and recommended for constructed wetlands in:
- Tropical climate zones of: Southern Africa

1. Plant species	
Common name	Lowveld reed
Scientific name (genus / species)	*Phragmites mauritianus*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Tropical
Geographic range	Tropical and Southern Africa (e.g. Congo, Ethiopia, Kenya, Sudan, Tanzania)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, persistent
Growth height	Up to 4 m, occasionally up to 7 m
Growth rate and period	Rapid (similar to *Phragmites australis*)
Reproduction	Mainly vegetative, but also low generative reproduction (similar to *Phragmites australis*)
Root and rhizome growth and development	Presumably similar to *Phragmites australis*
4. Habitat conditions and behaviour	
Natural Habitat	Commonly in saline (brackish) swamps ("reed swamps"), more at saline sites compared to *Phragmites australis (*Kabii, 1997).
Light demand, shade tolerance	Full sun (similar to *Phragmites australis*)
pH optimum and tolerances	No sufficient data available
Salinity tolerance	High (tolerates brackish and saline waters), presumably similar to *Phragmites australis*
Habitat dominance	Highly invasive, forms often monospecific stands (similar to *Phragmites australis*)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available, presumably similar to *Phragmites australis*
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	Although this species has only been investigated in only a few studies, treatment efficiencies similar to the other types of *Phragmites sp.* can be supposed due to the high morphological similarity.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the study conducted by Okurut (1999) in Kampala, Uganda (tropical climate, ≈ 1 °N), the removal performance of *Phragmites mauritianus,* planted together with *Cyperus papyrus* in a surface flow CW, was investigated. Removal rates are as follows: - COD: 43.0 % (mean influent conc.: 155.2 mg/L) - BOD: 51.2 % (mean influent conc.: 48.4 mg/L) → Very low-loaded influent concentration → Compared to Cyp*erus papyrus*, the effluent conc. of the *Phragmites mauritianus* system are slightly, but not significantly poorer. Another comparative study investigated the performances of *Phragmites mauritianus* and *Typha latifolia* in a subsurface flow CW for polishing of pre-treated domestic wastewater under tropical conditions in Tanzania (Kaseva, 2004). Removal efficiencies: - COD: 56.3 % (mean influent conc.:106.4 mg/L) → Similar performance compared to *Typha latifolia* (60.7 %)
Nitrogen and phosphorus compounds: evaluation of existing case studies	Ammonium reduction in the study conducted by Okurut (1999): 55.1 % (influent conc.: 54.1 mg/L NH_4^+). → Relatively low, but higher than with *Cyperus papyrus*. It can be supposed that *Phragmites mauritianus* has a root zone oxygenation capacity similarly high as *Phragmites australis.* Ammonium reduction according to Kaseva (2004) in the study conducted in Tanzania: NH_4^+-N: 25.2 % (mean influent conc.: 20.6 mg/L)

	→ Low performance, also similar to *Typha latifolia* (23.0 %)
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Can be supposed to be similar to *Phragmites australis*
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species (similar to *Phragmites australis*)
Biomass production, growth rates and yields	No data found
Biomass utilization options	Similar to those of *Phragmites australis*, e.g.: - the stems are used as building material for houses, - the fibres of stems can be used for construction purposes and handicrafts, - raw material for paper making, - renewable biomass source for fuel and energy.
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Very similar to *Phragmites australis* (difficult to separate from each other).

10.10 *Scirpus grossus* (greater club rush)

Suitable and recommended for constructed wetlands in:
- Subtropical and tropical climate zones of: Southeast Asia
- Subtropical climate zones of: South Asia (India, Pakistan, etc.)

1. Plant species	
Common name	Greater club rush
Scientific name (genus / species)	*Scirpus grossus*, syn.: *Actinoscirpus grossus*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native to Southeast Asia (e.g. Malaysia, South China, Indonesia, The Philippines, Thailand, Vietnam), India, Pakistan and Sri Lanka, Northern Australia (RiceIPM project, 2006)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, presumably persistent
Growth height	Up to 1.5 - 3 m (RiceIPM project, 2006)
Growth rate and period	Presumably rapid
Reproduction	Mainly vegetative, but also low generative reproduction (RiceIPM project, 2006)
Root and rhizome growth and development	
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater swamps, rice fields, along streams and ditches (RiceIPM project, 2006)
Light demand, shade tolerance	Presumably full sun
pH optimum and tolerances	No data found
Salinity tolerance	No data found
Habitat dominance	No data found
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	The study by Kantawanichkul (2003b) revealed that *Scirpus grossus* can withstand prolonged dry conditions as showed in the vertical flow bed (second stage) during the dry season (caused by very high evapotranspiration rates).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the investigation conducted by Kantawanichkul (2003b) in Thailand, *Scirpus grossus* was planted in a combined wetland system (first stage: horizontal subsurface flow CW, second stage: vertical flow CW). The following results were achieved:

	- COD removal: 94 - 98 % (influent conc.: ≈ 680 mg/L; corresponds to high strength municipal wastewaters.) → High efficiency, similar to *Typha angustifolia* also tested in this study. → *Scirpus grossus* grew better in the horizontal flow bed due to the higher moisture content, but coped better with the dryness in the vertical flow bed than *Typha angustifolia.* A very similar study was conducted by Kantawanichkul (2003a) in Thailand where *Scirpus grossus* was planted in experimental combined CW systems for treatment of anaerobic wastewater from a biogas digester (the same influent as in the study above). → High efficiency for TSS, BOD and COD reduction and nutrient removal.
Nitrogen and phosphorus compounds: evaluation of existing case studies	Nitrogen removal performance according to the investigation by Kantawanichkul (2003b): - TKN removal: 82 - 98 % (influent conc.: ≈ 230 mg/L, much higher compared to municipal wastewaters) → High efficiency, similar to *Typha angustifolia*; mainly due to microbial transformations. → Plant growth near the inlet zone of the horizontal bed was retarded due to the high ammonia concentrations.
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Potentially a high productive species
Biomass production, growth rates and yields	No data found
Biomass utilization options	Similar to the more common *Scirpus sp.*, e.g. *Scirpus validus:* - raw material for handicrafts, - can be used for making of mats, strings, etc.
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Robust plant species (Kantawanichkul, 2003b), - often considered as a weed species in rice fields (RiceIPM project, 2006).

10.11 *Typha orientalis* (broad-leaved cumbungi)

Suitable and recommended for constructed wetlands in:
- Tropical climate zones of: Southeast Asia
- Warm/temperate climate zones of: East Asia (Japan)
- Subtropical climate zones of: Northern Australia

1. Plant species	
Common name	Broad-leaved cumbungi (Aust.), raupo (NZ), cattail (US)
Scientific name (genus / species)	*Typha orientalis*, syn.: *Typha japonica*
Family	*Typhaceae*
2. Availability in climate zone	
Climatic range	Warm to tropical/subtropical
Geographic range	Native to East and Southeast Asia (e.g. Indonesia, Malaysia, The Philippines, Japan), Australia and New Zealand (Moerkerk, 2001; Smith, 1987)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous
Growth height	Up to 3 - 4 m (Chambers, 1994b; Fisher, 1996)
Growth rate and period	Very fast (PFAF, 2004), strongly responding to nutrient supply (Tanner, 1997); shows a markedly aboveground senescence and dieback during the autumn and winter season (Chambers, 1994a/b).

Reproduction	Spreads rapidly by vegetative reproduction, but also readily generative reproduction (similar to *Typha latifolia)*.
Root and rhizome growth and development	Relatively shallow root penetration, up to about 0.3 m into the depth (similar to *Typha latifolia*), (Fisher, 1996).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater and slightly brackish marshes, swamps, pond and lake margins, streams (CSU, 2005; PFAF, 2004)
Light demand, shade tolerance	Full sun (similar to *Typha latifolia)*
pH optimum and tolerances	No data found
Salinity tolerance	Low; but appears to be slightly higher than *Typha latifolia* since *Typha orientalis* is able to grow at slightly brackish sites.
Habitat dominance	Highly invasive and dominant species, aggressive colonizer; commonly forms dense monoculture stands (similar to *Typha latifolia*).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated irregularly to permanently up to 0.3 m (Tanner, 1997).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	According to Tanner (1997), *Typha orientalis* is well-suitable for surface flow wetlands due to the readily establishment in these systems. The removal efficiency of *Typha orientalis* was extensively investigated in a constructed wetland system in Richmond, NSW, Australia, under warm/temperate conditions (Fisher, 1990, 1996).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the study conducted by Fisher (1990, 1996), *Typha orientalis* was planted in a pilot scale subsurface flow gravel bed receiving primary treated effluent. - BOD removal rate: ≈ 93 % (mean influent conc.: 235 mg/L, HRT: 8.8 d) → High efficiency, similar to the other types of *Typha sp* In the study conducted by Heritage (1995) in NSW, Australia (warm/temperate climate, ≈ 34 °S), where *Typha orientalis* was planted in a VF wetland for treatment of primary urban sewage with relatively high fluctuating influent concentrations (134 - 575 mg/L BOD), the reduction of BOD achieved 96 - 98 % (Heritage, 1995).
Nitrogen and phosphorus compounds: evaluation of existing case studies	Removal efficiencies according to the investigation conducted by Fisher (1990, 1996): Total nitrogen (TN) removal rate: ≈ 60 % (influent conc.: 72 mg/L, HRT: 8.8 d). Compared to the other wetland species tested in this study (*Baumea articulata* and *Cyperus involucratus*), the removal performance for nitrogen and phosphorus declined into autumn due to the seasonal physiological response (strong winter dieback) of *Typha orientalis* (similar effect as observed with *Scirpus validus*, but less significant), (Heritage, 1995).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found, presumably similar to the other types of *Typha sp.*
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species with a high potential as a renewable source of biomass.
Biomass production, growth rates and yields	No sufficient data available
Biomass utilization options	Versatile utilization options, similar to the other types of *Typha sp.* (see also *Typha latifolia* in Chapter 8.8): - High potential as a renewable source of biomass, - fuel source (direct combustion) due to the high energy content comparable to conventional fuel sources, - additional material for composting purposes. Harvested leaves and stems have versatile applications (Rook, 2004; Wissing, 2002). - building material (thatching, roof materials),

	- can be used as weaving material, e.g. mats, chairs, etc., - raw material for paper making (source of fibres), - many others, e.g. insulation material, rayon production or packing material.
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No sufficient data available
Phosphorus: uptake and assimilation rates	No sufficient data available
9. Further remarks and comparisons with other plant species (if possible)	- Strong dieback of the shoots in winter (in warm/temperate climate, e.g. New Zealand), (Tanner, 1997), - produces large accumulations of standing and decomposing litter (typical for all *Typha sp.)*, (Tanner, 1997), - capable of forming floating mats of rhizomes, roots and accumulating plant litter on shallow open water sites (IWA, 2000).

