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ANALYSIS OF EXPOSURE PATHWAYS AND MEASURES TO MITIGATE THE EMANATING RISK OF SANITATION OPTIONS IN COASTAL AREAS OF ISLANDS IN THE SOUTH PACIFIC

Master thesis

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TABLE OF CONTENTS

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Abstract

Rural coastal areas of islands in the South Pacific are often characterized by shallow groundwater and are prone to floods. The prevalent sanitation (i.e. Single Pit System; ‘bush’, Dry, and Pour-Flush Toilets) may cause microbiological and chemical groundwater contamination. Floods involve the risk of spreading pathogens in the environment and may cause toilets to be inoperable. Composting Toilets (i.e. Double Vault non-Urine-Diverting Toilet) have been piloted in several island states to overcome these problems as they are built above ground and contain the excreta in watertight vaults. Urine-Diverting Dry Toilets (UDDTs; i.e. Double Vault Urine-Diverting Dry Toilet) are constructed similarly, with the difference of urine and faeces being treated separately. Both alternatives offer the possibility of reusing their output products (urine, faeces or excreta) as fertilizer.

This thesis assesses the applicability and emanating health risks of these three options under the given context. Each system was divided into its functional groups in order to identify exposure pathways and recommend measures to reduce the risk based on these entities. A focus was on the reuse-oriented systems’ reliability of treatment which determines the exposure during application of output products and consumption of products. A literature review was combined with field research in Vanuatu to approach the problem. The latter included meetings with NGOs and a governmental department, inspection of piloted Composting Toilets, identification of a pilot site to trial UDDTs, and introduction of UDDTs to chiefs and citizens to evaluate the disposition towards this system.

The prevalent system is not recommended in case it is planned to use groundwater for drinking in the future. Both alternatives are in principle suitable for the underlying conditions, whereas the treatment of UDDTs has shown to be more effective, reliable and simpler to manage as compared to Composting Toilets. The latter system is therefore not recommended. Reuse of urine and faeces imply great opportunities, but doing so includes also considerable health risks if personal protection, proper treatment and reuse practices are not adhered to.

Kurzfassung

Rurale Küstengebiete im Südpazifik weisen oft hohe Grundwasserspiegel auf und sind anfällig für Überschwemmungen. Gängige Sanitärsysteme (i.e. Single Pit System; ‘bush’, Dry, und Pour-Flush Toiletten) können zur mikrobiologischen und chemischen Belastung des Grundwassers führen. Überschwemmungen bergen außerdem das Risiko Krankheitserreger in der Umwelt zu verbreiten und können zur Unbenutzbarkeit der Toiletten führen. Komposttoiletten (i.e. Double Vault non-Urine-Diverting Toiletten) fassen die Fäkalien in überirdischen, wasserdichten Kammern und wurden daher als Alternative in mehreren Inselstaaten umgesetzt. Die Bauweise von Trockentrenntoiletten (UDDTs; i.e. Double Vault Urine-Diverting Dry Toilet) ist ähnlich, allerdings werden Urin und Kot getrennt behandelt. Bei beiden Alternativen können die behandelten Endprodukte (Urin, Kot oder Fäkalien) als Dünger wiederverwendet werden.

Die Masterarbeit untersucht die Eignung und die gesundheitlichen Risiken dieser drei Sanitärsysteme unter den vorherrschenden Bedingungen. Dazu wurden die Systeme in deren Funktionseinheiten unterteilt um Expositionspfade zu identifizieren und Maßnahmen zur Risikominierung vorzuschlagen. Ein Fokus liegt auf der Behandlung von Ausscheidungen der zwei Alternativsysteme, da dies das Risiko während der Düngeranwendung und letztendlich dem Konsum der Erzeugnisse bestimmt. Die Fragestellung wurde mittels Feldforschung in Vanuatu und einer Literaturrecherche bearbeitet. Die Feldforschung umfasste meetings mit NGOs und einer Behörde, die Inspektion von Komposttoiletten, und die Identifikation eines Pilotstandortes für UDDTs. Zudem wurden einigen chiefs und EinwohnerInnen UDDTs vorgestellt und ihre Einstellung dazu evaluiert.

Gängige Sanitärsysteme sind unter den vorherrschenden Bedingungen ungeeignet sofern Grundwasser in Zukunft als Trinkwasser verwendet werden soll. Beide Alternativsysteme sind grundsätzlich geeignet, allerdings ist die Behandlung der Exkremente bei UDDTs besser, zuverlässiger und einfacher im Vergleich zu Komposttoiletten. Letztere sind daher nicht zu empfehlen. Die Verwendung von Urin und Kot als Dünger hat großes Potenzial, beinhaltet aber auch Risiken sofern die Behandlung unzureichend ist oder persönliche Schutzmaßnahmen und Ausbringungspraktiken nicht eingehalten werden.

Abbreviations

ARGOSS	Assessing the Risk to Groundwater from On-Site Sanitation
CAWST	Centre for Affordable Water and Sanitation Technology
COD	Chemical Oxygen Demand
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DALY	Disability-Adjusted Life Year
DGMWR	Department of Geology, Mines and Water Resources
DM	Dry Matter
EcoSanRes	Ecological Sanitation Research
ENSO	El Niño-Southern Oscillation
EP_x	Exposure Pathway X (X = 1 – 9)
ESF	Ecosan Services Foundation
ET	Evapo-Transpiration
FAO	Food and Agriculture Organization of the United Nations
HDPE	High-Density Polyethylene
JMP	Joint Monitoring Programme for Water Supply and Sanitation by WHO and UNICEF
MDGs	Millenium Development Goals
MOH	Ministry of Health
MLMC	Mixed Latrine Microbial Composting Toilets
NGO	Non Governmental Organization
O&M	Operation and Maintenance
PE	Polyethylene
PPE	Personal Protection Equipment
PP	Polypropylene
PSIDS	Pacific Small Island Developing States
PVC	Polyvinyl Chloride
SIDS	Small Island Developing States
SOIL	Sustainable Organic Integrated Livelihoods
SOPAC	South Pacific Applied Geoscience Commission
TC	Tropical Cyclone
VIP	Ventilated Improved Pit
UDDT	Urine-Diverting Dry Toilet
UD	Urine Diversion
UD-VIP	Urine-Diverting Ventilated Improved Pit
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations International Children's Emergency Fund
uPVC	unplasticized PVC
USDA	United States Department of Agriculture
UV	Ultraviolet
VMGD	Vanuatu Meteorology and Geo-hazards Department
VMOH	Vanuatu Ministry of Health
VNSO	Vanuatu National Statistics Office
WHO	World Health Organization
WW	Wet Weight

1. INTRODUCTION

Soil layers of small coral islands, and sandy coastal areas of larger islands in the Pacific are usually thin and highly permeable. This makes the groundwater resources of islands belonging to the Small Island Developing States (SIDS; Box 1) prone to contamination by the prevalent pit-based sanitation. Small coral islands are especially of concern because their water table is usually (very) high (i.e. shallow) which increases the risk of groundwater pollution substantially. Especially the common practice in the Pacific to dig pits to the depth of the water table allows the direct contamination of the groundwater (Falkland, 2002; Dillon, 1997). Groundwater contamination from sanitation is generally of greater concern in urban and peri-urban areas due to higher population densities, but '[m]*any smaller villages however, also exhibit high bacterial levels in groundwater or have the potential for such pollution* [… which] *is a major constraint to improvements in water quality*' (Falkland, 2002, p. 17).
Islands of SIDS are further prone to natural disasters (floods, droughts, cyclones, earthquakes) and are affected by climate change (sea level rise, changing rainfall patterns/droughts, more severe tropical cyclones) (UN-DESA, 2017; Overmars & Gottlieb, 2009). '*The increased frequency in natural disasters such as floods and cyclones threatens existing infrastructure for sanitation, and further exacerbates the spread of diseases'* (PSIDS, 2009, p. 8f). Floods may cause toilets to overflow, spreading the contained pathogens in the environment as a result (Stenström et al., 2011). Besides, sanitation facilities are often useless when pits are filled up with sediments, or pits collapse due to weakened stability. Inaccessible toilets during and after floods may induce open defecation (Uddin et al., 2013). '*The lack of sanitation during times of natural disaster will likely hasten the spread of communicable diseases and vector-borne diseases*' (PSIDS, 2009, p. 9).

To overcome these shortcomings of pit-based sanitation systems, Composting Toilets have been piloted on many pacific island states since mid-1990s (Crennan & Booth, 2007; Crennan & Berry, 2002). These toilets contain the excreta in watertight vaults built above ground, making them suitable for areas prone to floods and groundwater contamination. Inactivation of pathogens is based on thermophilic composting (Berger, 2011). But the reliability of the treatment is subject to debates, because '[t]*hermophilic temperatures are seldom if ever attained eliminating this reliable mechanism of pathogen destruction'* (Hill & Baldwin, 2012, p. 1813).
Another option are Urine-Diverting Dry Toilets (UDDTs) which are based on watertight vaults built above ground as well. Urine and faeces are separated at the source by using a urine-diverting User Interface. This enables an isolated treatment of faeces (based on desiccation and high pH) and urine (storage in airtight tanks) (Rieck et al., 2012). Both Composting Toilets and UDDTs are reuse-oriented systems, designed to make use of the nutrients contained in excreta.

Subsistence farming plays a major role in the nutrition of people living in SIDS, but food security is threatened by climate change (UNFCCC, 2005). Reusing nutrients of excreta is a possible measure to increase the food security (Rieck et al., 2012). While Composting Toilets and Urine-Diverting Dry Toilets should reduce health risks associated with floods and groundwater contamination, risks may be even elevated if effective barriers (e.g. proper treatment, hand washing, using personal protection equipment) are not in place (Schönning & Stenström, 2004).

Small Island Developing States (SIDS) are a group of 37 member and 20 non-member states of the United Nations and are subdivided into three regions (Atlantic, Indian Ocean, Mediterranean and South China Sea; Caribbean; Pacific). They face similar problems as developing countries in general, but are further confronted with peculiar vulnerabilities and characteristics such as '*small size, remoteness, narrow resource and export base, and exposure to global environmental challenges and external economic shocks, including to a large range of impacts from climate change and potentially more frequent and intense natural disasters*' (UN-DESA, 2017, s.p.). The Pacific Region includes 13 UN members (Fiji, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga, Tuvalu, Vanuatu) and 7 non-members (American Samoa, Cook Islands, French Polynesia, Guam, Commonwealth of Northern Marianas, New Caledonia, Niue).

Box 1: Small Island Developing States (SIDS) (UN-DESA, 2017).

2. OBJECTIVE AND STRUCTURE OF THE THESIS

The overall OBJECTIVE of this thesis is to assess three different sanitation systems, viz

Single-Pit System
i.e. Dry Latrine, Ventilated Improved Pit Dry Latrine, Pour-Flush Latrine

Waterless System without Sludge Production
i.e. Double-Vault non-Urine-Diverting Toilet (Composting Toilet),

Waterless System with Urine Diversion
i.e. Double-Vault Urine-Diverting Dry Toilet,

regarding their applicability in rural coastal areas of islands that are prone to floods and have high groundwater tables, and to recommend measures to reduce the emanating health risks.
Toilets applied in these areas should prevent the precious groundwater resources from being contaminated in order to diversify the sources of drinking water (which are often limited to rainwater harvesting) and increase the resilience against natural climate phenomena, extreme weather events and climate change. It is further important to enable access to sanitation during floods to omit open defecation, and to contain the excreta in a way that pathogens do not spread in the environment.

To be more specific, the aim of this thesis is to

(i) identify exposure pathways along the sanitation systems under the given conditions,
(ii) review the current state of scientific knowledge about the reliability of pathogen inactivation of the respective system, and
(iii) recommend measures to reduce risks emanating
  - from the technical design and treatment;
  - during operation & maintenance, application/disposal of urine, faeces and excreta, and harvest of products;
  - from consuming products fertilized with urine, faeces or excreta.

The focus lies on rural areas, operation and maintenance of the three systems is considered on household level only. The thesis is based on Vanuatu as example for the underlying conditions.

The STRUCTURE of the thesis is as follows:

- Chapter 3 gives background information about Vanuatu to gain insight into the context.
- Chapter 4 describes the methods how the sanitation systems were classified into their functional groups in order to analyze the exposure pathways and give recommendations to mitigate the risk. Further the literature research including the most important sources and the on-site research is explained in detail.
- Chapter 5 covers the main part of the thesis and includes both results and discussion. First, general information about pathogens, their transmission and groundwater pollution is given. After that, the three systems are covered separately by processing each functional group one after another. For this purpose, the particular functional group is explained in detail first, and is followed by a short description of the respective situation in Vanuatu. Thereafter the analysis of the exposure pathways is undertaken and measures to mitigate the risks are recommended. Further each sanitation systems' reliability of treatment in regard of potential residual health threats is discussed in detail.
- In chapter 6 the results gained in the on-site research are laid out.
- Chapter 7 gives a conclusion of the thesis.

3. VANUATU – BACKGROUND INFORMATION AND CONTEXT

Vanuatu is an island state located in the South Pacific Ocean, Oceania. About 234.000 inhabitants (i.e. 'ni-Vanuatu' or 'ni-Van') populate 63 of the 83 main islands (census 2009). The official languages are English, French and Bislama (Pidgin English used in Vanuatu), but more than 105 local languages are spoken throughout the archipelago (VNSO, 2011a; SOPAC, 2007; VNSO, 2002). '*Vanuatu is an agriculture-based largely subsistence economy*' (SOPAC, 2007, p. vi). Subsistence farming plays an important role especially in rural areas where 39% of the population are subsistence workers (VNSO, 2011a).

3.1. Geography and geology

Vanuatu consists of 83 main islands (total land area 12.281km²) extending 1176km from north to south in a Y-shape (Figure 1). The islands are spread over an area of 612.000km² and are divided in six provinces (Torba, Sanma, Penama, Malampa, Shefa, and Tafea). Only 12 islands are significant regarding economy and population, the capital Port Vila is located on the most populous island Efate (Shefa Province), the second urban area named Luganville is on the biggest island, Espiritu Santo (Sanma Province). Suva (Fiji) is about 1071km east, Honiara (Solomon Islands) 1288km south-west and Cairns (Australia) 2394km west of Port Vila (VNSO, 2011a; VNSO, 2002).
Many islands are mountainous since they are the summits of mountain ranges rising from the ocean, with 35% of the total area lying 300m above sea level and 55% featuring slopes > 20°. The highest peak is called Mount Tabwemasana (Espiritu Santo) with 1879m, Ambae, Ambrym and Tanna have peaks over 1000m as well. About ¾ of the country is covered with natural vegetation, forests and secondary growth are mainly found on steeper terrain. Plains are characterized by coconut plantations and agriculture (VNSO, 2002).
The geographic situation of island states in the pacific, in particular the '[r]*emoteness, in conjunction with small size and internal dispersion, imposes additional costs of trade and transportation* […]. *The same factors also push up the cost and complexity of providing public services and fulfilling the basic functions of government*' (Esler, 2015, p. 2).

Vanuatu is part of the Pacific Ring of Fire and lies at the edge of the Pacific tectonic plate. The plate is forced up by and over the Indo-Australian plate which is the reason for frequent earthquakes and volcanic activity (VNSO, 2002).
Nine active volcanoes are still continuously creating new land. Two of these active volcanoes are submerged in the sea and 7 are found on various islands, with Mount Yasur (Tanna) being the most famous and accessible volcano, and Mount Garet (Gaua) being possibly the most dangerous one (SOPAC, 2007; VNSO, 2002).
Vanuatu is young from a geologically perspective, as the northern islands (Espiritu Santo, Malekula and Torres islands) emerged some 22 million years ago when a series of earth movements, i.e. geological activity of the New-Hebrides subduction zone, caused huge submerged mountains to be surfaced. The southern islands (Maewo and Pentecost) arose between 5 and 11 million years ago. The remaining islands have been formed less than 5 million years ago. Only a fraction of the present land was above sea level about two million years ago, a slow and continues uplift caused today's shape of the terrain and formed fringing coral reefs (VNSO, 2002). This uplift is still present, with '*some areas of Vanuatu such as west Efate are being uplifted at 2 cm per year whilst other areas are subsiding*' (SOPAC, 2007, p. 14).
Falkland (2002, p. 3) describes Vanuatu's island geology to be '*predominantly volcanic with coastal sands and limestone*'. According to Nunn et al. (2016), almost 60% of Vanuatu's islands are of volcanic origin, approximately 17% of limestone and of composite origin, respectively, the remaining islands are elevated coral reefs.

Figure 1: Map of Vanuatu with its six provinces Torba, Sanma, Penam, Malampa, Shefa, and Tafea (Gaba, 2013, adapted).

3.2. Population

The last census from 2009 determines a total population of 234.023 and a growth rate of 2.3% from 1999 – 2009 (Table 1). The two urban areas Port Vila (44.039 inhabitants) and Luganville (13.156 residents) account for 24.4% of the total population. The average household size is 4.8, more than 10% of the households have 10 members or more. The median age is 20.5 years, 39% of the population is younger than 15 years and only 6% are older than 60 years. Approximately 30% of people above the age of 15 have a regular income. About 39% of the rural population's main activity is subsistence work (i.e. growing and/or gathering produce, or fishing) which accounts for 60% of the main income in rural areas (VNSO, 2011a).

Table 1: Population size, growth rate, population density and doubling time from 1989, 1999 and 2009, '89 – '99, '99 – '09, respectively (VNSO, 2011a, p. 4, 7, adapted).

Region	**Total population size**			**Growth rate/a** [%]		**Population density** [people/km²]		**Doubling time** [a]	
	1989	**1999**	**2009**	**'89 – '99**	**'99 – '09**	**1999**	**2009**	**1999**	**2009**
Vanuatu	142.419	186.678	234.023	2.6	2.3	15	19	27	31
Urban	25.870	40.094	57.195	4.2	3.5	NA	NA	17	20
Rural	116.549	146.584	176.828	2.2	1.9	NA	NA	32	37
Torba	5.985	7.757	9.359	2.5	1.9	9	11	28	37
Sanma[a]	25.542	36.084	45.855	3.3	2.4	8	11	21	29
Penama	22.281	26.646	30.819	1.7	1.5	22	26	41	48
Malampa	28.174	32.705	36.727	1.4	1.2	12	13	49	60
Shefa[a]	38.023	54.439	78.723	3.4	3.7	36	52	20	19
Tafea	22.414	29.047	32.540	2.5	1.1	18	20	28	62

[a] Shefa and Sanma include the urban areas of Port Vila and Luganville

The focus of this thesis lies on rural areas, where more than ¾ of Vanuatu's population live (VNSO, 2011a). The rural population is '*generally found in coastal villages or near provincial centres*' (AusAID 2006a, p. 4).

About 75% of the total population and 66% of the rural population live within 1km distance from the coast. Figure 2 shows the distribution of rural village sizes (households per village) situated within 1km distance from the coast (red) and the corresponding inhabitants (orange) (note: adjacent suburbs of the two urban areas are excepted). More than 42% of the 1151 rural coastal villages consist of up to ten households, corresponding to ~15% of coastal inhabitants. Over 80% of rural coastal villages have 30 or less households, accounting for ~55% of the residents. The average rural household size is 4.91 people (VNSO, 2014, pers.comm., 28 October).

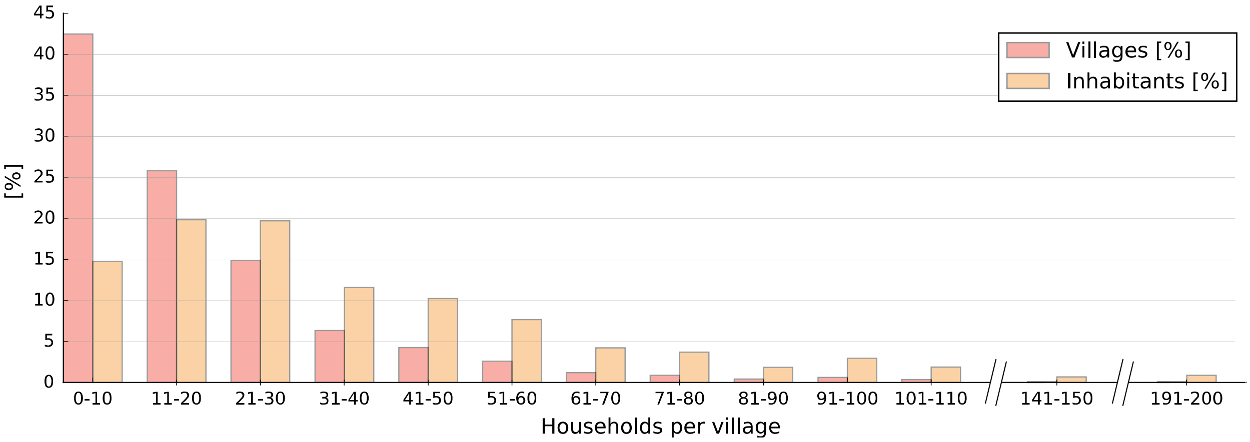


Figure 2: Distribution of rural village size (red) located within 1km from the coast in rural Vanuatu in 2009 and the corresponding share of inhabitants (orange) (Port Vila, Luganville and adjacent suburbs excluded in this chart) (based on VNSO 2014, pers.comm., 28 October).

3.3. Climate, natural disasters and global warming

Vanuatu's climate differs greatly within its north and south extent and is substantially influenced by the South Pacific Convergence Zone. The average temperatures range between 23.5 and 27.5°C, depending on the geographical location (Australian Bureau of Meteorology & CSIRO, 2011a). The north is tropical, humid and quite wet with an average annual rainfall of up to 4587mm in Sola, the south is less wet with the lowest rainfall of 1288mm/a in Whitegrass (VMGD, 2014, pers.comm., 3 February; Sullivan & Guglielmi, 2007). The decennial average rainfall per year (2004 – 2014) for six gauging stations spread over Vanuatu is shown in Figure 3. Rainfall patterns of bigger islands are influenced by mountains, resulting in higher precipitation on windward sides and lower rainfall on leeward side, especially in the dry season. Vanuatu's climate is further influenced by the El Niño-Southern Oscillation (ENSO). This phenomenon influences the climate of the whole world and appears in Vanuatu in form of El Niño (rainy season delayed and drier, dry season cooler), La Niña (rainy season earlier and more wet, dry season warmer) or a neutral phase. The wet and warmer season is from November to April, the dry and colder one from May to October (Australian Bureau of Meteorology & CSIRO, 2011a).