10.12 *Vetiveria zizanioides* (vetiver grass)

Suitable and recommended for constructed wetlands in:
- Subtropical to tropical climate zones of: Southeast Asia
- Subtropical climate zones of: Northern Australia

1. Plant species	
Common name	Vetiver grass
Scientific name (genus / species)	*Vetiveria zizanioides*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native to India, Sri Lanka, Burma and Southeast Asia (e.g. South China and Thailand) and subtropical Northern Australia (Queensland), (FAO, 2006; Truong, 2001)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and persistent, year-round growth in tropical climates (Kantawanichkul, 1999)
Growth height	Up to 1.5 - 2 m (Vetiver Network, 2005)
Growth rate and period	Rapid (Liao, 2003)
Reproduction	Mainly vegetative, but also marginal generative reproduction (Chaipat, 2005)
Root and rhizome growth and development	Extensive, strong and dense root system that penetrates vertically deep into the soil (up to 3 m under ideal conditions), (Chaipat, 2005; Vetiver Network, 2005).
4. Habitat conditions and behaviour	
Natural Habitat	Vetiver grass can grow in a wide range of areas and under various soil conditions (Chaipat, 2005).
Light demand, shade tolerance	Prefers full sun, but also tolerates semi-shade (Vetiver Network, 2005)
pH optimum and tolerances	pH tolerance according to Truong (2001): 3.0 - 10.5
Salinity tolerance	According to Truong (2001), vetiver grass can survive very high salt concentrations of up to about 31 ppt. However, in an investigation conducted by Klomjek (2005), *Vetiveria zizanioides* could not survive the following conditions: salt concentrations of about 10 ppt and prolonged flood conditions (eight weeks).
Habitat dominance	Non-invasive (Vetiver Network, 2005)
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	High tolerance to flooded conditions as well as longer drought periods, can survive complete submergence in water for up to three months (Vetiver Network, 2005).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	Numerous investigations and researches in North Australia, South China and Thailand have proved the effectiveness of *Vetiveria zizanioides* in constructed wetland systems for the treatment of domestic (municipal), industrial and agricultural

	wastewaters, but also landfill leachate (Truong, 2001). This plant was very successfully used in Australia for the treatment of domestic primary effluents from septic tanks (Truong, 2001).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	According to Liao (2000), *Vetiveria zizanioides* was able to grow at COD concentrations of 2,800 mg/L. → Tolerant to high-loaded organic wastewaters (Liao, 2000, in: Truong, 2001). In a study conducted by Kantawanichkul (1999) in subtropical Thailand, *Vetiveria zizanioides* was planted in a vertical flow CW treating diluted settled pig farm wastewater: → A mean COD influent conc. of 601 mg/L was tolerated with a removal performance of 78.7 % (HLR: 18.5 mm/d). In another study in subtropical South China, *Vetiveria zizanioides* was planted in an experimental culture system without a soil medium treating relatively high strength pig farm wastewaters (Liao, 2003). - Mean COD influent conc.: 825 mg/L, removal rate: 64 %, - mean BOD influent conc.: 510 mg/L, removal rate: 68 %. (HRT: 4 d) → The results show that vetiver grass has proved to be a well-suitable plant species for wastewater treatment, especially when planted in vertical flow systems.
Nitrogen and phosphorus compounds: evaluation of existing case studies	Generally, vetiver grass proved to be tolerant to eutrophic conditions and was able to grow at high strength NH_3-N concentrations of about 390 mg/L (Liao, 2000, in: Truong, 2001). In the study conducted by Klomjek (2005) in Thailand, *Vetiveria zizanioides* showed a good NH_3-N treatment performance for medium strength municipal wastewater. - Mean reduction: 76.5 % (mean influent conc.: 19.5 mg/L)
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	Due to the finely structured and dense root system, a stimulating effect on microbial transformation processes in the rhizosphere may be supposed (Chomchalow, 2003).
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species (Liao, 2003); usually harvested two or three times a year to export nutrients or for biomass utilization purposes (Truong, 2003).
Biomass production, growth rates and yields	- Typical biomass yield range in natural habitats: 15 - 30 t/ha, - under fertile and moist (irrigated) conditions: up to 100 t/ha are possible (Vetiver Network, 2005).
Biomass utilization options	Vetiver grass shows highly versatile utilization options. - Due to the extensive and deep root system often used for soil stabilization and erosion control. Leaves and stems can be used as: - Raw material for handicrafts (e.g. weaving of hats, mats, baskets, etc.), - construction and building material (e.g. thatching), - energy source: ethanol production and “green” fuel (a proportional mix of vetiver grass and water hyacinth (*Eichhornia Crassipes*) biomass serves as a high-quality source of “green” fuel), - industrial products (e.g. raw material for paper making), - agricultural purposes (mulching, making of vetiver compost), - animal food (e.g. for dairy cows, cattle, sheep or rabbits), - miscellaneous other utilization options (medicinal applications, mushroom culture, etc.). (Chaipat, 2005; Vetiver Network, 2005)
8. Nutrients: uptake and storage capacities	
General aspects	*Vetiveria zizanioides* appears to show high uptake and assimilation capacities of nitrogen and phosphorus (Truong, 2001). However, no data and numbers were available for this thesis.
Nitrogen: uptake and assimilation rates	No appropriate data available
Phosphorus: uptake and assimilation rates	No appropriate data available

9. Further remarks and comparisons with other plant species (if possible)	- Very robust species, highly tolerant to adverse climatic conditions (heat periods up to 45 °C, prolonged drought or inundation periods), (Truong, 2001), - tolerates low temperatures up to - 9 °C, however, sensitive to severe frost periods (Chaipat, 2005), - significantly higher water use rates compared to other common wetland species, e.g. *Typha sp., Phragmites sp.* or *Scirpus sp.* (Truong, 2001), - highly tolerant to elevated concentrations of certain heavy metals (e.g. Cd, Cu, Cr, Pb, Ni or Zn), (Truong, 2001).

11 Alternative and not commonly used plants

11.1 Plant species recommended for constructed wetlands

- *Carex fascicularis* (tassel sedge)
- *Coix lacryma-jobi* (Job's tears)
- *Cyperus latifolius* (broad-leaved sedge)
- *Cyperus malaccensis* (Shichito matgrass)
- *Lepironia articulata* (tube sedge)
- *Lolium perenne* (perennial ryegrass)
- *Miscanthidium violaceum* (Miscanthidium)
- *Miscanthus sacchariflorus* (Amur silver grass)
- *Pennisetum purpureum* (Napier grass)

11.2 *Carex fascicularis* (tassel sedge)

Suitable and recommended for constructed wetlands in:
- Warm/temperate to subtropical climate zones of: Australia

1. Plant species	
Common name	Tassel sedge
Scientific name (genus / species)	*Carex fascicularis*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Warm/temperate to subtropical
Geographic range	Native to Australia and New Zealand (Browning, 2003; pers. comm.)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous (WAH, 2005)
Growth height	Up to 1.5 m (WAH, 2005)
Growth rate and period	Moderate to rapid (Browning, 2003)
Reproduction	Mainly vegetative reproduction (similar to the other types of *Carex sp.*)
Root and rhizome growth and development	
4. Habitat conditions and behaviour	
Natural Habitat	Along watercourses, pond edges and swamps (WAH, 2005)
Light demand, shade tolerance	No data found
pH optimum and tolerances	No data found
Salinity tolerance	Low (freshwater species), (Greenway, pers. comm.)
Habitat dominance	No data found
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can be inundated only temporarily (Greenway, pers. comm.).
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	The suitability of *Carex fascicularis* in CWs was investigated in a research project in Brisbane, Queensland, Australia under subtropical conditions (Browning, 2003). → This field project has showed that *Carex fascicularis* is as effective as the standard species *Baumea articulata* for use in subsurface flow CWs. Additionally, this species showed high regrowth rates after harvesting (Browning, 2003). According to Greenway (pers. comm.), *Carex fascicularis* is only suitable for subsurface flow wetlands. Other studies for *Carex fascicularis* are not available (Greenway, pers. comm.)
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In this study *Carex fascicularis* was planted, together with other plant species, e.g. *Baumea articulata*, in a gravel bed subsurface flow wetland receiving low-loaded secondary

	treated effluent. → High efficiency in reduction of TSS and COD, but poor removal of ammonium or phosphorus
Nitrogen and phosphorus compounds: evaluation of existing case studies	No data found
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Relatively high potential as a productive species including high regrowth rates.
Biomass production, growth rates and yields	Harvestable biomass yield after 9 months growth of *Carex fascicularis* according to Browning (2003): 19.9 t/ha → Similar to *Baumea articulata* in the same study: 21.6 t/ha. → However, *Carex fascicularis* showed high a regrowth of aboveground biomass following harvesting and could achieve a harvestable aboveground biomass within 6 months (compared to the retarded and slow regrowth of *Baumea articulata*), (Browning, 2003).
Biomass utilization options	According to Greenway (pers. comm.), there are no biomass utilization options for *Carex fascicularis.*
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No appropriate data available
Phosphorus: uptake and assimilation rates	No appropriate data available
9. Further remarks and comparisons with other plant species (if possible)	- Frost tolerant (WAH, 2005)

11.3 *Coix lacryma-jobi* (Job's tears)

Suitable and recommended for constructed wetlands in:
- Subtropical climate zones of: Central America and Caribbean region

1. Plant species	
Common name	Job's tears
Scientific name (genus / species)	*Coix lacryma-jobi*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native to tropical Southeast Asia and East India; widely introduced to many subtropical and tropical regions worldwide, esp. Central America (e.g. Costa Rica, Dominican Republic, Haiti or Honduras), limited to about 22 °N and °S (Dallas, 2004; FAO, 2006).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial (in the tropics), green year-round in frost-free climates (NewCROP, 2005)
Growth height	Up to 2 m (NewCROP, 2005) - 3 m (Cook, 1974)
Growth rate and period	Fast, rapid establishment (Dallas, 2004)
Reproduction	Mainly vegetative, generative reproduction only under suitable climates and under favourable conditions (FAO, 2006)
Root and rhizome growth and development	Appears to have a deeply penetrating root system (Dallas, 2004).
4. Habitat conditions and behaviour	
Natural Habitat	Swamps and wet grasslands (PFAF, 2004)
Light demand, shade tolerance	Presumably full sun
pH optimum and tolerances	pH tolerance: 4.5 - 8.4 (NewCROP, 2005)
Salinity tolerance	No sufficient data available
Habitat dominance	No sufficient data available
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Tolerant to inundations; but no drought tolerance (FAO, 2006)

6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	The removal performance of *Coix lacryma-jobi* was investigated in a study conducted by Dallas (2004) in Monteverde, Costa Rica (tropical climate, ≈ 10.5 °N) for treatment of domestic (pre-treated) greywater. The multistage system consisted of two subsurface flow beds in series, planted with *Coix lacryma-jobi*, followed by a pond. - BOD removal (second SSF bed): > 98.2 % (mean influent conc.: 167 mg/L) → High efficiency concerning BOD reduction → In this study, *Coix lacryma-jobi* proved to be a resilient and viable plant species in constructed wetland systems This wetland system was also highly efficient in removal of faecal coliforms and pathogens. → According to numerous guidelines for wastewater reuse, removal of pathogen bacteria is an essential criteria if the treated effluent should be reused (e.g. for irrigation purposes), (Dallas, 2004).
Nitrogen and phosphorus compounds: evaluation of existing case studies	No sufficient data available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	*Coix lacryma-jobi is* considered as a very useful and productive species with a high potential as a renewable biomass source (NewCROP, 2005).
Biomass production, growth rates and yields	Observed standing biomass yield under tropical conditions in a natural freshwater swamp: 10 - 20 t/ha (NewCROP, 2005).
Biomass utilization options	- High potential as a source of renewable energy and fuel source (NewCROP, 2005), - can be used as forage plant (FAO, 2006), - stems can be used for making of mats (PFAF, 2004), - versatile other utilization options, e.g. edible and medicinal uses (NewCROP, 2005; PFAF, 2004), - can also be used for paper making (Chang, 2004). - In some Southeast Asian states the seeds are considered as an auxiliary food crop, especially as a substitute for rice due to the high starch (50 - 60 %), protein (about 19 %) and fat (about 7 %) content (NewCROP, 2005).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Cultivated in many parts of the tropics