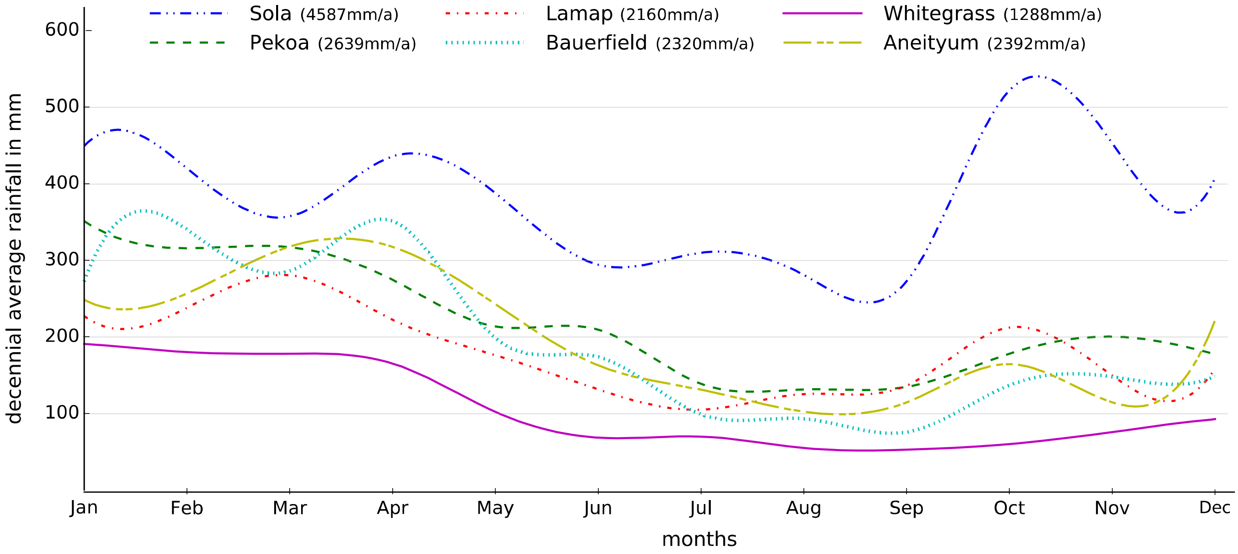


Figure 3: Decennial average monthly rainfall from six gauging stations spread over Vanuatu (2004 – 2014; for locations see Figure 1) (based on VMGD, 2014, pers.comm., 3. February 2015).

'*Vanuatu is situated on the Ring of Fire making it prone to numerous and severe earthquakes, and is in the center of the South Pacific's Cyclone Alley*' (SOPAC, 2007, p. ii). It is further vulnerable to natural disasters like floods, landslides, volcanic eruptions, tsunamis, droughts and storm surges (Bani, 2010). The World Risk Report ranked Vanuatu's risk to be harmed by an extreme natural event as number one by far for the sixth time in a row since it was first published in 2011 (Mucke et al., 2016).

Floods

Low-lying coastal regions and low-lying atolls are prone to floodings and in further consequence erosion, caused by storms, intense rainfall and/or sea level rise (SOPAC, 2007). Floods also occur inland on low-lying flood plains of rivers and are either caused by sustained rainfall during the wet season, intense rainfall in La Niña years, or cyclones (UNESCO, 2012).

Cyclones

Two to three cyclones pass Vanuatu per year during the wet season on average (most frequent in January and February), but there is a high interannual variability (Australian Bureau of Meteorology & CSIRO, 2011a). In March 2015, one of the strongest cyclones ever recorded in the region, Tropical Cyclone (TC) 'Pam' (category 5), hit Vanuatu with wind speeds of 250km/h and wind gusts up to 320km/h. The cyclone caused 11 fatalities, ~65.000 people were displaced from their homes and ~16.000 dwellings were damaged or destroyed. The livelihood of more than 80% of the rural population has been compromised due to extensive crop losses. Over 70% of the sanitation infrastructure has been destroyed in the four affected provinces, since the most common systems, pit toilets and VIPs, are mainly out of local bush materials (Esler, 2015).

Droughts

Parts of the country are subject to severe droughts periodically. Moderate droughts occur once to twice, and severe droughts approximately once within 20 years (Australian Bureau of Meteorology & CSIRO, 2011b; Bani, 2010). West Ambae, Ambrym, Epi and Torba are often affected by droughts during the dry season (SOPAC, 2007).

Global warming

The impacts of global warming are expected to be manifold, the most important in the context of this thesis are less frequent, but more intense cyclones, more extreme rainfall days, and rising sea levels. Furthermore, there will be more very hot days, change in rainfall patterns (decrease of dry seasons and increase of wet seasons rainfall) and increase of the oceans acidity (Australian Bureau of Meteorology & CSIRO, 2011a). Relative sea level records determine a sea level rise of +2.2mm/a, satellite based measurements estimate it at +6mm/a (Australian Bureau of Meteorology & CSIRO, 2011b; AusAID, 2006b). Table 2 shows identified climate-sensitive health risks that are likely to arise in Vanuatu in the future.

Table 2: Climate-sensitive health risks that may arise from climate change in Vanuatu (Spickett et al., 2013, p. 48).

Risk category	Health issue
Extreme	Water-borne diseases, Food-borne diseases
High	Vector-borne diseases, Malnutrition, Non-communicable diseases, Temperature-related illnesses, Occupation-related illnesses
Medium	Respiratory infections, Skin conditions, Eye diseases, Mental health disorders, Traumatic injuries and deaths

3.4. Water supply

'*Water supply does not meet demand in either urban or rural areas*' (SOPAC, 2007, p. iv). Vanuatu's larger islands are endowed with groundwater resources and mostly surface water, some smaller islands lack both potential sources of water (e.g. Mataso and Buninga from Shepherd islands, all islands from the Torres Group, small islands off Malekula and Santo). Information regarding groundwater or surface water quality is hardly available. Outdated data from the aquifers supplying the two urban centres attesting them good quality, but some isolated locations have had elevated levels of nitrogen and/or faecal coliform bacteria. Surface water quality is believed to be deteriorated in many places, but data is lacking (SOPAC, 2007).

The water supply of the two urban centres are fed by shallow groundwater aquifers via open wells and bores, costs are covered via fees and tariffs. A french operating, private company (UNELCO) is responsible for the water supply in Port Vila until 2032, Public Works provide service in Luganville, and in the provincial centres Isangel and Lakatoro (Government of Vanuatu, 2010; SOPAC, 2007). Increasing pressure on aquifers due to the high and continuous population growth in agglomeration areas cause decreasing water levels (Sullivan & Guglielmi, 2007).

Rural areas draw on different sources such as springs, wells, surface water and rainwater collection which is usually stored in ferro cement or polyethylene tanks. Rivers are fluctuating seasonally and are often contaminated from upstream pollutants (human and/or animal origin). The quality of the supplied water is often low, supply systems in rural areas are partly in poor condition or even not existent (AusAID, 2006a). A report by SOPAC (2007) highlights that a quarter of rural water supply systems need major repairing, another quarter minor repairs. '*Many water sources are unprotected and affected by pollution, and in some cases contaminated by volcanic ash and gas emissions, and increasingly, saline intrusion to groundwater*' (SOPAC, 2007, p. iii).

Table 3 shows the source of drinking water of rural and urban households compiled in 2013. 90.4% of households (rural: 87.5%, urban: 97.2) obtain water from improved sources. Piped water availability differs substantially between rural (30%) and urban areas (64%), but 85% of the households have water on their premises (urban: 97.4, rural: 79.8%). The proportion of 37.3% of rural households relying on rainwater is remarkable (VNSO, 2014).

The ratio of rural households which have to travel to the next water source improved from ~60% (2007), to 40% (2010) and finally 15% (2013) (VNSO, 2014; VNSO, 2012, VMOH, 2008).

An analysis by Cleary (2011, as cited in ISF-UTS, 2011) denotes past data up to 2008 to be '*unrepresentative* [… due to] *varying interpretations of 'improved' supply used by surveyors*' (ISF-UTS, 2011, p. 1). A review has shown a decrease of rural improved water supply coverage in the period 1999 – 2006 from 69 to 65%. UNELCO estimates urban water supply coverage at only ~80% (ISF-UTS, 2011; Government of Vanuatu, 2010; SOPAC, 2007).

Table 3: Source of drinking water of rural and urban households in Vanuatu (VNSO, 2014, p. 21, adapted).

Source of drinking water	**Households [%]**		
	Rural	**Urban**	**Total**
Improved source (subtotal)	(87.5)	(97.2)	(90.4)
Piped water into dwelling/yard	30.2	63.6	40.2
Public tap/standpipe	7.2	4.4	6.4
Tube well or borehole	1.9	0.2	1.4
Protected dug well	7.3	2.8	5.9
Protected spring	3.5	0.5	2.6
Rainwater	37.3	25.8	33.9
Non-improved source (subtotal)	(9.5)	(2.5)	(7.4)
Unprotected dug well	2.3	0.3	1.7
Unprotected spring	6.8	0.0	4.8
Tanker truck	0.3	0.3	0.3
Bottled water	0.1	1.9	0.6
Other	2.9	0.3	2.1
Total	100.0	100.0	100.0

3.5. Sanitation

There is no specific legislation nor any ministry or department in charge of sanitation in Vanuatu. The 'National Water Strategy for Vanuatu (NWS) 2008 – 2018' suggested to establish a 'Department of Water (DoW)' which would be responsible for sanitation, but the strategy has not been approved by the government so far. The 'Department of Geology, Mines & Water Resources' and the 'Ministry of Health' are both implementing scattered sanitation projects, but there is no overall coordination or a master plan due to the lack of leadership (ISF-UTS, 2011).

A sewer system is not present in Vanuatu (Government of Vanuatu, 2010). The hospital and three hotels in the capital Port Vila are equipped with a treatment facility, but they are not well maintained and the sewer network is limited (Castalia, 2005). A centralized system for Port Vila is planned, but a final decision which treatment will be used is pending (Kassis, 2010).

Rural areas '*have very poor sanitation facilities mostly comprising pit latrines or bush toilets*' (SOPAC, 2007, p. iii). Flush toilets are not widely used in rural areas '*because there is no piped water system to provide the water required for a flush toilet system*' (VNSO, 2013, p. 70).

'*In the small islands* [of Vanuatu,] *the water table is elevated and the underground water is very susceptible to contamination from latrines*' (Kingston, 2004, p. 2). Water supplies are often polluted due to wastewater runoff caused by heavy rainfall or floods, surface water contaminated by human and animal waste, and/or the lack of a proper source protection (Kingston, 2004). Especially higher population densities near urban areas cause inland ground- and surface waters to be contaminated and coastal water quality to be diminished (SOPAC, 2007).

'*Households without proper toilet facilities are more exposed to the risk of diseases such as dysentery, diarrhoea and typhoid fever than those with improved sanitation facilities*' (VNSO, 2014, p. 22). Diarrhea and worm infestation due to improper sanitation and water supply is of major concern in Vanuatu and a common reason for hospital admission (VMOH, 2012; VMOH, 2010). 'C*ommunicable diseases associated with poor sanitation continue to contribute significantly to disease burden*' (VMOH, 2012, p. 1). Areas with higher population densities and poor sanitation are of major concern since '*an outbreak of communicable water borne disease can quickly spread and affect a large number of people*' (UNESCO, 2012, p. 2).

A comprehensive database of water quality is lacking. Monitoring and surveillance is undertaken infrequent, records are bad and information gained is rarely made available for other policy makers. The groundwater quality in and around Port Vila was tested more than twenty years ago and detected slightly elevated nitrogen levels and raised levels of faecal coliform bacteria in peri-urban areas. Records of surface water quality testing are poor too, but monthly sampling data from Tagabe River (Port Vila watershed) is available (SOPAC, 2007). These measurements revealed '*high levels of bacteria from human waste, and high COD* [i.e. chemical oxygen demand] *and nitrogens from industry and human waste*' (SOPAC, 2007, p. 19).

Statistics about the sanitation coverage compiled in the past do not comply with the official classification by JMP, making the data not or only badly comparable on national level and to other countries. In the MDG Report from 2010, Vanuatu classified improved toilet facilities such as '*flush, water seal and Ventilated and Improved Pit (VIP) toilets, whether shared or not* [as improved, and …] *pit latrines, any 'other' form of toilet and not having a toilet* [as not improved]' (VNSO, 2011b, p. v). On the other hand, data sampled during the Multiple Cluster Survey 2007 is divided in pit latrines with and without a slab, but it is not discerned between shared and private facilities. Based on this data, 63.5% of household members used improved sanitation facilities (urban: 91.1%, rural: 55.1%) (VMOH, 2008).

An estimate by the JMP from 2012 comes up with similar figures, as it classifies 58% of Vanuatu's sanitation facilities as improved (urban: 65%, rural: 55%), 20% as improved but shared, 20% as unimproved, and the remaining 2% as open defecation (WHO & UNICEF, 2014a).

The latest data from the 'Demographic and Health Survey 2013' (data basis: 2200 households) uses the official JMP classification of improved facilities for the first time (Table 4). This data reveals a different picture, by determining the households with access to improved sanitation by 50.7% (urban: 45.8%, rural: 52.7%) (VNSO, 2014). Rural areas rely mainly on pit-based sanitation. Unimproved facilities are primarily determined by shared facilities and pit latrines without slab/open pit (i.e. called 'bush toilet' in Vanuatu). Water-based facilities are dominating urban areas (septic tanks) where shared facilities are common.

Table 4: Main toilet facility used by households in rural and urban areas in alignment with the classification of improved and non-improved facilities by JMP (VNSO, 2014, p. 22, adapted).

Type of toilet	**Households [%]**		
	Rural	**Urban**	**Total**
Improved, not shared facility (subtotal)	(52.7)	(45.8)	(50.7)
Flush/pour flush to piped sewer network	1.4	6.6	3.0
Flush/pour flush to septic tank	2.8	29.8	10.9
Flush/pour flush to pit latrine	2.9	2.0	2.6
Ventilated improved pit (VIP) latrine	13.8	2.9	10.5
Pit latrine with slab	31.8	4.5	23.7
Non-improved facilities (subtotal)	(46.4)	(53.5)	(48.5)
Any facility shared with other households	18.7	48.0	27.4
Flush/pour flush not to sewer/septic tank/pit latrine	0.0	0.3	0.1
Pit latrine without slab/open pit	25.2	4.0	18.9
No facility/bush/field	2.5	1.2	2.1
Other	0.4	0.0	0.3
Total[1]	100.0	100.0	100.0

[1] Total percent may not add up to 100 due to rounding off or exclusion of 'missing' cases.

Statistics about sanitation available from 'Vanuatu National Population and Housing Census 2009' are not aligned with JMP's definition too, but the data is of interest since its sample size is the total population and it gives a better understanding about shared facilities (Table 5).

Table 5: Main toilet facility used by households in rural and urban areas (VNSO, 2011b, p. 177, adapted).

Type of toilet		**Households [%]**		
		Rural	**Urban**	**Total**
Flush	Private	5.3	43.3	14.6
	Shared	1.3	22.3	6.4
Water Sealed	Private	6.1	3.4	5.4
	Shared	2.3	6.3	3.3
VIP	Private	17.2	5.7	14.4
	Shared	8.4	6.5	7.9
Pit Latrine	Private	46.4	7.8	36.9
	Shared	12.2	4.6	10.3
None		1.0	0.1	0.8
Total		100	100	100

The classification does not distinguish between pit latrines with (i.e. improved) and without proper slabs (i.e. unimproved), reducing its comparability that way. Nonetheless, 58.6% of rural households depend on pit latrines and 25.6% use VIPs. This sums up to 84.2% of rural households relying on pit-based latrines as opposed to 24.6% in urban areas. Water borne facilities are secondary in rural (15.0%) as compared to urban areas (75.3%) (VNSO, 2011b).

'[A]*ccess to improved sanitation systems depends more on the geographic location, less on the vulnerability status* [in terms of poverty]' (VNSO, 2013, p. 15). Figure 4 shows this geographic dependence and high variability of used systems. The majority of households in the provinces of Penama, Torba and Tafea use pit-based toilets (95.4%, 94.0% and 93.4%, respectively) (VNSO, 2011b). Over 60% of households in Malampa and Penama use 'bush toilets', i.e. lack a slab (VMOH, 2008).

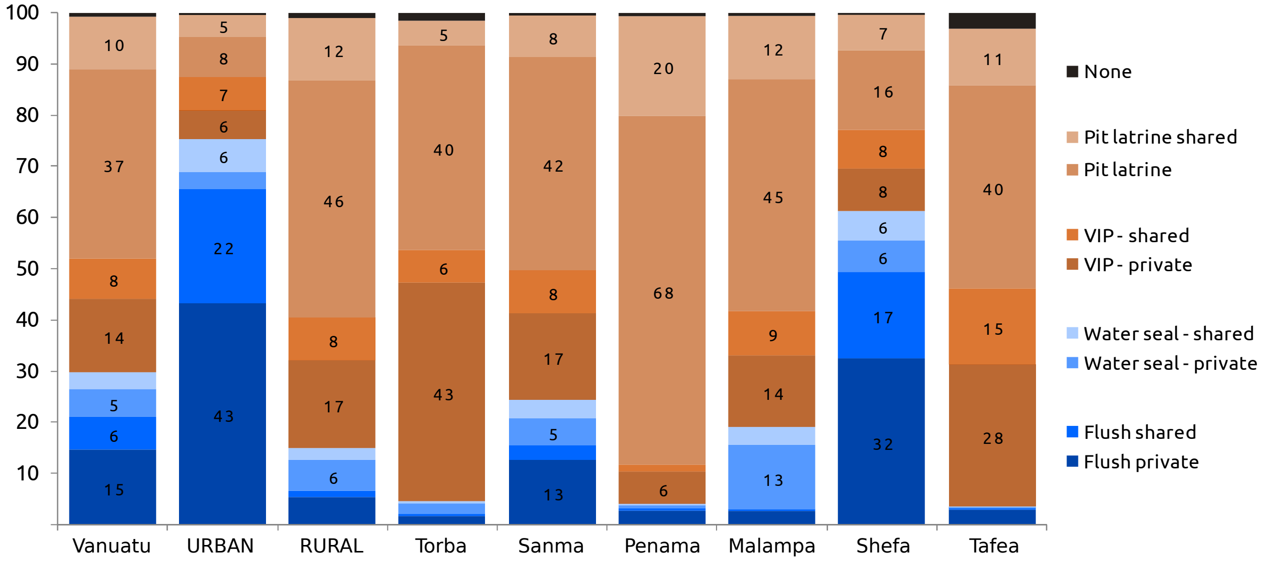


Figure 4: Main toilet type facility of Vanuatu's provinces, urban and rural areas (VNSO, 2011a, p. 140, adapted).

4. METHODS

The methods of this thesis comprise of how the sanitation systems were classified in order to identify the exposure pathways and recommend measures to reduce the associated risk. Further the literature research and the on-site research are described in detail.

4.1. Identification of exposure pathways and measures to mitigate the risk

For the analysis of exposure pathways and measures to reduce the emanating risk of the three sanitation systems, each system was split into its *functional groups* according to Tilley et al. (2014). Functional groups are technologies (i.e. infrastructure, methods or services) with similar functions, designed to contain, transform or transport products. These products may originate directly from humans (e.g. urine), are required for the operation (e.g. flushwater), or result from storage or treatment (e.g. dehydrated faeces). Each sanitation system can be described via input and/or output products that are processed by functional groups as apparent in Figure 5 (Tilley et al., 2014). The functional groups User Interface (U), Collection & Storage/Treatment (S), Conveyance (C), and Use and/or Disposal (D) were used. A fifth group used by Tilley et al. (2014), (Semi-) Centralized Treatment (T), was not applicable in the context of the thesis.

Figure 5: A sanitation system may be described by its input/output products that travel through the functional groups which either contain, transform or transport these products (Tilley et al., 2014, p. 18, adapted).

Potential exposure pathways for all functional groups of the three systems were identified based on a literature research. A set of 9 different exposure pathways (EP_X) have been used as classification according to Stenström et al. (2011, p. 11, adapted):

EP_1 Ingestion of excreta
Transfer of excreta (urine and/or faeces) through direct contact to the mouth from the hands or items in contact with the mouth.

EP_2 Dermal contact
Infection where a pathogen is entering through the skin (through the feet or other exposed body parts; e.g. hookworms).

EP_3 Contact with flies/mosquitoes
Refers to the mechanic transfer of excreta from a fly to a person or food items. Further includes bites from a mosquito or other biting insects that could be carrying a disease.

EP_4 Inhalation of aerosols and particles
Inhalation of micro-droplets of water and particles which may not be noticeable, but may carry a pathogenic dose, and emanate or results from a sanitation technology.

EP_5 Contaminated groundwater/surface water
Refers to the ingestion of water, drawn from a ground or surface source, that is contaminated from a sanitation technology.

EP_6 Contact with overflowing/leaking contents
Refers to subsequent contact as a result of malfunction of a sanitation technology (e.g. pit or tank overflowing due to flooding, groundwater intrusion or general malfunction).

EP_7 Falling into pit
People may fall into pits due to cracked, broken or toppled slabs. Abandoned pits that are improperly covered or backfilled may cause people falling into/sinking in pits.

EP_8 Ingestion of urine
Refers to the specific case of ingestion of urine from handling practices of specific technologies.

EP$_9$ Consumption of contaminated produce

Refers to consumption of plants that have been grown on land irrigated or fertilized with a sanitation product or where accidental contamination is likely to occur.

After the description of the respective exposure pathway, measures to mitigate the emanating risk are recommended. These measures were identified via a literature research as well.

4.2. Literature research

A vast number of papers, documents, research and information about sanitation in developing countries are provided by journals, governments and non-governmental organizations and are available on the internet. These resources were the main source of information for this thesis, they were obtained via searching the respective keywords in search engines (e.g. google.com, scholar.google.com, BOKU:LITsearch, ncbi.nlm.nih.gov), using libraries and forums of dedicated portals about sanitation in developing countries (e.g. sswm.info, susana.org), and searching the reference lists of documents.

Key sources for country specific information about Vanuatu were obtained from the Vanuatu National Statistics Office (VNSO), the South Pacific Applied Geoscience Commission (SOPAC) was an important source for information about Vanuatu and the South Pacific region.

Volume 4 of the ‘WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater’ (2006) was an essential source in the main chapter about exposure pathways and measures to reduce the risks, as it comprises official recommendations about reuse of urine, faeces and excreta. Stenström et al. (2011) was further a key document for the analysis of exposure pathways, Tilley et al. (2014) was used for the classification of the systems and for general information. Furthermore Berger (2011) was an important source for the analysis of Composting Toilets, Münch & Winker (2011) as well as Rieck et al. (2012) were key sources for Urine-Diverting Dry Toilets.

4.3. Field research

The field research in Vanuatu (Nov, Dec. 2015) comprised of and was based on:

- Meetings and interviews with NGOs and the governmental department in charge of sanitation. Interviews were based on semi-structured interview guidelines and took between one and three hours to cover all the essential aspects.
- Inspection and assessment of five pilot sites where Composting Toilets have been implemented. The assessment included a visual inspection of the facilities (e.g. structural condition, design weaknesses, use of cover material, excessive moisture) and interviews with the users or people in charge of operation and maintenance.
- Identification and inspection of a potential pilot site featuring the underlying conditions (i.e. rural area, high groundwater table, proneness for floods). Interviews with village chiefs were conducted to understand problems emerging with the current sanitation systems.
- Introduction of Urine-Diverting Dry Toilets to the chiefs of four communities and a group of inhabitants. Since this type of toilet has not been piloted in Vanuatu so far, this undertaking helped to evaluate the disposition of people towards this technology.

5. ANALYSIS OF EXPOSURE PATHWAYS AND MEASURES TO MITIGATE THE RISK

The aim of this analysis is to identify exposure pathways along three different systems under the given context and to recommend measures to mitigate the emanating risk. The three analyzed systems comprise of the most common used sanitation system in rural Vanuatu (Single-Pit System including ‘bush’, Dry, Ventilated Improved and Pour-Flush Toilets), a system proposed by NGOs to be applicable under the given conditions (Double Vault non-Urine-Diverting Toilet, or Composting Toilet) as well as Double Vault Urine-Diverting Dry Toilets which have not been piloted in the country so far. A special focus lies on potential health risks emanating from impacts of high groundwater tables and floods to these systems and vice versa. Another focal point lies on recommendations for the safe reuse of nutrients from urine and faeces. The application and operation of the systems is considered in rural areas on household level only.