11.4 *Cyperus latifolius* (broad-leaved sedge)

Suitable and recommended for constructed wetlands in:
- Tropical climate zones of: Africa

1. Plant species	
Common name	Broad-leaved sedge; cheffe, iKhwane grass (indigenous names in Africa)
Scientific name (genus / species)	*Cyperus latifolius*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Tropical

Geographic range	Tropical and Southern Africa (e.g. Ethiopia, Kenya, Uganda)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial
Growth height	Up to 2.5 m (personal evaluation of existing data)
Growth rate and period	Presumably rapid
Reproduction	Vegetative and generative
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Typically forms large swamps, similar to the "papyrus swamps" or "Miscanthidium swamps"
Light demand, shade tolerance	No sufficient data available
pH optimum and tolerances	No sufficient data available
Salinity tolerance	Presumably low, appears to be similar to *Cyperus papyrus*
Habitat dominance	No sufficient data available
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	Only one study for *Cyperus latifolius* that investigated this species in a constructed wetland system was available (Nyakang'o, 1999).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	Among other species, *Cyperus latifolius* was planted in a multistage constructed wetland/pond system in Nairobi, Kenya (tropical climate, ≈ 1.3 °S) for the treatment of domestic wastewater. The wetland-pond system showed high removal efficiencies: - BOD (mean): 98.4 % (influent conc.: 625 mg/L) - COD (mean): 96.5 % (influent conc.: 954 mg/L) However, it should be considered that the main reduction occurred in the first stage (a horizontal subsurface flow wetland planted with *Typha sp.*). *Cyperus latifolius,* however, was planted in the third treatment stage, thus, was not exposed to the high influent concentrations.
Nitrogen and phosphorus compounds: evaluation of existing case studies	No sufficient data available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Appears to be a high productive species, although there are only few data available.
Biomass production, growth rates and yields	Biomass yield (standing stock) in the constructed wetland in Nairobi, Kenya ((tropical climate, ≈ 1.3 °S) for the treatment of domestic wastewater: 44.2 t/ha dry wt (Nyakang'o, 1999). According to Kotze (2001), the *Cyperus latifolius* swamps in tropical Africa have the potential to sustainable supply more than 90,000 t/yr of fibrous leaf material for various handicrafts, e.g. weaving material.
Biomass utilization options	- Appears to have a high potential as a source of renewable biomass, - leaves can be used as weaving material, e.g. mats, bags, etc., - stems can be used as building material, e.g. thatching. (Kotze, 2001)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No appropriate data available
Phosphorus: uptake and assimilation rates	No appropriate data available
9. Further remarks and comparisons with other plant species (if possible)	- Closely related to *Cyperus papyrus* and *Cyperus involucratus*

11.5 *Cyperus malaccensis* (Shichito matgrass)

Suitable and recommended for constructed wetlands in:
- Subtropical and tropical climate zones of: Southeast Asia

1. Plant species	
Common name	Shichito matgrass (according to USDA-IPIF, 2005)
Scientific name (genus / species)	*Cyperus malaccensis*, possible syn.: *Cyperus tegetiformis*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native from Middle East (Persian Gulf) to Southeast Asia, (e.g. The Philippines, Polynesia, South China and Taiwan) to Northern Australia (Queensland), (PFAF, 2004; USDA-IPIF, 2005)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous
Growth height	Up to about 1 - 1.3 m (personal evaluation of existing data)
Growth rate and period	No sufficient data available
Reproduction	Vegetative and generative
Root and rhizome growth and development	No sufficient data available
4. Habitat conditions and behaviour	
Natural Habitat	Swamp margins and salt (brackish) marshes (PFAF, 2004)
Light demand, shade tolerance	Prefers full sun, but not shade tolerant (PFAF, 2004)
pH optimum and tolerances	No data found
Salinity tolerance	Tolerates saline soil conditions (PFAF, 2004)
Habitat dominance	No data found
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the investigation conducted by Yang 1995) in Bainikeng, Shenzhen, South China (subtropical climate, ≈ 24 °N), *Cyperus malaccensis* was planted in the second and forth stage of the constructed wetland system for treatment of municipal wastewater. The multistage treatment system showed a high removal efficiency concerning organic pollutants (BOD and COD) and suspended solids (TSS), and further, a high tolerance to varying influent concentrations. → Although the *Cyperus malaccensis* bed showed the best BOD removal performance in the corresponding treatment stages compared to the other species in this wetland system (*Lepironia articulata* and *Phragmites australis*), the differences were not significant and no conclusions from these results can be made. (Yang, 1995)
Nitrogen and phosphorus compounds: evaluation of existing case studies	No sufficient data available
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Moderate to high productive species; however, no sufficient data available
Biomass production, growth rates and yields	No data found
Biomass utilization options	- The fibres of the stems and leaves, but also the whole leaves can be used as weaving material (e.g. baskets, mats, etc.), - especially in China, this species is cultivated for the fibres obtained from the leaves. (PFAF, 2004)
8. Nutrients: uptake and storage capacities	

General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	

11.6 *Lepironia articulata* (tube sedge)

Suitable and recommended for constructed wetlands in:
- Subtropical and tropical climate zones of: Southeast Asia

1. Plant species	
Common name	Tube sedge, grey rush
Scientific name (genus / species)	*Lepironia articulata*
Family	*Cyperaceae*
2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native to Southeast Asia (e.g. Malaysia, South China, Taiwan) and Northern Australia (Sim, 2003; Yang, 1995), also in India and Madagascar (Cook, 1974)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, grows in clumps (Sim, 2003)
Growth height	Up to 2 - 3 m (Sim, 2003)
Growth rate and period	Presumably moderate to rapid
Reproduction	Mainly vegetative, but also generative reproduction (Sim, 2003)
Root and rhizome growth and development	No data found
4. Habitat conditions and behaviour	
Natural Habitat	Swamps, shallow lakes, ditches and ex-mining ponds (Cook, 1974; Sim, 2003)
Light demand, shade tolerance	No data found
pH optimum and tolerances	Tolerates low pH (up to pH 3), (Sim, 2003)
Salinity tolerance	No data found
Habitat dominance	No data found
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	According to Sim (2003), *Lepironia articulata* appears to be a species well-suitable for planting in a constructed wetland treatment system.
Organic constituents (BOD and COD) and sus-pended solids (TSS): evaluation of existing case studies	In an investigation conducted in Bainikeng, Shenzhen, South-China (subtropical climate, ≈ 24 °N), *Lepironia articulata* was planted in the forth and last stage of a constructed wetland system treating municipal wastewater. This multistage treatment system showed a high removal efficiency concerning organic pollutants (BOD) and suspended solids (TSS), and a high tolerance to varying influent concen-trations. However, the forth treatment stage with *Lepironia articulata* planted in a gravel bed received only a very low-loaded influ-ent (BOD conc.: 14.9 mg/L) and served more as a final polish-ing unit. → No conclusions concerning tolerances to high organic load-ings and removal efficiencies at higher BOD and COD con-centrations that are more typical for primary effluents could be made (Yang, 1995).
Nitrogen and phosphorus compounds: evaluation of existing case studies	No data found
Root zone effects: oxygenation capacity and ef-fect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and eco-	

nomic potential	
Potential productivity	Appears to be a moderate to high productive species; however, no sufficient data available
Biomass production, growth rates and yields	No data found
Biomass utilization options	- Stems and leaves can serve as raw material for handicrafts, e.g. weaving of mats, bags, hats, sacks, etc., - in China, *Lepironia articulata* is cultivated for a fibre used for divers handicrafts (Cook, 1974)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	

11.7 *Lolium perenne* (perennial ryegrass)

Suitable and recommended for constructed wetlands in:
- Temperate climate zones of: Europe and Asia
- Warm/Mediterranean climate zones of: Southern Europe

1. Plant species	
Common name	Perennial ryegrass
Scientific name (genus / species)	*Lolium perenne*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Warm/Mediterranean to temperate
Geographic range	Native from Central and Southern Europe to temperate East Asia and North Africa; introduced to many temperate regions worldwide (e.g. North and South America, Australia and New Zealand), (FAO, 2006).
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial, evergreen and year-round growth in warm /Mediterranean climates (USDA-FS, 2006)
Growth height	Up to 0.9 m (NewCROP, 2005)
Growth rate and period	Fast, rapid establishment (NewCROP, 2005)
Reproduction	Mainly generative, vegetative reproduction usually less significant (USDA-FS, 2006).
Root and rhizome growth and development	Dense and deeply growing, but short-lived, root system (up to 1 - 1.5 m into the depth may be possible). However, the majority of the belowground biomass can be found in the upper 0.15 m of the soil layer (FAO, 2006; USDA-FS, 2006).
4. Habitat conditions and behaviour	
Natural Habitat	Moist meadows and grasslands (PFAF, 2004)
Light demand, shade tolerance	Full sun, not shade tolerant (FAO, 2006)
pH optimum and tolerances	pH tolerance according to NewCROP(2005): 4.5 - 8.2; however, prefers slightly acid to neutral conditions (FAO, 2006).
Salinity tolerance	Moderate (NewCROP, 2005)
Habitat dominance	Good competitor; can out-compete most other grasses (USDA-FS, 2006).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Can tolerate short periods of inundations (FAO, 2006) and is moderately drought tolerant (PFAF, 2004).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	The use of *Lolium perenne* in constructed wetlands has only been researched in China by Chang (2004) and Yue (2004) under subtropical conditions. Although this species is native to temperate Europe and Asia, no investigations were available for these regions.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the study conducted by Yue (2004), *Lolium perenne* was planted, together with *Canna indica,* in a medium-scale pilot system (vertical/reverse-vertical flow CW) for treatment of domestic wastewater in Ningbo, Zhejiang Province, China

	(subtropical climate, ≈ 30 °N). → High mean removal efficiencies for COD (≈ 91 %) and BOD (≈ 95 %), the influent corresponded to a low strength municipal wastewater (mean influent conc.: COD: ≈ 250 mg/L and BOD: ≈ 150 mg/L). → According to this study, *Lolium perenne* can be considered as a species suitable to treat domestic wastewater. In the investigation by Chang (2004), *Lolium perenne* was used, together with *Coix lacryma-jobi*, for the treatment of a polluted wastewater mix consisting of domestic, agricultural and aquaculture effluents. The system was the same as used by Yue (2004). → Removal efficiency for COD was relatively poor (about 41 %); however, the influent was very low-loaded concerning organic matter (range of COD influent: 39 - 52 mg/L).
Nitrogen and phosphorus compounds: evaluation of existing case studies	Removal efficiencies according to the study by Yue (2004): - Total nitrogen: average removal rate: ≈ 76 % (mean influent: ≈ 64 mg/L) - Ammonium-nitrogen: average removal rate: ≈ 87 % (mean influent: ≈ 50 mg/L) - Total phosphorus: average removal rate: ≈ 72 % (mean influent: ≈ 5.4 mg/L) → Very high efficiency without clear seasonal variations under subtropical conditions.
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	High productive species with a high potential as a renewable source of biomass and energy crop (NewCROP, 2005).
Biomass production, growth rates and yields	Range of annual biomass yield for temperate regions, especially in Europe, reported by NewCROP (2005): 5 - 25 t/(ha*yr)
Biomass utilization options	*Lolium perenne* shows mainly agricultural utilization options: - Can be used as pasture grass and hay, (the hay is nutritious, but only of moderate quality), → important as a pasture and hay grass in many temperate regions worldwide (e.g. in Australia, New Zealand and USA), - high potential as a renewable energy and fuel source. (NewCROP, 2005) - Important as a high-quality forage grass for livestock (e.g. cattle and sheep) due to the high nutritional value (USDA-FS, 2006; Chang, 2004).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Robust plant species (FAO, 2006), - adapted to a wide range of soil conditions (Ogle, 2003), - adapted to mild temperate climates, sensitive to severe frosts, but also high temperatures (FAO, 2006).

11.8 *Miscanthidium violaceum* (Miscanthidium)

Suitable and recommended for constructed wetlands in:
- Tropical climate zones of: Africa

1. Plant species	
Common name	Miscanthidium, swamp grass
Scientific name (genus / species)	*Miscanthidium violaceum*, syn.: *Miscanthus violaceus*
Family	*Poaceae (Gramineae)*

2. Availability in climate zone	
Climatic range	Tropical
Geographic range	Tropical and Southern Africa (e.g. Kenya, Rwanda, Uganda)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, green year-round
Growth height	Up to 2.5 m (personal evaluation of existing data)
Growth rate and period	Presumably rapid
Reproduction	Vegetative and generative
Root and rhizome growth and development	Miscanthidium forms thick (up to 1.3 m) and compact floating root mats over shallow open waters that restrict vertical movement of wastewater into the mat (in contrast to *Cyperus papyrus*), (Kansiime, 2001).
4. Habitat conditions and behaviour	
Natural Habitat	Freshwater marshes, pond edges, lakes and rivers
Light demand, shade tolerance	Presumably full sun
pH optimum and tolerances	No sufficient data available
Salinity tolerance	No sufficient data available
Habitat dominance	No sufficient data available
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	Generally, the thick and compact root mat results in a lower flow resistance and less contact between wastewater and root mat (Kansiime, 2001). This effect can limit the nutrient availability and thus results in lower nutrient uptake rates through the plant (Kansiime, 2003).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	No sufficient data available
Nitrogen and phosphorus compounds: evaluation of existing case studies	In the comparative study conducted by Kyambadde (2004) in Kampala, Uganda, *Miscanthidium violaceum* showed a moderate ammonia removal of 61.5 % and a phosphorus removal rate of 48.4.2 %. Compared to *Cyperus papyrus,* this species showed markedly lower nutrient removal efficiencies due to the adverse root structure and root development (less root surface area and number of roots, impeded vertical wastewater penetration), (Kyambadde, 2004).
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Moderate to high productive species; however, no sufficient data available
Biomass production, growth rates and yields	Compared to *Cyperus papyrus*, *Miscanthidium violaceum* showed significantly lower aboveground biomass yields caused by the root mat morphology that limits the nutrient exchange between wastewater and the plants, and thus, nutrient uptake (Kansiime, 2003).
Biomass utilization options	No utilization options found
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Capable of forming floating mats of roots on open water sites (Kansiime, 2003).

11.9 *Miscanthus sacchariflorus* (Amur silver grass)

Suitable and recommended for constructed wetlands in:
- Warm/temperate climate zones of: East Asia
- Subtropical climate zones of: Southeast Asia

1. Plant species	
Common name	Amur silver grass, silver banner grass
Scientific name (genus / species)	*Miscanthus sacchariflorus*
Family	*Poaceae (Gramineae)*
2. Availability in climate zone	
Climatic range	Warm/temperate to subtropical
Geographic range	Native to East Asia (e.g. China, Japan, Korea, Taiwan)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous (PFAF, 2004)
Growth height	Up to 3 m (PFAF, 2004)
Growth rate and period	Rapid (PFAF, 2004)
Reproduction	Mainly vegetative, but also low generative reproduction rate (DHS, 2004)
Root and rhizome growth and development	Large, very vigorous, long creeping rhizome system (DHS, 2004)
4. Habitat conditions and behaviour	
Natural Habitat	Flood plains and river banks, along streams or ponds (DHS, 2004; PFAF, 2004)
Light demand, shade tolerance	Semi shade to full sun (PFAF, 2004)
pH optimum and tolerances	pH optimum for *Miscanthus x giganteus*: 5.5 - 7.5 (Nixon, 2001). Data for *Miscanthus sacchariflorus* could not be found.
Salinity tolerance	No data found
Habitat dominance	No data found
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	No sufficient data available
6. Removal efficiencies, tolerance to waste-water constituents and root zone effects	
General aspects	The study conducted by Lei (2004) showed that *Miscanthus sacchariflorus* appears to be well-suitable for use in subsurface flow wetlands. However, no other investigation was available that proved the suitability of this species, especially at high organic loadings and under eutrophic conditions.
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In the study conducted by Lei (2004), *Miscanthus sacchariflorus* was used in a full-scale constructed wetland system in Shenzhen City, Southern China (subtropical climate, ≈ 22 °N). The system was designed as a multistage system consisting of a pre-treatment unit including a facultative pond, a horizontal subsurface flow (first stage) and a vertical flow (second stage) constructed wetland system. *Miscanthus sacchariflorus* was planted in the first stage wetland. The influent was a mix of industrial and domestic wastewater. Raw wastewater concentrations: - COD: up to 250 mg/L, - BOD: up to 80 mg/L, - TSS: up to 110 mg/L). → Good removal efficiency of organic pollutants. (BOD: 85 %, COD: 82 % and TSS: 86 %) → Good, year-round growth of *Miscanthus sacchariflorus*; cold temperatures (daily minimum: about 4 °C) during winter were tolerated without serious injured phenomenon caused by freezing. However, a direct comparison with the other species also planted in this system (*Canna indica, Phragmites australis, Scirpus validus* and *Thalia dealbata*) concerning removal performances was not possible.
Nitrogen and phosphorus compounds:	Moderate TN (≈ 45 %, mainly due to biological transformations

evaluation of existing case studies	and plant uptake) and high TP (≈ 82 %, mainly due to soil adsorption processes) reduction in the wetland system in Shenzhen, Southern China. → Comparison between plant species was not possible.
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species with a high potential as a renewable source of biomass.
Biomass production, growth rates and yields	Biomass production data for *Miscanthus sacchariflorus* were not available for this thesis. The most data relate to *Miscanthus x giganteus* as it has been one of the most extensive studied potential energy crops in Europe. Typical range of biomass yield for *Miscanthus x giganteus* under temperate conditions in Central Europe: 20 - 30 t/ha (Pude, 2006) It can be supposed that growth rates and biomass yields of *Miscanthus sacchariflorus* are potentially higher under the subtropical and warm conditions of Southeast and East Asia.
Biomass utilization options	*Miscanthus sp.* in general show versatile biomass utilization options and have generally a high potential as energy source. - Fuel source (direct combustion) due to the high energy content; caloric value: 29,300 - 33,770 kJ/kg (in: Wissing, 2002). → Higher than *Phragmites australis* - The fibres can be used for pulp and paper production due to the relatively high lignin and cellulose content, - building, insulation and packing material, - can serve as raw material for agricultural purposes, e.g. composting. (Jones, 2001; Niklas, 1990; Pude, 2006)
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Moderately frost tender; tolerant up to between -5 °C and - 10 °C when fully developed (PFAF, 2004), - a further *Miscanthus sp.* closely related to *Miscanthus sacchariflorus* is *Miscanthus sinensis* (Chinese or Japanese silver grass, eulalia grass). → *Miscanthus sinensis* is also native to East Asia, but extends more northern into temperate Eastern Asia than *Miscanthus sacchariflorus* (North China, temperate Russia), and is frost tolerant up to -20 °C when fully developed (PFAF, 2004). Extensive research work has been done in Europe using *Miscanthus* x *giganteus* (a natural hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus)* as a biomass fuel or fiber source (Jones, 2001). → 20 tons of *Miscanthus* x *giganteus* are equivalent to 12 tons of coal and 8,000 l of oil (Nixon, 2001).

11.10 *Pennisetum purpureum* (Napier grass)

Suitable and recommended for constructed wetlands in:
- Subtropical and tropical climate zones of: South Asia and Southeast Asia

1. Plant species	
Common name	Napier grass, elephant grass
Scientific name (genus / species)	*Pennisetum purpureum*
Family	*Poaceae* (*Gramineae*)

2. Availability in climate zone	
Climatic range	Subtropical to tropical
Geographic range	Native to tropical Africa (e.g. Kenya, Uganda, Zimbabwe); introduced to Southeast Asia (e.g. India, Pakistan, The Philippines, Taiwan, Thailand), South America (e.g. Brazil, Costa Rica) and Northern Australia (Queensland)
3. Growth characteristic and reproduction	
Life cycle and growth form	Perennial and rhizomatous, grows in dense clumps (NewCROP, 2005).
Growth height	Normally up to 4 m; however, 6 - 7 m are possible (USDA-IPIF, 2005)
Growth rate and period	Very fast, rapid regrowth rates after harvesting, strongly responding to nutrient supply (FAO, 2006).
Reproduction	Mainly vegetative, generative reproduction usually low due to the poor seed production (FAO, 2006).
Root and rhizome growth and development	Deep, extensive and vigorously growing root and rhizome system (FAO, 2006)
4. Habitat conditions and behaviour	
Natural Habitat	Moist grasslands and forest margins (FAO, 2006)
Light demand, shade tolerance	Grows better in full sun, but tolerates semi-shade (FAO, 2006).
pH optimum and tolerances	pH tolerance according to NewCROP (2005): 4.5 - 8.2
Salinity tolerance	No sufficient data available
Habitat dominance	Forms dense, pure stands that can out-compete other vegetation (USDA-IPIF, 2005).
5. Water regime	
Hydroperiod: tolerance to inundations, droughts and water levels	Does not tolerate prolonged inundations; tolerates drought periods quite well when established due to the deep root and rhizome system (FAO, 2006).
6. Removal efficiencies, tolerance to wastewater constituents and root zone effects	
General aspects	*Pennisetum clandestinum* cannot be used in surface flow constructed wetlands since it is not tolerant to prolonged inundations. The use of this unconventional plant species in constructed wetlands was first investigated in Taiwan by Yang (2001). In this study, *Pennisetum purpureum* was tested on both soil and gravel based systems for treatment of primary sewage. → The best performance was achieved for the gravel bed system (Yang, 2001, in: Kivaisi, 2001).
Organic constituents (BOD and COD) and suspended solids (TSS): evaluation of existing case studies	In a pilot scale study conducted by Tayade (2005) near Bombay, India (subtropical climate, ≈ 19 °N), *Pennisetum clandestinum* was planted, together with *Typha latifolia,* in a horizontal subsurface flow system for treatment of primary treated municipal wastewater; removal efficiencies: - BOD: 85 % (mean influent conc.: 152 mg/L) - TSS: 83 % (mean influent conc.: 144 mg/L) → Influent corresponds to low strength domestic raw wastewater. → High removal efficiency
Nitrogen and phosphorus compounds: evaluation of existing case studies	Removal efficiencies for nitrogen and phosphorus according to the study of Tayade in India: - TKN: 60 % (mean influent conc.: 24 mg/L) - TP: 46 % (mean influent conc.: 2.8 mg/L) → Good removal efficiency
Root zone effects: oxygenation capacity and effect on microbial transformations (nitrification and denitrification activity)	No plant-specific information found
7. Productivity, utilization options and economic potential	
Potential productivity	Highly productive species, one of the highest yielding tropical forage grasses (NewCROP, 2005). Has also a very high potential as a renewable energy crop (NewCROP, 2005).
Biomass production, growth rates and yields	Biomass and forage yields depend on fertility, moisture, temperature and management (harvesting); common and typical yields according to Cook (2005): 10 - 30 t/(ha*yr) dry wt.