The following analysis does not strictly follow but covers many essential aspects of the Sanitation Safety Planning (SSP) manual published in 2015. The SSP was developed to assist stakeholders in a step-by-step procedure to implement the WHO *Guidelines for the safe use of wastewater, excreta and greywater* (WHO, 2015). These underlying guidelines were first formulated in the early seventies and have had a substantial influence on technical standards and policy setting since that time. The current, third edition from 2006 emphasizes the potential of excreta and wastewater effluents to improve nutrition for poor households and increase food security. Increasing pressure on water resources, lack of nutrients as well as health and environmental concerns led to an increase of interest in this issue. Nonetheless, reclaimed water reuse and nutrient recycling entails risks and threats which have to be considered thoroughly. The objective of the framework is to prevent the transmission of disease, maximizing the health and environmental benefits that way (WHO, 2006a).

The overall objective of sanitation is to protect public health, which is traditionally covered by the health sector. SSP aims to include a human health perspective in non-health sectors such as agriculture or engineering. It enables actors from different disciplines working together on the identification of health risks along sanitation systems to come up with improvements and monitoring strategies (WHO, 2015).

5.1. Pathogens in excreta and their transmission

Excreta-related diseases or carriership (asymptomatic infection) are common in developing countries. Faeces of infected individuals contains pathogens proportionally to the severity and type of infection. Environmentally transmitted pathogens usually cause gastro-intestinal symptoms (e.g. diarrhea, vomiting, stomach cramps), but some affect other organs and may include severe health implications (Stenström et al., 2011).

Burden of disease

‘[B]*urden of disease can be thought of as a measurement of the gap between current health status and an ideal situation where everyone lives into old age, free of disease and disability*’ (WHO, 2009, p. 5). Unsafe water, sanitation and hygiene was the second leading risk factor in causing burden of disease in low-income countries, with 53 million Disability-adjusted life years (DALYs) lost in 2004. DALYs are a currency to measure disability and deaths at different ages, with one DALY representing a loss of one ‘healthy’ year (WHO, 2009).

In low-income countries, diarrheal diseases are ranked as third leading cause of death. Especially children under five years are affected, with diarrhea being the second leading cause of death and the leading cause of malnutrition. In total, approximately 1.7 billion cases of diarrheal disease occur worldwide per year (WHO, 2014; WHO, 2013).

Pathogen related factors

Four groups of pathogens can be distinguished concerning sanitation: bacteria, viruses, protozoa and helminths (WHO, 2006b). These pathogens may differ in and can be described with the following pathogen-related factors (Mara, 2003):

• Excreted load	Amount of excreted pathogens. The actual load depends on the type of pathogen and the state of infection.
• Persistence	Ability of a pathogen to survive outside of the human body in the environment. Pathogens with a long persistence are of major concern.
• Infectivity	Probability of an infection emanating from a pathogen. Despite its importance, an essential knowledge gap regarding infectivity of pathogens exists.
• Multiplication	Pathogens need appropriate conditions to multiply which are often only present in their hosts. Some are able to multiply outside of hosts under favorable environmental conditions. In this case, small amounts of excreted pathogens may state a substantial risk. Viruses and protozoa are not able to multiply outside of a host, a high infectivity is therefore necessary for a successful transmission.
• Latency	Some pathogens need a certain period of time to become infectious (few days to weeks). This factor is important when it comes to helminths. Bacteria, viruses and protozoa (except Cyclospora) do not have a latency.

Bacteria

Bacteria are the only type of pathogen that are able to multiply (i.e. grow) outside of hosts, as long as environmental conditions are favorable (Westrell, 2004). These single-celled microorganisms (0.2 – 10µm) are therefore ubiquitous in the environment. Large colonies of commensal bacteria are formed in the intestines which are beneficial for human beings. Pathogenic bacteria however are harmful for persons. Enteric (i.e. live or potentially able to live in intestines) pathogenic bacteria include the highest risks and are therefore of major concern (WHO, 2003). The persistence of bacteria is generally shorter as compared to other pathogens and their infectious dose is rather high, but may be low in some cases (Westrell, 2004).

Viruses

Viruses are only contained in excreta of infected persons because they multiply exclusively inside of infected host cells. Over 140 different pathogenic enteric viruses are excreted with faeces of human beings. With a size between 0.01 to 0.3µm, viruses are the smallest among all pathogens. The excreted load in faeces of infected persons is generally high and the minimal infectious dose is low (WHO, 2003). The structure of viruses (DNA or RNA surrounded by a layer of protein, or in some cases a lipid membrane) makes them more persistent in the environment as compared to bacteria with their cell walls and membranes (Westrell, 2004). Analytical techniques for identification of viruses are complex and costly, thus knowledge about actual compositions, types and contents is poor, especially in developing countries (Jimenez et al., 2010).

Protozoa

These single-celled parasitic organisms are between 2 and 60µm in size and have a complex life cycle. Infection occurs via ingestion of mature cysts which withstand gastric juices. They break down in the small intestine to be transformed into trophozoites, which are embedded in the wall of the intestine where they feed on bacteria and dead cells. The trophozoites can develop into cysts again to be excreted with faeces. Protozoa rely on hosts for reproduction and their persistence is high with survival rates of several months up to years if environmental conditions are favorable (WHO, 2003).

Helminths

Parasitic helminths (i.e. worms) are multicellular organisms that occur in sizes of 1mm to several meters in length. The infective agents are their ova (i.e. eggs), not the worms itself. Their life cycle is complex and manifestation differs widely. Generally spoken, helminths cause intestinal wall damage, haemorrhages, deficient blood coagulation and undernourishment, and may lead to cancer tumors. Especially children, elderly and poor people are prone to helminth infections. Infected children are often retarded in growth and have a decreased physical fitness (Jimenez-Cisneros & Maya-Rendon, 2007). Only three species may be infective immediately after excretion, all other helminths have latencies or rely on one or more intermediate hosts. The infective dose is (very) low, with infections may be caused by a single ovum or larva, ova are very resistant to environmental conditions (i.e. high persistence) (Feachem et al., 1983).

Table 6 shows epidemiological data for selected pathogens to highlight differences between bacteria, viruses, protozoa and helminths regarding morbidity, amount and duration of excretion and infectivity (ID_{50}, i.e. infectious dose required to infect 50% of exposed individuals).

Table 6: Example of different epidemiological data for selected pathogens (Westrell, 2004, p. 19, adapted).

Pathogen	**Morbidity** [%]	**Excretion** [per g faeces]	**Duration of excretion** [days]	**ID_{50}**
Bacteria				
Salmonella	6-80	10^{4-8}	26 - 51	23600
Campylobacter	25	10^{6-9}	1 - 77	900
EHEC	76-89	10^{2-3}	5 - 12	1120
Viruses				
Hepatitis A virus	70	10^{4-6}	13 - 30	30
Rotavirus	50	10^{7-11}	1 - 39	6
Norovirus	70	10^{5-9}	5 - 22	10
Adenovirus	54	10^{11}	1 - 14	1.7
Protozoa				
Cryptosporidium	39	10^{7-8}	2 - 30	165
Giardia	20-40	10^{5-8}	28 - 284	35
Helminths				
Ascaris	15	10^{4}	107 - 557	0.7

'[P]*athogens with long persistence in the environment and low minimal infective doses that elicit little or no human immunity and having long latency periods* [...] *have a higher probability of causing infections than others. According to this, helminth infections, where endemic, pose the greatest risks* [when excreta is reused]*'* (Drechsel et al., 2010, p. 33).

Transmission

The transmission of pathogens is described by the following terms (USDA & USEPA, 2012):

Route of exposure (route of intake)	point where pathogens come into contact with the human organism. Three common routes can be distinguished: ingestion, inhalation and direct contact (skin, eyes, ears and sexual).
Exposure pathway (route of transmission)	physical movement of pathogens from their source to the occurrence of exposure. Mode of transmission may be wind, flowing water, equipment movement, or vector organism, and transmission may occur via aerosolization, water, food, soil, faecal-oral, and/or inanimate sources.

Exposure pathways can be further divided into primary and secondary pathways. *Primary transmission* takes place when pathogens are spread via direct contact with faeces or contaminated surfaces, directly from person-to-person (related to hygiene), or by short distance airborne transmission. *Secondary transmission* occurs either vehicle-borne (e.g. food, water) or vector-borne (mainly by providing breeding sites) (WHO, 2015; Stenström et al., 2011).

The *faecal-oral pathway* is considered as main route of disease transmission concerning sanitation. This exposure pathway describes the route pathogens travel from the source (i.e. faeces of an infected person) until it reaches a new host through its mouth. Figure 6 shows a widely used representation of this pathway in an 'F-diagram'. Sanitation including good hygiene (e.g. hand washing after bowel movement, clean facility) act as the *primary barrier* to prevent the spread of pathogens in the environment. Pathogens that still find their way into the environment (due to an ineffective or absent primary barrier) may reach a new host either directly (gray paths), or indirectly (red paths). Improved water supplies and good hygiene behavior (e.g. cleaning hands, utensils, and surfaces before food is prepared; cooking food thoroughly) act then as *secondary barriers* (Curtis et al., 2000). Urine is another potential pathway for infections (urine-oral route) (Höglund, 2001). The health risk is lower compared to faeces, but this route is important in regard of urine-diverting systems and when urine is used as fertilizer (WHO, 2006b).

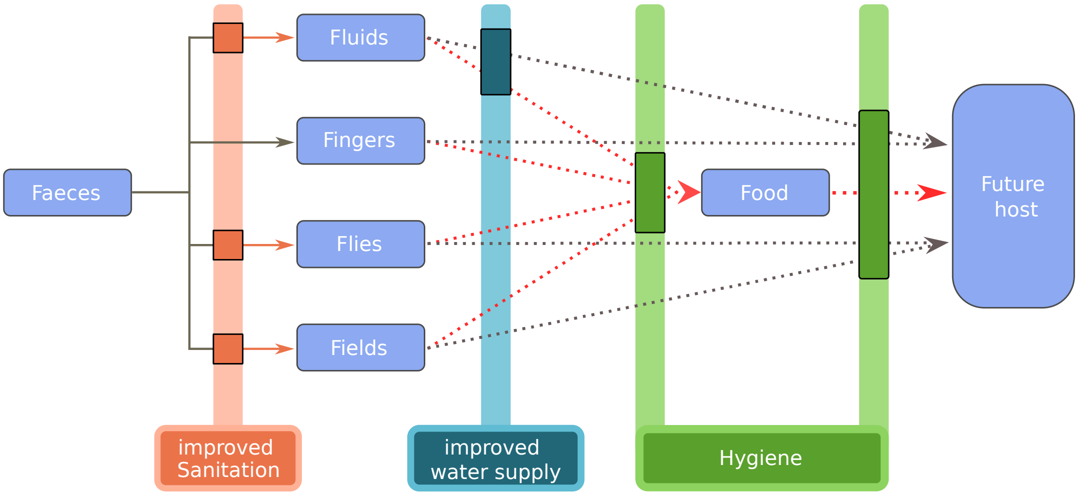


Figure 6: Representation of the faecal-oral pathway in a F-Diagram including primary (orange) and secondary (blue and green) barriers (Wagner & Lanoix, 1958, p.12, adapted).

Pathogen-host relationship

A precondition for a potentially successful infection is an actual infective dose reaching a new host, meaning that (WHO, 1989)

- (i) an excreted load of pathogens already contains an infective dose; or
  an excreted non-infective dose multiplies to form an infective dose; or
  a latent pathogen becomes infective after a certain period of time;
- (ii) the infective dose is persistent until it reaches a new human host,
- (iii) the host becomes infected, and
- (iv) the infection causes disease and/or further transmission.

An actual risk for public health does only occur if level (iv) is reached, the steps (i), (ii) and (iii) include merely a potential risk. As a consequence, interrupting at any point before arriving at step (iv) stops the sequence and prevents the formation of an actual risk (WHO, 1989).
Pathogen related factors determine therefore if an infective dose does or does not reach a potential host under the given environmental conditions. If this infective dose causes a successful infection depends further on *host characteristics and behavior*, such as immunity (natural, or due to infection, vaccination or mother's milk), nutritional status, health status, age, sex, personal hygiene and food hygiene. The pathogen-host relationship determines if either (Carr, 2001)

- (i) no transmission,
- (ii) transmission and symptomless infection, or
- (iii) transmission and infection with manifest sickness

occurs in the end.

Faeces

'*From a risk perspective, exposure to untreated faeces is always considered unsafe, due to the potential presence of high levels of pathogens, depending on the prevalence in a given population*' (WHO, 2006b, p. 31). Table 7 shows examples of pathogens that may be excreted with faeces including induced diseases and their symptoms.

BACTERIA. Enteric bacterial infections are of major concern. Typhoid fever (*Salmonella typhi*) and cholera (*Vibrio cholerae*) are common in areas with poor sanitation and/or water supply, shigellosis (*Shigella*) is common in developing countries with low hygienic and sanitary standards. Further, *Campylobacter* and enterohaemorrhagic *E. coli* (EHEC) are important disease causing bacteria. The latter two are together with *Salmonella* especially important for reuse of faeces (WHO, 2006b).

VIRUSES. The most common viruses excreted with faeces are members of enterovirus, rotavirus, enteric adenovirus and norovirus groups. Further Hepatitis A and E are important food- and waterborne diseases when faeces is reused as fertilizer or in case of low sanitary standards (WHO, 2006b).

PROTOZOA. *Cryptosporidium parvum* is important concerning waterborne outbreaks, *Giardia intestinalis* has high prevalences as an enteric pathogen. Further *Entamoeba hystolytica* is of importance in developing countries, the global role of *Cyclospora* and *Isopora* are under debate (WHO, 2006b).

HELMINTHS. The most important species of soil-transmitted helminths excreted with faeces are roundworm (*Ascaris lumbricoides*), whipworm (*Trichuris trichiura*) and hookworm (*Necator americanus*, *Ancylostoma duodenale*) (WHO, 2016a). Ova of blood flukes (*Schistosoma mansoni*, *S. japonicum*, *S. mekongi*, *S. guineensis*, and related *S. intercalatum*) causing schistosomiasis may be excreted with faeces, with geographical different distribution of the species (WHO, 2016b).

Urine

Health risks emanating from urine are comparatively low. From a reuse-oriented point of view, cross-contamination with faecal matter poses a high risk and is of major concern (Stenström et al., 2011). Urine in the bladder of a healthy person is sterile, but bacteria cumulate in the urinary tract. Freshly excreted urine contains less than 10.000 bacteria per ml. The amount of bacteria is significantly higher in case of an urinary tract infection, but these are usually not transmitted to other individuals via the environment. Sexually transmittable pathogens may be excreted with urine, but there is no indication of being a public health concern (WHO, 2006b).

The most common infections causing significant amounts of pathogens in human urine are urinary schistosmiasis (*Schistosoma haematobium*) and typhoid (*Salmonella typhi* and *Salmonella paratyphi*) (WHO, 2006b; Schönning & Stenström, 2004; Feachem et al., 1983).

Salmonella typhi and *S. paratyphi* are excreted with urine during typhoid and paratyphoid fevers. Urine-oral transmission is uncommon compared to faecal-oral transmission (WHO, 2006b). With a focus on reusing urine, *Schistosoma haematobium* is of highest concern in endemic regions from a risk point of view (Muench & Winker, 2011).

S. haematobium is a blood-dwelling fluke worm nourishing from blood particles, it relies on human beings and freshwater snails as hosts. It enters the body via penetrating the skin, then it migrates to the liver with the help of the bloodstream. After maturing into adult worms and pairing, females release eggs 4 – 7 weeks later and do not cease producing eggs until they die 3 – 5 years later (ages up to 30 years have been documented). Each female produces some hundreds of eggs per day, about half of them are penetrating through the bladder wall and exit the human body via urine excretion. The rest of the eggs are entrained with the bloodstream, causing the disease *schistosmiasis.* Eggs leaving their hosts via the bladder hatch as soon as they get in contact with fresh-water. The larvae survives up to 48 hours and locates the snail-hosts by using snail-derived chemicals and light. Asexual multiplication takes place in the snail, leading to thousands of larvae released per day. These remain viable for up to 72 hours and locate the human host with the help of skin-derived chemicals and water turbulence (IARC, 2012).

Table 7: Examples of pathogens that may be excreted with faeces including induced diseases and their symptoms (WHO, 2006b, p. 33).

Pathogen	Disease and symptoms
Bacteria	
Aeromonas spp.	Enteritis
Campylobacter jejuni/coli	Campylobacteriosis – diarrhea, cramps, abdominal pains, fever, nausea, arthritis; Guillain-Barré syndrome
Escherichia coli (EIEC, EPEC, ETEC, EHEC)	Enteritis
Plesiomonas shigelloides	Enteritis
Salmonella typhi/paratyphi	Typhoid/paratyphoid Fever – headache, fever, malaise, anorexia, bradycardia, splenomegaly, cough
Salmonella spp.	Salmonellosis – diarrhea, fever, abdominal cramps
Shigella spp.	Shigellosis – dysentery (bloody diarrhea), vomiting, cramps, fever; Reiter's syndrome
Vibrio cholerae	Cholera – watery diarrhea, lethal if severe and untreated
Yersinia spp.	Yersiniosis – fever, abdominal pain, diarrhea, joint pains, rash
Viruses	
Enteric adenovirus 40 and 41	Enteritis
Astrovirus	Enteritis
Calicivirus (incl. norovirus)	Enteritis
Coxsackievirus	Various: respiratory illness; enteritis; viral meningitis
Echovirus	Aseptic meningitis; encephalitis; often asymptomatic
Enterovirus types 68-71	Meningitis; encephalitis; paralysis
Hepatitis A virus	Hepatitis – fever, malaise, anorexia, nausea, abdominal discomfort, jaundice
Hepatitis E	Hepatitis
Poliovirus	Poliomyelitis – often asymptomatic, fever, nausea, vomiting, headache, paralysis
Rotavirus	Enteritis
Parasitic protozoa	
Cryptosporidium parvum	Cryptosporidiosis – watery diarrhea, abdominal cramps and pain
Cyclospora cayetanensis	Often asymptomatic; diarrhea, abdominal pain
Entamoeba histolytica	Amoebiasis – often asymptomatic; dysentery, abdominal discomfort, fever, chills
Giardia intestinalis	Giardiasis – diarrhea, abdominal cramps, malaise, weight loss
Helminths	
Ascaris lumbricoides (roundworm)	Ascariasis – generally no or few symptoms; wheezing, coughing, fever, enteritis, pulmonary eosinophilia
Taenia solium/saginata (tapeworm)	Taeniasis
Trichuris trichiura (whipworm)	Trichuriasis – unapparent through vague digestive tract distress to emaciation with dry skin and diarrhea
Ancylostoma duodenale/Necator americanus (hookworm)	Itch, rash, cough, anaemia, protein deficiency
Schistosoma spp. (blood fluke)	Schistosomiasis, bilharzia

Source: adapted from Ottoson (2003)

Table 8 lists urogenital pathogens that are of major concern. The risk concerning disease transmission of the listed pathogens contained in urine is generally considered to be insignificant. Other pathogens (e.g. coliform and other bacteria) may be detected in numerous amounts during urinary infections but do not constitute a public health risk (Feachem et al., 1983). Besides, micro-pollutants like natural hormones, pharmaceutical residues, heavy metals and persistent organic pollutants may be excreted with urine (Münch & Winker, 2011).

Table 8: Pathogens in urine and their importance (Schönning & Stenström, 2004, p. 4, adapted).

Pathogen	**Urine as a transmission route**	**Importance**
Salmonella typhi and *Salmonella paratyphi*	Probably unusual, excreted in urine in systemic infection	Low compared to other transmission routes
Schistosoma haematobium (eggs excreted)	Not directly but indirectly, larvae infect humans via freshwater	Need to be considered in endemic areas where freshwater is present
Mycobacteria	Unusual, usually airborne	Low
Viruses: CMV, JCV, BKV, adeno, hepatitis and others	Not normally recognized other than single cases of hepatitis A and suggested for hepatitis B. More information needed	Probably low
Microsporidia	Suggested, but not recognized	Low
Venereal disease causing	No, do not survive for significant periods outside the body	–
Urinary tract infections	No, no direct environmental transmission	Low

Groundwater contamination from on-site sanitation

On-site sanitation may cause microbiological and chemical contamination of the groundwater. The most important *chemical contaminants* are nitrate (NO_3) and chloride (Cl). Elevated chloride levels are less of a health concern, but it may lower the groundwater's' acceptance to be used for drinking. Nitrate by contrast is dangerous for infants as it may cause methemoglobinemia ('Blue Baby Syndrome'). Drinking water should not exceed nitrate levels of 50mg/L according to WHO. Nitrate does not degrade in shallow aquifers because it is very stable under aerobic conditions. Dilution is therefore the only mechanism to lower the concentrations. *Microbiological contamination* of groundwater is caused by bacteria, viruses and protozoa, helminths are usually not of concern since they are mechanically filtered due to their size. Attenuation of microbiological contaminants in the ground occurs due to natural die-off, predation, dilution/dispersion, filtration, and adsorption. Biological degradation, filtration and adsorption are the most important processes to attenuate microbiological pathogens in the unsaturated zone. The upper layers are more effective in removing, retarding and transforming microbes since the biological activity decreases with increasing depth. As soon as the groundwater (i.e. saturated zone) is reached, biological processes are almost negligible. Attenuation of pathogens occurs then at a much lower rate and is mainly based on natural die-off, dilution and dispersion. The goal is that the water's travel time between the source of contamination (i.e. sanitation) and the point of extraction (i.e. water supply) is sufficient to reduce pathogen contents to acceptable levels (ARGOSS, 2001). '*The soil is the main zone in which surface pollutants are attenuated. However, pit latrines place the pollutant below this zone and so the unsaturated zone represents the first line of natural defence*' (ARGOSS, 2002, p. 10). A biologically active layer may develop around the filled sections of pits over time. Predatory antagonistic organisms settle and grow in this layer causing pathogens to be inactivated. It takes usually several weeks until the layer is fully developed, the actual duration depends on the hydraulic load, soil type and pathogen volumes. The growth of micro-organisms, accumulation of solids from the effluent, and slimes produced by certain bacteria reduce the effective pore openings in this zone. This zone acts then like a filter that hold back pathogens. Filtration occurs if the average size of the particles or organisms is 5% greater than the average pore size. Bacteria and protozoa are therefore more prone to filtration as compared to viruses (Figure 7). Filtration plays merely a minor role in retaining pathogens outside this layer, an exception are fine-grained sediments in the saturated zone (ARGOSS, 2002).

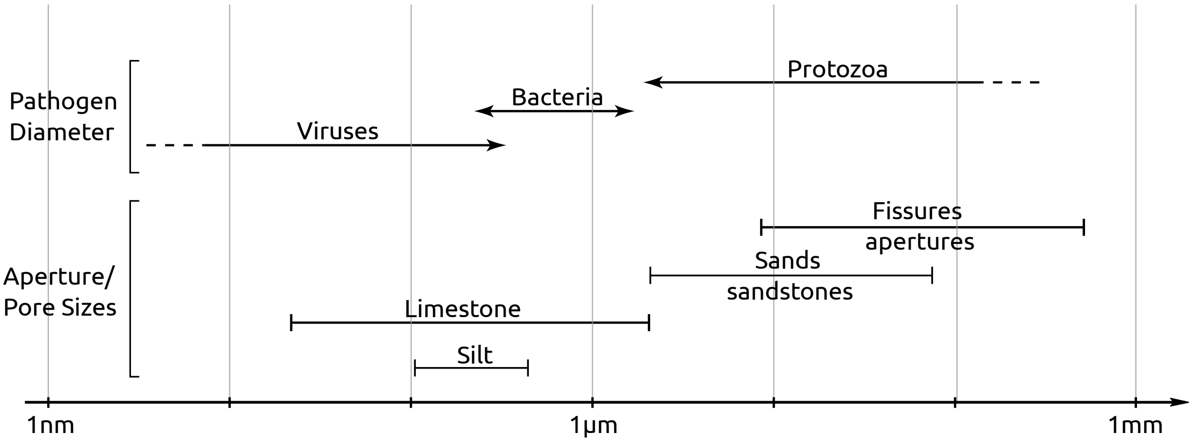


Figure 7: Pathogen diameters compared with grain sizes of different sediments (ARGOSS, 2002, p. 14, adapted).