	Other recorded yields reported of annual productivities much higher (up to 85 t/ha dry wt per year) than the range mentioned above. However, such high biomass yields can only be obtained under ideal conditions: use of nitrogen fertilizers, harvesting three or four times a year and optimum climatic conditions (much rainfall and warm temperatures), (FAO, 2006; NewCROP, 2005).
Biomass utilization options	One of the most valuable forage and silage crops in the tropics with high dry matter yields: - Can be made into nutritious silage of high quality and is highly palatable to animals, - young stands can be made into hay of good quality, - widely used for the production of dehydrated grass pellets in Taiwan. (Cook, 2005; FAO, 2006) - Can also be used for paper making (NewCROP, 2005).
8. Nutrients: uptake and storage capacities	
General aspects	
Nitrogen: uptake and assimilation rates	No data found
Phosphorus: uptake and assimilation rates	No data found
9. Further remarks and comparisons with other plant species (if possible)	- Very robust species (NewCROP, 2005), - sensitive to frost periods (FAO, 2006), - usually needs to be planted vegetatively due to the poor seed germination rate (Cook, 2005).

11.11 Other species tested for constructed wetlands

This chapter briefly presents very unconventional and alternative plant species that have been tested in constructed wetland systems. However, for this thesis the most studies were not available, thus, the information and data given below are based on a few summaries and abstracts.

Bamboo species

Description and utilization options

Bamboos are perennial plants of the grass family (*Poaceae* / *Gramineae*) and include over 1,200 species worldwide in more than 100 genera. They are widespread throughout the subtropical and tropical regions worldwide, particularly in South Asia, Southeast Asia, as well as in East Asia, but also in tropical Africa and South America (Brazil), (INBAR, 2006). However, they tolerate also warm/temperate climates such as the Mediterranean region (De Vos, 2000).
The largest bamboo stands can be found in China (3 million ha) and India (8 million ha). They range from small plants only 3 m tall growing under desert conditions to over 30 m high and 0.3 m in diameter under tropical conditions. Many bamboo species are markedly adaptable plants that tolerate a wide range of climatic conditions. Bamboos are usually fast growing and highly productive species and one of the most widely utilized natural resources in the world. The utilization options are highly versatile, e.g.:

- Biomass fuel (renewable source of energy, e.g. briquets production)
- Timber of high quality (wood for furniture, construction material for housing)

- High strength fibre (e.g. for fibreboard and particle-board production, laminated products, veneers)
- Pulp and paper production
- Livestock forage

(De Vos, 2000; Whish-Wilson, 2002)

Bamboo species in constructed treatment wetlands

The potential of bamboo in constructed wetlands was first investigated by Wolverton (1983) who compared the treatment efficiency of an unvegetated experimental microbial filter with vegetated filters planted with common reed (*Phragmites australis*), broad-leaved cattail (*Typha latifolia*), soft rush (*Juncus effusus*) and bamboo *(Bambusa multiplex*) under greenhouse conditions.
Bamboo performed the poorest BOD removal compared to all other systems including the unvegetated filter. However, the bamboo filter was more effective in reduction of TKN and ammonium nitrogen than the unvegetated system, but less than the other three plant species. Altogether, from this early study can be concluded that bamboos appear to be suitable for use in constructed wetlands.

A further investigation was conducted within the scope of the research project "Bamboo for Europe" supported by the EEC (Contract Nr.: FAIR-CT96-1747). The main objective of this project was "to define and to overcome major problems and limitations to large-scale introduction of bamboo in the European Community". One specific objective, beside many others, was to utilize two bamboo species in a constructed wetland and to compare their treatment efficiency to a standard wetland species (*Phragmites australis*).
Therefore, two bamboo species (*Phyllostachis Nidularia* and *Phyllostachis heteroclada*) were planted in a vertical flow system treating a primary effluent from a septic tank or Imhoff tank. The system constructed in Portugal was in operation for one year and complied fully with the regulation imposed by European standard.
The study concluded that there exists a high potential for further developments in Europe and in other areas. The study suggested that bamboo stands could be irrigated with secondary treated effluents that would avoid any water contamination and produce valuable biomass yields suitable for industrial purposes (De Vos 2000; De Vos 2004).

***Musa* and *Saccharum* species**

A demonstration project was conducted at the "Beelarong Community Farm" at Morningside near Brisbane in Queensland, Australia to treat the discharge from a septic system on-site under field conditions. A variety of fast growing tropical grasses, trees and crops including banana (*Musa sp.*, family: *Musaceae*) and sugar cane (*Saccharum sp.*; family: *Poaceae*) were tested in this project.
However, these plant species failed at absorbing the effluent discharge from the septic tank and the project was continued with vetiver grass (*Vetiveria zizanioides*) which showed a high efficiency in improving the effluent quality (in: Truong, 2001). Further information about this project was not available.

12 Recommendation tables

This chapter contains the recommendation tables, one table for each climate zone. The 46 plant species (bamboo species are referred as one species) investigated in the Chapters 8 - 11 (except for *Musa* and *Saccharum* sp.) are assigned to their corresponding climate zones and local regions where they naturally grow and, thus, can be selected for constructed wetlands in these areas. The most species can be used in more than one region and to a lesser extent also in different climate zones. In particular, many species adapted to temperate climates are also tolerant to cold/boreal conditions, and many subtropical species can also grow in tropical regions.
The plants were evaluated concerning their productivity, versatility of biomass utilization options and potential as a renewable biomass source for energy purposes according to the information and data that were available for this thesis. Where data were not available or insufficient, a tendency was given. It should be considered that it is only possible to compare the productivity of different plant species within a definite climate zone.

Comments on the evaluation of the recommendation tables:

1. Productivity / growth rate:

The indications in this column are mainly based on data that could be found in the literature, e.g. production rates and biomass yields in tons per year. However, for many species no exact information was available. In such cases, the productivity / growth rate was estimated according to the information and conclusions that were available about the plant species.

2. Versatility of potential biomass utilization options:

It was possible to classify the utilization options found in the plant-specific tables (Chapters 8 - 11) in the following six different main categories:

1. Handicrafts
2. Agricultural purposes (fertilizer or composting purposes)
3. Animal and cattle feed
4. Building and construction material
5. Paper making
6. Fuel and energy source

The evaluation of the plant species in the corresponding column was conducted in the following way:

Possible utilization options	Versatility
0 or 1 of 6	Low (or unknown)
2 of 6	Low to moderate
3 of 6	Moderate
4 of 6	Moderate to high
5 of 6	High
6 of 6	Very high

For example, if a plant species is functional for two utilization options, e.g. for handicrafts and paper making, the versatility of this species in the recommendation tables is defined as “low to moderate”. No or a low versatility was summarized in the same category. For some species, no utilization options could be found. However, it may be possible that these plants could be used for at least one of these six options, but the necessary information was not available.

3. Potential as energy source

The indications in this column are primarily based on the information that could be found in the literature, e.g. have there been profitable or promising experiments and investigations to utilize a given plant for energy purposes. If no appropriate information could be found, a tendency was given mainly based on the productivity and growth rate.

The case studies investigated for the plant-specific tables showed that all plant species are suitable for use in constructed treatment wetlands for municipal wastewaters. The removal capacities were similarly high for all species and no significant differences in the treatment efficiency could be found. Thus, the plants were not compared concerning their treatment efficiencies.
It was not possible to compare the plant species concerning their tolerance ranges to wastewater pollutants. The influent concentrations found in the case studies were highly diverse depending on wastewater type (e.g. municipal or agricultural) and treatment level (raw, primary or secondary influent). In some case studies using multistage systems the plant species were not planted in the first treatment stage of the wetland system, and thus, not exposed to the high influent concentration.

It is possible to draw conclusions that all plant species are suitable for treatment of municipal wastewaters, but tolerance ranges cannot be given for the most plants due to the wide research differences between the investigated case studies.

The tables illustrate which plant species can be selected for which region, and further provide general information about productivities. More detailed data, however, can be taken from the plant-specific tables (Chapters 8 - 11).

12.1 Recommendation table for cold/boreal climate zones

Climate zone	**Region**	**Plant species**	**Remarks concerning the geographic distribution**	**Productivity / growth rate**	**Versatility of potential utilization options**	**Potential as energy source**
Cold/boreal	**Northern Europe** (Scandinavia)	*Carex acuta*		Low to moderate	Low	Low
		Carex aquatilis		Low to moderate	Low (or unknown)	Low
		Carex rostrata	Also common in Iceland	Low to moderate	Low to moderate	Low
		Glyceria maxima		High	Moderate	High
		Phalaris arundinacea		High	Moderate	High
		Phragmites australis		High	Very high	High
		Typha latifolia		High	Very high	High
	North America (Canada, Northern USA)	*Carex aquatilis*	Also common in Alaska, USA	Low to moderate	Low (or unknown)	Low
		Scirpus cyperinus	Common species in Canada	Moderate	Low	Low
		Scirpus validus		Moderate to high	High (similar to *Scirpus lacustris*)	Moderate
		Phragmites australis		High	Very high	High
		Typha latifolia		High	Very high	High
	Northern Asia (Northern Russia, Arctic region and Siberia)	*Carex aquatilis*	Common species in the Russian Arctic	Low to moderate	Low (or unknown)	Low
		Phragmites australis		High	Very high	High
		Typha latifolia		High	Very high	High

12.2 Recommendation table for temperate climate zones (1)

Climate zone	Region	Plant species	Remarks concerning the geographic distribution	Productivity / growth rate	Versatility of potential utilization options	Potential as energy source
Temperate (Northern Hemisphere)	**Central and Eastern Europe** (e.g. Austria, Czech Republic, France, Germany, etc.)	*Carex acuta*		Low to moderate	Low	Low
		Juncus effusus		Low to moderate	Moderate	Low
		Glyceria maxima	Also common in West Asia	High	Moderate	High
		Phalaris arundinacea	Also common in West Asia	Very high	Moderate	High
		Phragmites australis		Very high	Very high	High
		Scirpus lacustris		Moderate to high	High	Moderate
		Typha angustifolia		Very high	Very high	High
		Typha latifolia		Very high	Very high	High
		Lolium perenne (A)	Also common in West Asia	High	Moderate	High
	North America (mainly USA)	*Juncus effusus*		Low to moderate	Moderate	Low
		Phragmites australis	Not in all parts of the USA	Very high	Very high	High
		Scirpus acutus		Moderate to high	Moderate to high	Moderate
		Scirpus californicus		High	Moderate to high	Potentially high
		Scirpus maritimus	More in coastal areas	Moderate to high	Low to moderate	Moderate
		Scirpus pungens		Moderate	Low to moderate	Moderate
		Scirpus validus		Moderate to high	High (similar to *Scirpus lacustris*)	Moderate
		Typha angustifolia		Very high	Very high	High
		Typha latifolia		Very high	Very high	High
		Zizaniopsis miliacea	Mainly in the southern parts	High	Low (or unknown)	Potentially high
	East Asia (e.g. Japan, Korea, North China)	*Phragmites australis*	Most commonly used wetland plant in Japan	Very high	Very high	High
		Typha orientalis	Warm/temperate parts of Japan	Very high	Very high	High
		Zizania latifolia	Common in China and Japan	High	Moderate to high	High
		Lolium perenne (A)		High	Moderate	High
		Miscanthus sacchariflorus (A)	More in the warmer parts of East Asia	High	Moderate to high	High
		Bamboo species	Mainly in the warm/temperate parts of China and Japan	Very high	Presumably very high	High