‘*However, the benefits of a biologically-active layer may be limited in time as the layer becomes more developed, pores may become clogged and greatly reduce effluent infiltration lower in the pit, encouraging greater infiltration at higher layers*’ (ARGOSS, 2001, p. 34). A sufficient retention time in the unsaturated zone is therefore crucial to limit the risk of groundwater pollution. When water (i.e. effluent) percolates to the saturated zone, it travels through pore spaces between solid particles which are either filled with water or air. The water is held in the pores because it is under tension from molecular forces (i.e. adhesion, cohesion) which get greater the smaller the pores are. The maximum moisture content retained in the unsaturated zone decreases with increasing soil moisture tension, which in turn, depends on the pore size distribution of the sediments (Figure 8, (a)) (ARGOSS, 2002). ‘*Coarser sediments with large pores (e.g. sands, sandstones) drain rapidly at low tensions whilst finer-grained sediments, clays and silts, drain relatively few pores as their water is strongly retained in the smaller pores*’ (ARGOSS, 2002, p. 12). The flow rate in the unsaturated zone is usually below 0.2 m/d, but may be much higher in fractured formations and when hydraulic loadings are high. The hydraulic conductivity of fine-grained sediments is low and hardly influenced by the moisture content, whereas the hydraulic conductivity of coarse sediments (and especially fissures) may be several orders of magnitude higher, as the moisture content converges saturated conditions (Figure 8, (b)). Rock type, consolidation and presence of fractures are therefore key factors for the flow rate in the unsaturated zone, considerably determining the aquifer pollution vulnerability (ARGOSS, 2002).

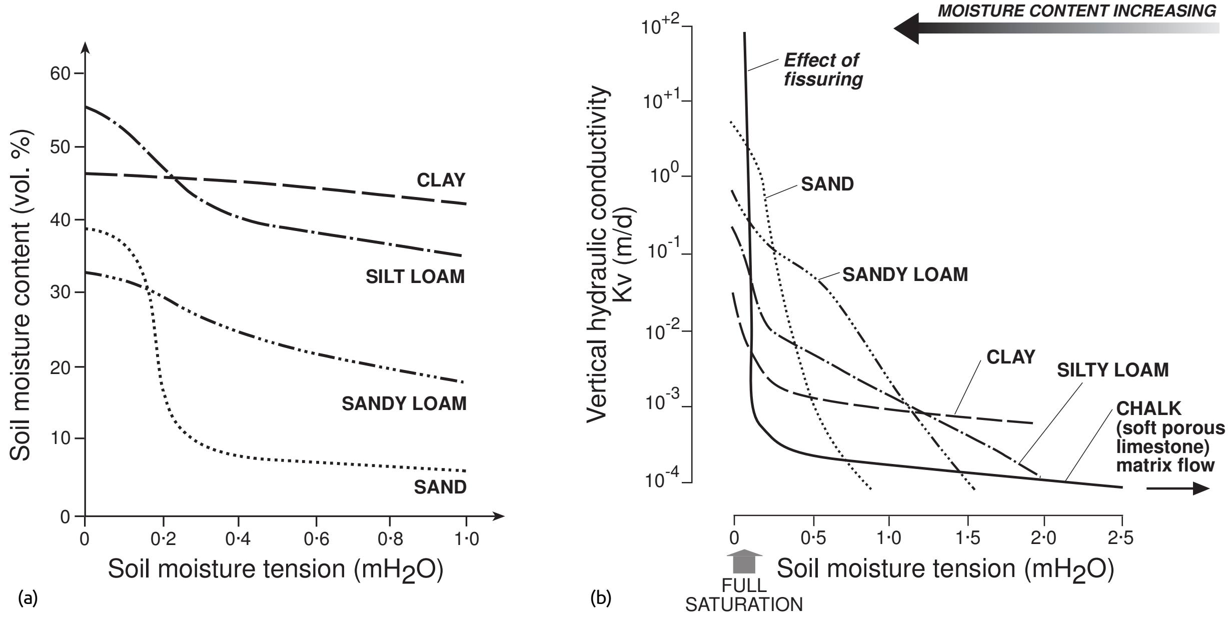


Figure 8: Soil moisture retention curves of different sediments in the unsaturated zone (a), and the hydraulic conductivity in the unsaturated zone as a function of soil moisture tension (b) (ARGOSS, 2002, p. 13).

Adsorption is a complex physiochemical process between microbes, water and sediments. Only bacteria and especially viruses are affected because of their small size. Under most natural pH conditions, suspended microbes usually have a net negative charge like the greater part of mineral surfaces in the ground, hence they are repelled and remain suspended. If certain pH conditions in the groundwater or mineral properties occur, microbes may be retarded by becoming attached to particles. Since the process of adsorption is reversible, changing groundwater chemistry (e.g. through heavy rainfall; infiltration of water with lower ionic strength or pH) can cause microbes to be released again. Furthermore, dispersion of microbes occurs during their movement through sediments, leading to the spread of contaminant plumes in groundwater which increases the travel time. Dispersion is easier to determine for chemical contamination since microbes are present in discrete numbers and tend to clump (ARGOSS, 2002).

The flow rate in the saturated zone depends on the hydraulic gradient, saturated hydraulic conductivity, and porosity of the aquifer. Typical rates are < 2 m/d because the hydraulic gradient is usually low. But flow rates can be significantly higher exceeding 10 and even 100 m/d under certain geological conditions (e.g. coarse sand and gravel, or fractured consolidated aquifers) (ARGOSS, 2002). The traveling distance of pathogens in the saturated zone of coarser-grained sediments can be therefore considerable as apparent in Figure 9 (Krauss & Griebler, 2011).

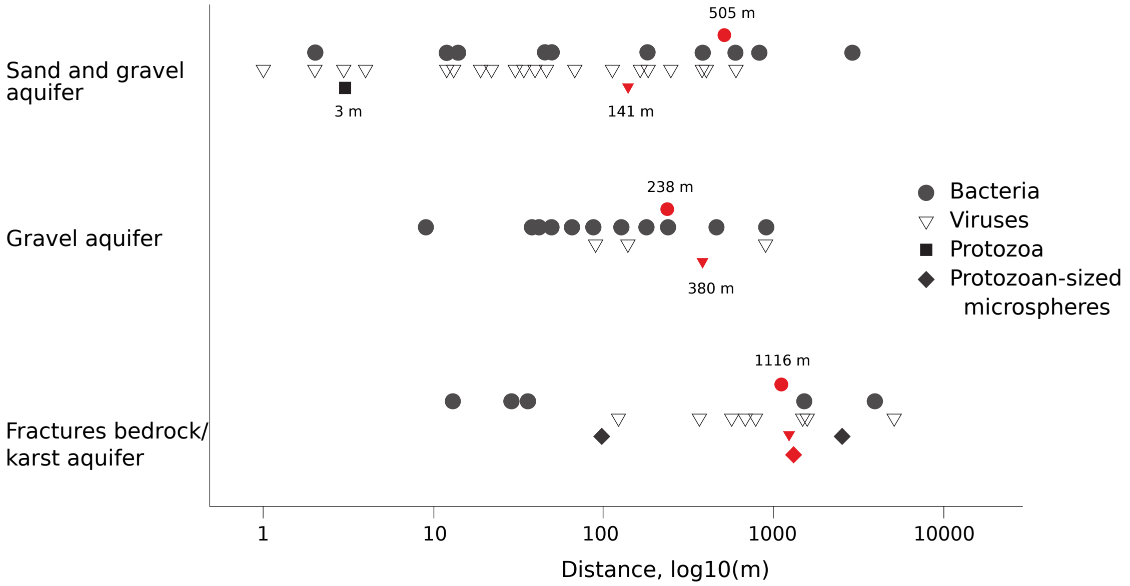


Figure 9: Travel distance of pathogens in three different types of aquifers (average distances shown in red) (Krauss & Griebler, 2011, p. 16).

Empirical evidence from a limited number of studies suggest that a travel time of 25 days between the source of contamination (i.e. sanitation facility) and the point of water extraction (i.e. water supply) is sufficient to reduce faecal indicator bacteria to acceptable levels. Nonetheless, these studies did not examine the travel time of other contaminants like viruses, which are generally more persistent than bacteria (ARGOSS, 2001). Hence, '[a] *50 day travel time distance is the preferred level of protection* […]. *However a 25 day travel time may be more realistic in some circumstances, where there are space (or distance) constraints, accepting that the risk of contamination although low is higher than for the 50 day travel time distance*' (ARGOSS, 2002, p. 27). ARGOSS (2001, p. 35) introduced three levels of risk, depending on the travel time:

significant risk	less than 25 days travel time
low risk	between 25 and 50s days travel time
very low risk	greater than 50 days travel time

Nonetheless, it hast to be highlighted that '*microbiological contamination is perhaps of more immediate concern,* [but] *nitrate may represent a more persistent problem in the longer term*' (ARGOSS, 2002, p. 40).

5.2. Single Pit System

Figure 10 shows the schematic of a Single Pit System. This system can be operated with or without water, using either a Pour-Flush Toilet or a Dry Toilet as User Interface. The Collection, Storage and Treatment of Dry Systems takes place in a Single Pit or a Single Ventilated Improved Pit (Single VIP). Wet Systems rely on Single Pits only, ventilation of the pit is not required since the water seal prevents odours anyhow (Tilley et al., 2014).

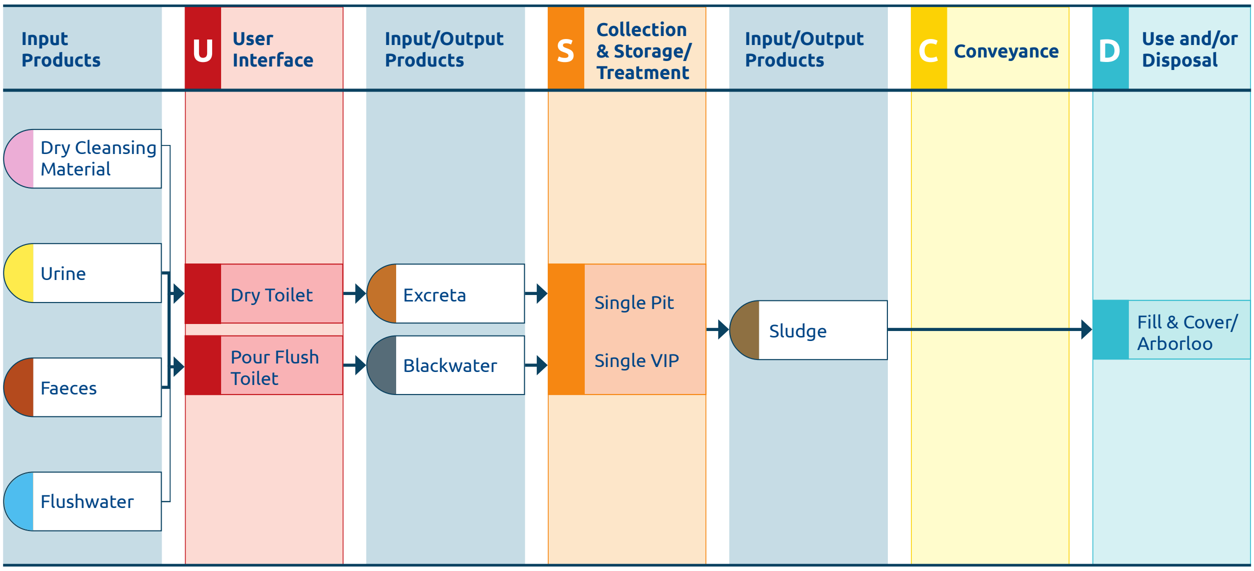


Figure 10: System overview of the Single Pit system (Tilley et al., 2014, p. 20, adapted).