(A): Alternative species

12.3 Recommendation table for temperate climate zones (2)

Climate zone	Region	Plant species	Remarks concerning the geographic distribution	Productivity / growth rate	Versatility of potential utilization options	Potential as energy source
Warm/ Mediterranean	**Southern Europe and North Africa** (coastal regions)	*Arundo donax*	Mainly in Southern Europe	Very high	High	Very high
		Phragmites australis		Very high	Very high	High
		Scirpus maritimus		Moderate to high	Low to moderate	Moderate
		Typha angustifolia		Very high	Very high	High
		Typha domingensis	Mainly in Southern Europe	Very high	Very high	High
		Lolium perenne (A)		High	Moderate	High
	Eastern USA (California, USA)	*Phragmites australis*		Very high	Very high	High
		Scirpus acutus		Moderate to high	Moderate to high	Moderate
		Scirpus californicus		High	Moderate to high	Potentially high
		Scirpus pungens		Moderate	Low to moderate	Moderate
Temperate (Southern Hemisphere)	**Southern South America** (e.g. Argentina, Chile, Uruguay)	*Scirpus californicus*		High	Moderate to high	Potentially high
		Typha subulata		Very high	Very high	High
		Zizaniopsis bonariensis		High	Low (or unknown)	Potentially high
	South Africa	*Pennisetum clandestinum*	Also in (sub)tropical Africa	High	Moderate	Potentially high
		Phragmites australis		Very high	Very high	High
		Scirpus lacustris		Moderate to high	High	Moderate
		Typha capensis		Very high	Very high	High
	Southern Australia (mainly NSW) and New Zealand	*Baumea articulata*	Common plant in Australia and New Zealand	Low to moderate	Low (or unknown)	Low
		Eleocharis sphacelata		Moderate to high	Low to moderate	Low
		Juncus ingens	Mainly in Australia	High	Low (or unknown)	Potentially high
		Scirpus validus	Mainly in New Zealand	Moderate to high	High (similar to *Scirpus lacustris*)	Moderate
		Zizania latifolia	Only in restricted parts of New Zealand	High	Moderate to high	High
		Carex fascicularis (A)		Moderate to high	Low (or unknown)	Moderate

(A): Alternative species

12.4 Recommendation table for subtropical climate zones

Climate zone	Region	Plant species	Remarks concerning the geographic distribution	Productivity / growth rate	Versatility of potential utilization options	Potential as energy source
Subtropical	**Central America** (The Caribbean, Mexico, South Florida, USA)	*Canna flaccida*		High	Low	Rather low
		Canna indica		High	Low	Rather low
		Typha angustifolia	Mainly in Mexico	Very high	Very high	High
		Typha domingensis		Very high	Very high	High
		Coix lacryma-jobi (A)		High	Moderate to high	Potentially high
	South Asia (e.g. India, Nepal, Pakistan)	*Arundo donax*		Very high	High	Very high
		Canna indica		High	Low	Rather low
		Phragmites karka		Very high	Very high (similar to *Phragmites australis*)	High
		Scirpus grossus		High	Presumably high	Moderate
		Pennisetum purpureum (A)		Very high	Moderate to high	High
		Bamboo species	Especially in India and Nepal	Very high	Presumably very high	High
	Southeast Asia (e.g. Cambodia, South China, Taiwan, Thailand, etc.)	*Canna indica*		High	Low	Rather low
		Cyperus involucratus		Moderate to high	Moderate to high	Potentially high
		Scirpus grossus		High	Presumably high	Moderate
		Typha angustifolia		Very high	Very high	High
		Vetiveria zizanioides		Very high	Very high	High
		Cyperus malaccensis (A)		Moderate to high	Low to moderate	Rather low
		Lepironia articulata (A)		Moderate to high	Low to moderate	Moderate
		Miscanthus sacchariflorus (A)		High	Moderate to high	High
		Pennisetum purpureum (A)		Very high	Moderate to high	High
		Bamboo species	Especially in Burma and South China	Very high	Presumably very high	High
	Northern Australia (mainly Queensland)	*Cyperus involucratus*		Moderate to high	Moderate to high	Potentially high
		Eleocharis sphacelata		Moderate to high	Low to moderate	Low
		Typha domingensis		Very high	Very high	High
		Typha orientalis		Very high	Very high	High
		Vetiveria zizanioides		Very high	Very high	High
		Carex fascicularis (A)		Moderate to high	Low (or unknown)	Moderate
		Bamboo species	Only in the northern parts of Queensland (Australia)	Very high	Presumably very high	High

(A): Alternative species

12.5 Recommendation table for tropical climate zones

Climate zone	Region	Plant species	Remarks concerning the geographic distribution	Productivity / growth rate	Versatility of potential utilization options	Potential as energy source
Tropical	**Southeast Asia** (e.g. Indonesia, Malaysia, New Guinea, The Philippines)	*Phragmites karka*		Very high	Very high (similar to *Phragmites australis*)	High
		Scirpus grossus		High	Presumably high	Moderate
		Typha angustifolia		Very high	Very high	High
		Typha orientalis		Very high	Very high	High
		Cyperus malaccensis (A)		Moderate to high	Low to moderate	Rather low
		Lepironia articulata (A)		Moderate to high	Low to moderate	Moderate
		Pennisetum purpureum (A)		Very high	Moderate to high	High
		Bamboo species	In all regions	Very high	Presumably very high	High
	Central and Southern Africa (e.g. Kenya, Uganda, Zaire)	*Cyperus involucratus*	More in Southern Africa	Moderate to high	Moderate to high	Potentially high
		Cyperus papyrus		Very high	Moderate to high	Very high
		Phragmites mauritianus		Very high	Very high (similar to *Phragmites australis*)	High
		Cyperus latifolius (A)		Moderate to high	Moderate	Potentially high
		Miscanthidium violaceum (A)		Moderate to high	Low (or unknown)	Moderate
		Bamboo species	Tropical and Southern Africa	Very high	Presumably very high	High
	South America (Brazil: Amazon basin)	*Pennisetum purpureum* (A)	Possible, could not be verified by case studies	Very high	Moderate to high	High
		Bamboo species	Subtropical and tropical Brazil	Very high	Presumably very high	High

(A): Alternative species

13 Discussion

13.1 Geographical location of constructed wetlands worldwide

The investigation of this thesis shows that constructed wetlands for wastewater treatment are used in nearly all regions and climate zones worldwide. Apart from some climatically extreme regions (mainly very arid and polar climates), they can be found on practically all continents, even under cold arctic conditions, e.g. in the Russian Arctic. Thus, it was possible to find numerous case studies of many areas worldwide that could be used for this thesis. Research projects and reports in the field of constructed wetlands of approximately 40 countries were evaluated and classified to their corresponding climate zone and global location.
The analysis of all information that was available for this thesis showed an unequal geographical location of constructed wetlands all over the world. The following three regions are the main focus areas for the development of treatment wetland systems:

- Europe: primary Central and Northern Europe, but to a lesser extend also the Mediterranean region of Southern Europe
- North America: primary USA
- Australia

The majority of constructed wetlands planted with emergent macrophytes are used in Central Europe. Many investigations have also been conducted under the cold/boreal conditions in Northern Europe, particularly in Norway and Sweden.
A lot of operational wetland systems have been constructed in the USA, but also in Australia where initial research projects can be dated back to the late 1980s. Thus, a great variety of suitable plant species could be selected for each of these three regions as one can see in the recommendation tables.

These results show that the most important research areas are located in the developed countries. However, one objective of this thesis was to find plant species for constructed wetlands in developing countries that are mainly located in subtropical and tropical environments. The implementation of this technology in the abovementioned countries is relatively new and started primarily in the middle of the 1990's.

Within the subtropical and tropical regions throughout the world, the most case studies were found in South and Southeast Asia. While India and Nepal are the main research areas in subtropical South Asia, South China and Thailand form the basis for the plant choice in the subtropical region of Southeast Asia. A lot of constructed wetland systems with different plant species have been tested in South China and Thailand. Constructed wetlands are also a well-proven technology in the tropical regions of Southeast Asia. Several reports and studies could be found on Indonesia, Malaysia and The Philippines. As a result, a lot of different, mainly high-productive plant species were included in the recommendation tables for the subtropical and tropical regions of South Asia and Southeast Asia.

In recent years, researches in the field of constructed wetlands have also been done under tropical conditions in Central and Southern Africa. Especially in Kenya and Uganda, several systems have been tested using high productive plant species and achieved promising treatment results.

The most important research area in South America is located in Southern Brazil where warm temperate conditions are prevailing. Since the available corresponding studies on this region have all used the same plants, only three species could be selected for the recommendation tables.

However, there are also regions where no or only few case studies of operational wetland systems were available. Generally, no wetland systems could be found in the following arid desert climates:

- North Africa (Sahara) and Arabia
- Central Australia.

The use of cosmopolitan and robust plant species such as common reed (*Phragmites australis*) may be possible in the abovementioned regions, but this could not be proved by an existing constructed wetland system. However, *Phragmites australis* was successfully used in a horizontal subsurface flow bed for treatment of domestic wastewater under semi-arid conditions in Iran (Badkoubi, 1998).

In the following temperate to tropical regions, constructed wetland systems did not find a widespread use to date at the present time:

- Tropical South America (the Amazon basin in Brazil in particular)
- Subtropical Central America and the Caribbean region
- Temperate Asia (Russia, Asian part) and Eastern Europe (mainly Ukraine)

The Brazilian Amazon basin is a region with extreme climatic conditions that include heavy rainfall, high temperatures throughout the year and a high humidity. Otherwise cosmopolitan or widely distributed plant species such as *Phragmites australis* are not present in this region. The tropical recommendation table suggests two plant species (including bamboos) that may be possible. However, more investigations are to be done in the Amazon area.

The implementation of constructed wetlands in subtropical Central America is still in the early stages. Two studies of 2004 that were conducted in Central Mexico and Costa Rica could be evaluated for this thesis. A high potential for use of alternative, natural treatment systems such as constructed wetlands could be concluded from these studies due to the lack of wastewater treatment facilities in large parts of Central America, especially in rural communities where untreated greywater is often discharged directly into the nearest stream or watershed.

The temperate regions of Asia and Eastern Europe proved to be a special issue for this thesis. Although constructed wetland systems have been built in Russia (Vasilevskaya, pers. comm.) and Ukraine (Magmedov, 1996), the corresponding case studies were not available. It can be supposed that the most plant species naturally found in Central Europe, e.g. *Glyceria maxima, Phalaris arundinacea* and *Typha latifolia*, are also suitable for constructed wetlands in Eastern Europe (Belarus, Ukraine) and the European part of Russia.

13.2 Diversity of the selected plant species

In this thesis, 46 plant species were considered for the recommendation tables. As it was already mentioned in the last chapter, the number of evaluated and selected species for a specific region correlates often with the number of existing case studies found. The subtropical and tropical regions of South Asia and Southeast Asia appear to have the highest diversity of suitable plant species and include the most alternative species selected for the recommendation tables.
The most plants belong to the sedge family (*Cyperaceae*) and grass family (*Poaceae*), followed by the cattail family (*Typhaceae*). The remaining species belong to the rushes (*Juncaceae*), cannas (*Cannaceae*) and bamboos (the latter are referred as one species in this thesis).

Some species show very high similarities to other species of the same genus, particularly within the genera *Phragmites* and *Typha*. However, they are biologically considered as segregate species with morphological distinctions and different geographic distributions. The taxonomical classification of some species, especially of the *Phragmites* genus, is not standardized up to the present time and this could make the precise segregation difficult.

13.3 Other plant species

Beside the 46 plant species chosen for the recommendation tables, a lot of other wetland plants were found and evaluated during the investigation conducted by this thesis. These plants are also suitable for use in constructed treatment wetlands. However, they were not considered for the recommendation tables due to at least one of the following aspects:

- The suitability in constructed treatment wetlands could not be proved (no appropriate case study available)
- Low productivity or low versatility of biomass utilization options
- Supplementary wetland species (species that are more suitable for bed margins, not as the main species for wetland planting, e.g. *Iris sp.*)

Other plant species that were found for cold/temperate to warm/Mediterranean climates mainly Europe including Mediterranean region, North Africa, North America and West Asia:

- *Iris pseudacorus* (yellow flag, yellow iris)
- *Iris versicolor* (blue flag, blue iris)
- *Juncus acutus* (spiny rush, sharp rush)
- *Juncus maritimus* (sea rush)
- *Panicum hemitomon* (maidencane)
- *Pontederia cordata* (pickerelweed)
- *Sagittaria latifolia* (duck potato, arrowhead)
- *Sparganium erectum* (branched bur-reed, exotic bur-reed)

Other plant species that were found for subtropical to tropical climates, mainly South Asia and Southeast Asia, also Southern Africa:

- *Acorus calamus* (sweet flag)
- *Commelina communis* (Asiatic dayflower)
- *Digitaria bicornis* (Asia crab grass)
- *Eleocharis dulcis* (Chinese water chestnut)
- *Ludwigia octovalsis* (water primrose, primrose willow)
- *Thalia dealbata* (powdery thalia)
- *Zantedeschia aethiopica* (calla lily, arum lily)

All these plant species can be used in operational constructed wetlands, e.g. *Iris sp., Sparganium erectum* or *Acorus calamus* (Wissing, 2002) or have been successfully tested in experimental and laboratory studies, e.g. *Digitaria bicornis* (Klomjek, 2005) or *Commelina communis* and *Ludwigia octovalsis* (Jing, 2002).
Eventually, it should be considered that numerous other wetland plant species may also have the potential capability to purify polluted wastewaters.

13.4 Comparison of treatment efficiencies and tolerance ranges

Treatment efficiencies

It was already mentioned that all plants that were selected in this thesis are suitable in constructed wetlands treating municipal or domestic wastewater. In the plant-specific tables (Chapters 8 - 11), this is demonstrated by removal efficiencies (e.g. for BOD, COD or ammonium-nitrogen) given in percentage. However, these data are to prove the general suitability of the plant species. It is difficult or impossible to directly compare various species concerning their removal performance in order to make a ranking which plant is better than other ones. Earlier analyses of several constructed wetland systems concluded inconclusive results for the question which plant might be the best for removal of wastewater pollutants. Differences in the treatment performance are mostly not significant (Kadlec and Knight, 1996).

The difficulties are particularly obvious when removal efficiencies for nitrogen are to compare. On the one hand, ammonium can be removed both by bacterial transformations and plant uptake (Chapter 5.2). Many studies do no differ between these two removal pathways, thus, the direct contribution of the plants concerning the total nitrogen reduction performed by the wetland system cannot be specified. On the other hand, nitrification is generally difficult to quantify and the plants are often in competition with nitrifying bacteria for free ammonium. Finally, nitrogen removal by plant uptake is normally not significant compared to the total removal efficiency of a wetland system, independent of the plant species chosen.

One can conclude that the plant vegetation may be chosen on the basis of other more important factors such as productivity and growth, rapid establishment, robustness and ecological acceptability in the given area (weed risk) rather than treatment efficiency which is nearly on a similar level for all plant species.

Wastewater tolerance ranges

The plant-specific tables (Chapters 8 - 11) reveal that the following species appear to be tolerant to high organic loadings or eutrophic conditions: *Carex acuta*, *Phragmites australis*, *Scirpus lacustris*, *Scirpus validus*, *Typha latifolia, Typha angustifolia*, *Glyceria maxima*, *Cyperus involucratus* and *Vetiveria zizanioides*. However, exact tolerance ranges and limits could not be found for these species. It is supposed that also the most other species, especially those of the genera *Carex*, *Phragmites*, *Scirpus* and *Typha* show similar tolerance ranges.

Generally, it was not possible to compare directly the wastewater tolerance ranges of the 46 selected species due to the insufficient information on this aspect.

13.5 Comparison of plant productivity and utilization options

Plant productivity and biomass utilization are critical criteria for the recommendation tables in Chapter 12. One of the main focuses of this thesis was to find productive species with versatile utilization options and, if possible, a high potential as a renewable energy source.
The purpose of the recommendation tables is to compare the plant species with respect to their biomass production and utilization options according to the information that was available. Although the evaluation cannot be considered as universally valid, the following conclusions can be made:

Plant productivity

Typha sp., *Phragmites sp*. and the most other grasses (*Poaceae*) such as *Arundo donax, Vetiveria zizanioides*, *Zizania latifolia*, but also *Glyceria maxima*, *Phalaris arundinacea, Pennisetum sp.*, *Zizaniopsis sp.*, *Miscanthus sacchariflorus, Lolium perenne* and bamboos are high or very high productive plants.
Scirpus sp. and *Cyperus sp.* show generally moderate to high productivities (except for *Cyperus papyrus* that is high productive). The species of the genera *Juncus* (apart from *Juncus ingens*), *Carex* and *Baumea* have a low to moderate productivity. However, they show other advantages such as a high frost tolerance (*Carex sp.*), high stability in constructed wetlands and year-round growth (*Baumea articulata*) or high robustness (*Juncus effusus*).

It should be recapitulated that growth rates and biomass yields of different plant species can only be effectively compared within a climate zone. However, other aspects affecting growth rates are also to consider, e.g. nutrient availability in wastewater (primary, secondary or advanced treated influents), diverse stress factors (e.g. high strength wastewaters, excessive hydraulic loading rates, saline conditions, toxic compounds or adverse environmental conditions) and biological factors (e.g. resistance to pests and diseases). All these factors must be taken into account for a reliable comparison of growth and biomass production rates. The recommendation tables depend on the available information, and thus, can only provide a general tendency.

Plant utilization options

This investigation shows that the most plants can be utilized versatilely; especially those species that are characterized through high growth and biomass production rates, above all *Typha sp.*, *Phragmites sp.*, *Vetiveria zizanioides*, *Arundo donax* and bamboos show a high or very high versatility. Low productive species such as the most *Carex sp.* and *Baumea articulata* appear to have lower versatilities. No information could be found for the following moderate to fast growing species despite their relatively high productivity and potential as renewable biomass source: *Carex fascicularis*, *Juncus ingens*, *Miscanthidium violaceum* and *Zizaniopsis sp.*

An evaluation of the type of utilization options given in the plant-specific tables resulted in the following classification ordered according to decreasing significance:

1. Handicrafts (especially weaving material)
2. Potential fuel and energy source (direct combustion, biogas production)
3. Building and construction material (especially thatching)
4. Industrial purposes: paper making, insulation and packing material
5. Animal and cattle feed
6. Composting purposes and fertilizer production (agriculture)
7. Other agricultural purposes: silage, bedding materials (hay or straw)
8. Miscellaneous purposes (e.g. decoration)

Not all plant utilization options that may be theoretically possible can also be implemented in constructed wetlands. Beside the options listed above, many other possibilities to utilize a wetland plant exist. For example, *Typha sp.* and other rhizomatous species store large amounts of starch and sugars in their rhizomes that can be used as feedstock for ethanol production via hydrolysis and fermentation (Lakshman, 1987). However, only the harvestable aboveground biomass can be utilized for economical purposes in constructed wetlands. Although the belowground biomass production can be significant, it is clear that the roots and rhizomes cannot be removed from an operational wetland system as this would negatively affect the treatment performance and the re-growth of the plant vegetation. Thus, the economical use of plant biomass in constructed treatment wetlands is confined to the aboveground plant parts (mainly stems and leaves).
Many wetland plants have also medical or edible uses. However, the practical suitability and acceptability of wetland plants that are exposed to a high variety of (possible toxic) compounds found in municipal or domestic wastewaters can be at least considered as problematic for such uses.

13.6 Mostly recommended plant species

The following table presents the plant species that are mostly suggested according to the recommendation tables, apart from *Typha sp.* and *Phragmites sp*. These two genera are generally recommended for all regions and climate zones where the corresponding subspecies are indigenous or naturally occur. Species that have a high productivity, but low or unknown utilization options (*Zizaniopsis sp.* and *Juncus ingens*) were also not considered in the table below (Table 13.1).

Table 13.1: Mostly suggested plant species for constructed wetlands

Climate zone	Geographic region	Mostly recommended plant species
Cold/boreal	Northern Europe	*Glyceria maxima*
		Phalaris arundinacea
	Northern North America	*Scirpus validus*
Temperate	Central and Eastern Europe	*Glyceria maxima*
		Phalaris arundinacea
		Scirpus lacustris
	North America	*Scirpus validus*
		Scirpus californicus
	East Asia	*Zizania latifolia*
		Miscanthus sacchariflorus
	Southern South America	*Scirpus californicus*
	South Africa	*Scirpus lacustris*
	Southern Australia	*Scirpus validus*
Warm/Mediterranean	Southern Europe	*Arundo donax*
	Eastern USA (California)	*Scirpus californicus*
Subtropical	Central America	*Coix lacryma-jobi*
	South Asia	*Arundo donax*
		Scirpus grossus
		Pennisetum purpureum
	Southeast Asia	*Vetiveria zizanioides*
		Scirpus grossus
		Pennisetum purpureum
		Miscanthus sacchariflorus
	Northern Australia	*Vetiveria zizanioides*
Tropical	Southeast Asia	*Scirpus grossus*
		Pennisetum purpureum
	Africa	*Cyperus papyrus*
		Cyperus involucratus
	South America	*Pennisetum purpureum* (possible)

Comments:
Species that were not considered in this table:
- *Typha sp., Phragmites sp.* and bamboo species (generally recommended species)
- Species with low or unknown utilization options, but a high productivity: *Zizaniopsis sp.* and *Juncus ingens*

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14 Conclusions

Using three selection criteria (availability in climate zone, treatment efficiency and wastewater tolerance, plant productivity and biomass utilization options), this thesis aims to provide a systematic overview of suitable wetland plants for all climate zones worldwide, and also to find alternative species that are not typical for constructed wetlands. The results are presented in a recommendation table.

The investigation conducted in this thesis shows that constructed wetlands are in operation in nearly all regions and climate zones worldwide. Beside temperate regions with a long tradition in this field (Europe, North America and Australia), many systems have also been constructed and tested in subtropical and tropical areas, especially in the South Asian and Southeast Asian countries, e.g. India, Indonesia, Nepal, South China and Thailand, but also in tropical Africa. Regions with less or no constructed wetlands projects are the subtropical Central American and Caribbean region, and the tropical Brazilian Amazon basin.

Numerous wetland plants are potentially suitable for wastewater treatment in constructed wetlands. Among the many plants that were found and evaluated for this thesis, 46 different species were eventually considered for the recommendation tables. The most plants could be found in regions with increased research intensities. Nearly all selected species belong to one of the following plant families, ordered in decreasing significance: *Cyperaceae, Poaceae* and *Typha*.

The plant choice was made with particular consideration to find productive and economically useable species. The most plants in the recommendation tables are at least moderate productive. *Typha sp.*, *Phragmites sp.* and the other species of the *Poaceae* family including bamboos show a high or a very high productivity. Low to moderate productive species are mainly common in the cold/boreal climate zones. The majority of the plants that were chosen for the recommendation tables has also a high potential as a renewable energy and fuel source.
Finally, it should be considered that plant productivities can only be effectively compared within a definite climate zone.

Wetland plants growing under nutrient-enriched conditions such as municipal wastewaters produce usually high harvestable annual biomass yields that can serve as an alternative resource base for economical utilization purposes. This can at least partially offset the treatment and operation costs.
The plant-specific investigations in this thesis reveal that the biomass utilization options for the most plant species are versatile. The most common utilization options of the aboveground plant biomass are agricultural purposes, animal and cattle feed, diverse handicrafts, energy and fuel source, building and construction material and industrial purposes, especially pulp and paper making. Particularly in developing countries, constructed wetland systems using fast-growing species can provide a good, unconventional source for such utilization possibilities, beside their primary function in wastewater treatment. However, the frequency, and thus, the cost of harvesting have also to be considered.

Perspectives

This thesis shows that there are versatile possibilities to use the biomass of productive wetland plants growing in constructed wetlands. Productivity and economic versatility of macrophyte species can be a crucial decision and design factor for the choice of suitable plant species because differences in wastewater treatment efficiency are mostly not significant.

However, the investigation of the numerous case studies and reports that were used for this thesis lead to the conclusion that at present it is not a widespread practise to harvest and use the biomass of constructed wetlands for secondary purposes. Although wetland plants are cultivated for diverse utilization purposes in many regions worldwide, the combination of wastewater treatment with constructed wetlands as a primary purpose and utilization of the wetland biomass as a secondary purpose has not been widely performed up to the present time. Here appears to be an economical potential where further researches are recommended and needed due to the high productivity and versatility of many emergent plant species as it is showed in this thesis.

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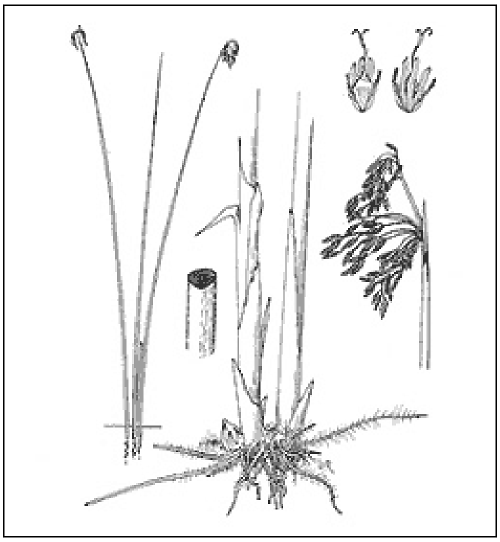
Appendix

A Pictures and drawings of selected plants used in constructed wetlands

Bulrushes (*Scirpus sp.*)



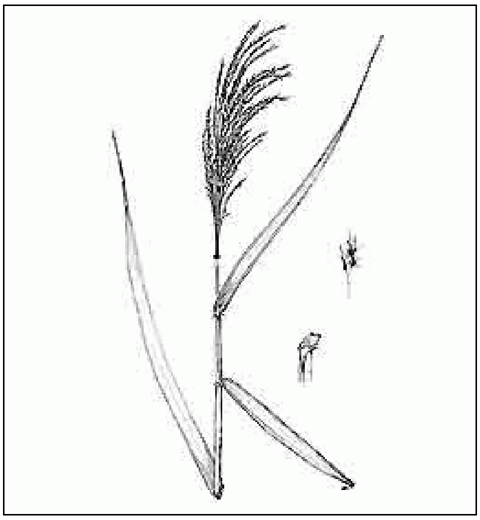
(Drawing taken from: Center for Aquatic and Invasive Plants, Institute of Food and Agricultural Sciences, University of Florida, 2005. Online available on: http://plants.ifas.ufl.edu/welcome.html)

(Picture taken from: "AQUAPLANT", Texas A&M University, USA, Department of Wildlife and Fisheries Sciences, 2006. Online available on: http://aquaplant.tamu.edu/index.htm)

Cattails (*Typha sp.*)

(Drawing and picture taken from: Center for Aquatic and Invasive Plants, Institute of Food and Agricultural Sciences, University of Florida, 2005. Online available on: http://plants.ifas.ufl.edu/welcome.html)

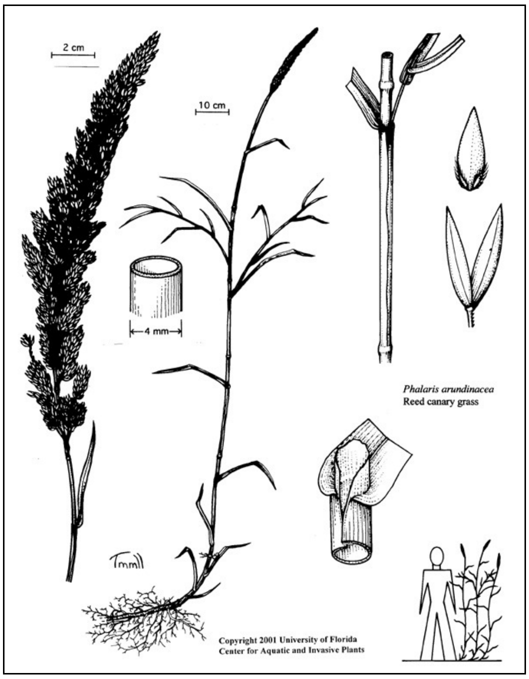
Common reed *(Phragmites australis)*



(Drawing taken from: Center for Aquatic and Invasive Plants, Institute of Food and Agricultural Sciences, University of Florida, 2005. Online available on: http://plants.ifas.ufl.edu/welcome.html)

(Picture taken from: "AQUAPLANT", Texas A&M University, USA, Department of Wildlife and Fisheries Sciences, 2006. Online available on: http://aquaplant.tamu.edu/index.htm)

Reed canary grass (*Phalaris arundinacea*)



(Drawing and picture taken from: Center for Aquatic and Invasive Plants, Institute of Food and Agricultural Sciences, University of Florida, 2002. Online available on: http://plants.ifas.ufl.edu/welcome.html)

Sedges (*Carex sp.*)

(Drawing taken from: Center for Aquatic and Invasive Plants, Institute of Food and Agricultural Sciences, University of Florida, 2005. Online available on: http://plants.ifas.ufl.edu/welcome.html)

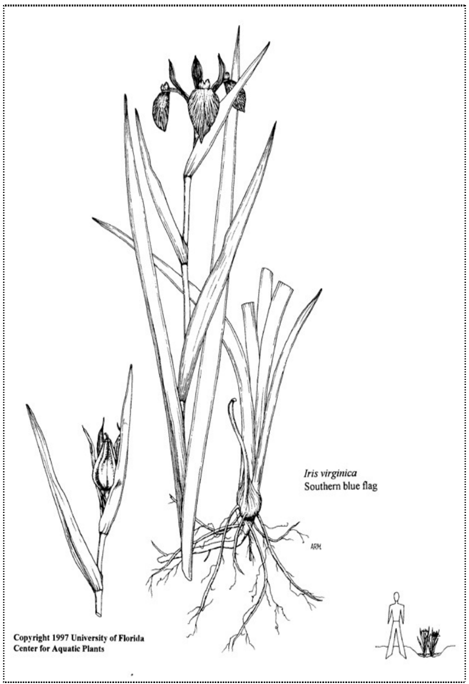
(Picture taken from: “AQUAPLANT”, Texas A&M University, USA, Department of Wildlife and Fisheries Sciences, 2006. Online available on: http://aquaplant.tamu.edu/index.htm)

Soft rush (*Juncus effusus*)

(Drawing taken from: Center for Aquatic and Invasive Plants, Institute of Food and Agricultural Sciences, University of Florida, 2005. Online available on: http://plants.ifas.ufl.edu/welcome.html)

(Picture taken from: “AQUAPLANT”, Texas A&M University, USA, Department of Wildlife and Fisheries Sciences, 2006. Online available on: http://aquaplant.tamu.edu/index.htm)

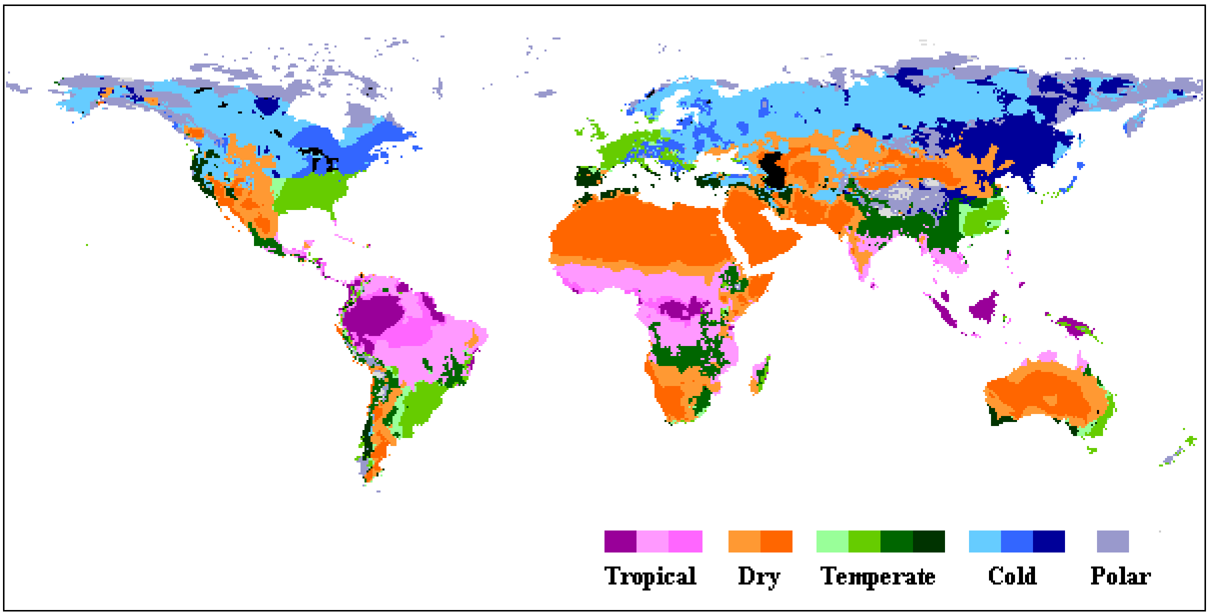
Blue flag (*Iris virginica*)



(Drawing taken from: Center for Aquatic and Invasive Plants, Institute of Food and Agricultural Sciences, University of Florida, 2001. Online available on: http://plants.ifas.ufl.edu/welcome.html)

(Picture taken from: “AQUAPLANT”, Texas A&M University, USA, Department of Wildlife and Fisheries Sciences, 2006. Online available on: http://aquaplant.tamu.edu/index.htm)

B Koeppen's climate classification



Source: FAO - SDRN - Agrometeorology (AGROMET) Group; modified
Online available on: http://metart.fao.org/