Single VIP Toilets, Single Pit Toilets with a slab as well as Pour-Flush Toilets are classified as improved toilets by the Joint Monitoring Programme (JMP) of the Millennium Development Goals (MDGs). Sanitation facilities that do not ensure a hygienic separation of excreta from human contact are considered to be unimproved. The most important criteria is the presence of a proper slab or platform to ensure this separation (WHO & UNICEF, 2014b).

Situation in Vanuatu

Single Pit Toilets without a proper slab are commonly named ‘bush toilets’ in Vanuatu. Since there is enough space in rural areas and desludging is not undertaken, it is common practice in Vanuatu to abandon pit latrines once they are full and dig new ones instead (Fill and cover/Arborloo for Use and/or Disposal) (Kassis, 2010). Hence, Conveyance (Emptying and Transport) is not included in the analysis of this system.

Desludging services are only provided in the capital Port Vila on the main island Efate and are too expensive for the majority of people. The sludge is disposed of on a sanitary landfill near the capital without any pretreatment (Castalia, 2005). This disposal pit overflows during heavy rainfalls into the adjacent Teouma River (Kassis, 2010).

According to SOPAC (2007, p. 35f), '[r]*ural areas* [in Vanuatu] *generally have very poor sanitation facilities mostly comprising pit latrines or bush toilets* [, furthermore ...] *there is serious concern over the poor construction, inappropriate siting, inadequate supply, and poor maintenance of pit style latrines* [in and around Port Vila]'.

This chapter considers all common types of pit-based latrines present in Vanuatu:

(i) ‘Bush toilet’ (Single-Pit Dry Latrine lacking a proper slab, i.e. unimproved),
(ii) Single-Pit Dry Latrine,
(iii) Single-Pit Ventilated Improved Pit Dry Latrine, and
(iv) Single-Pit Pour-Flush Latrine.

5.2.1. User Interface

The health risk of User Interfaces is related to individual behaviour of the users and the cleanliness of the toilet. Depending on the handling of anal cleansing material, a risk to subsequent users may exists. The person responsible for cleaning and maintenance of the toilet is always at risk, which is determined by the degree of contact, proper completion of the task and hygienic measures applied during and after the implementation (Stenström et al., 2011).

DRY TOILET

The User Interface of Dry Toilets is operated without flushwater. The interface is either implemented as a squatting pan for users who squat, or pedestals for those who sit (Figure 11, Option 1 and 2, respectively). Urine and faeces fall through a simple drop hole into the pit. A proper slab should cover the pit sufficiently to ensure the separation of users from faeces and prevent stormwater from entering the pit. Further, slabs should be moveable to allow its reuse (Tilley et al., 2014). Pit latrines without a slab (i.e. ‘bush toilets’) are classified as unimproved sanitation facilities (WHO & UNICEF, 2014b). Slabs have at least one properly sized hole to install the User Interface, a second one is necessary in case the pit is vented (Mara, 1984).

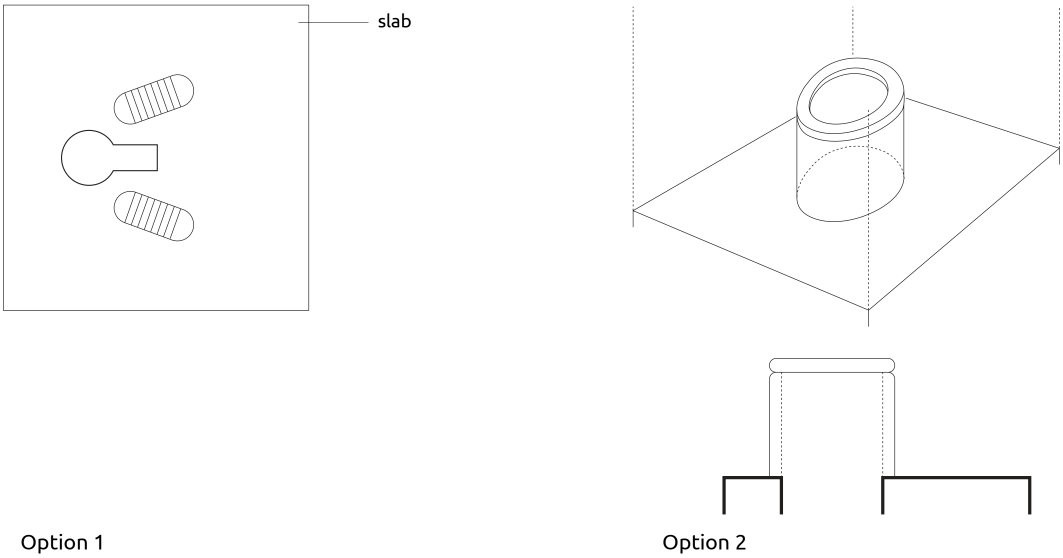


Figure 11: Schematic overview of the Dry Toilet User Interface (Option 1: squatting toilet, Option 2: sitting toilet) (Tilley et al., 2014, p. 44).

Situation in Vanuatu

This simple User Interface is often self-made out of wood or concrete using a mold. Additionally, prefabricated pedestals built from fiber-glass are available from a local manufacturer (examples are shown in Figure 12).

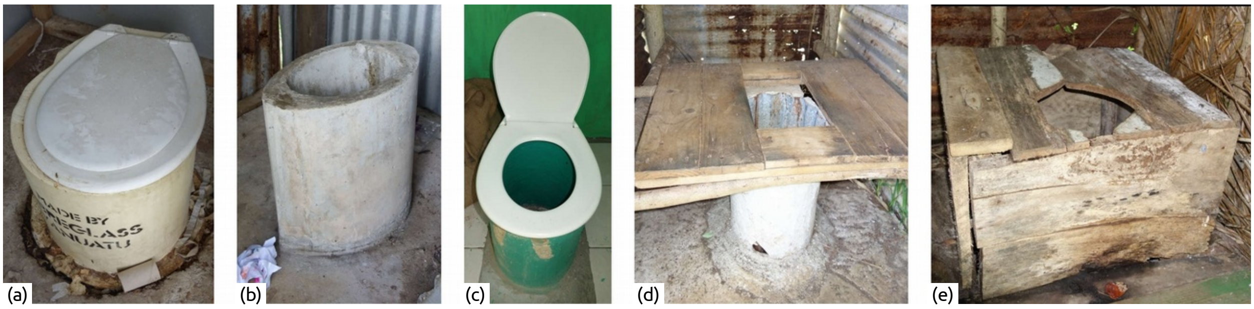


Figure 12: Examples of the Dry Toilet User Interface from Vanuatu made out of (a) fiber-glass (prefabricated by Fiberglass Vanuatu); and locally made out of (b) concrete; (c) concrete with coating; (d) concrete lined with corrugated iron, wooden frame; and (e) wood.

EXPOSURE PATHWAYS AND RISK MITIGATION

EP$_1$ EP$_2$ EP$_3$ EP$_{Other}$

(EP$_1$) Ingestion of excreta

Poorly cleaned toilets (both, pedestal & squatting) involve a risk for hand-oral transmission when hands or feet are contaminated due to contact with soiled surfaces. Contaminated feet or shoes can cause pathogens to travel into the home environment posing a risk of further contamination and transmission. Sitting on the toilet pedestal can result in direct contact with pathogens. Nonetheless there is generally no higher risk of exposure when compared to squatting toilets (Stenström et al., 2011). More unwanted contact with soiled surfaces may occur if a VIP is used since the toilet cubicle has to be kept semi-dark.

Risk mitigation

Cleanliness of the toilet is of high importance to minimize the risk of exposure to pathogens. It is important to apply personal protection equipment (PPE) during regular cleaning, followed by hygienic measures like hand washing (Stenström et al., 2011). The Dry Toilet is the simplest User Interface and can be prefabricated out of porcelain, fiber-glass or stainless steel or produced locally out of concrete. The surfaces of the squatting pan or the toilet seat should be dry and clean to impede the transmission of pathogens and limit odours (Tilley et al., 2014). Concrete interfaces should be finished with paint to allow better cleaning. Alternatively, toilet seats can be built entirely from wood (simpler to make locally; can be warmer and smoother than e.g. concrete), but keeping it clean is more difficult (Reed & Shaw, 2012a).

A study in Tanzania has shown that proper slabs are significantly reducing *E. coli* points of hand contact in toilet cubicles. Materials of higher quality used for slabs, walls, doors and roofs resulted in significant lower concentrations of *E. coli* at these surfaces due to better cleanability and less hospitality to growth (Exley et al., 2015).

(EP$_2$) Dermal contact

Hookworms may be transmitted to users via soiled surfaces when entering the toilet barefooted. Especially coarse floors (slabs) are difficult to keep clean, the presence of faecal remains increase the likelihood of hookworm transmission (Reed & Shaw, 2012a; Stenström et al., 2011).

Risk mitigation

It is assumed that wearing shoes minimizes the exposure to helminths, but the effectiveness of this control strategy has probably been overestimated (Bird et al., 2014; Albonico et al., 1999). The drop holes of squatting toilets should have a sufficient diameter to avoid soiling of the slab; especially the area near the drop hole should be smooth to allow better cleaning; foot rests of squatting pans should be elevated (Stenström et al., 2011). The floor's surface (i.e. slab) should be smooth and durable to be easily cleaned, minimizing the likelihood of helminth transmission that way (e.g. polished concrete, screed or tiles) (Rieck et al., 2012; Stenström et al., 2011). Finishing the slab with a suitable paint may increase its cleanability substantially. This measure may also increases the user's appreciation of the toilet via valorization, which may induce improved cleanliness of the toilet by this means.

(EP$_3$) Contact with flies/mosquitoes

Vectors (flies and mosquitoes) may access and breed in the pit due to the absence of a barrier like in case of a water sealed toilet. The flies and mosquitoes can act as a mechanical vector of disease transmission (Stenström et al., 2011). Besides, flies may feed and/or breed on soiled slabs (Reed & Shaw, 2012a). This may occur also on toilet seats and pedestals.

Risk mitigation

A smooth, easy to clean surface of the slab helps to prevent flies from breeding on it. In case of a Single Pit, a tight-fitting lid covering the drop hole reduces breeding of vectors in the pit and limits odours. Some lid designs include a mechanism to open and close them with a rope or by foot which minimizes potential exposure points (Reed & Shaw, 2012a). Non-tight-fitting lids in VIPs prevent the incident of light into the vaults, limiting the number of flies exiting the pit via the interface, while still enabling an air flow at the same time (Buckley et al., 2008a). A minimum distance of 25mm between lid and pedestal is recommended to allow an unobstructed air flow (Mara, 1984). Nevertheless, VIPs rely on a steady supply of air via the interface, a non-tight-fitting lid may hamper the air flow rate, potentially causing odours (see Ventilation pipes of pit latrines, p. 28).

Wet pit latrines are breeding sites of *Culicinae*, a vector of bancroftian filariasis. Since mosquitoes are less attracted by light than flies are, considerable numbers may leave the pit via the interface. A mosquito trap (i.e. fly trap) mounted on top of the interface may be a measure to reduce the risk (Tilley et al., 2014; Mara, 1984).

(EP$_{Other}$) Other exposure

Rodents may intrude the pit via the User Interface to feed (Tilley et al., 2014). Other vermin like cockroaches are attracted by latrines too (Franceys et al., 1992).

Risk mitigation

A lid covering the interface prevents rodents from entering the pit (Tilley et al., 2014). Cockroaches may migrate between latrines and places where food is stored or prepared. Hence, toilets should be located as far away as possible from those places (Franceys et al., 1992). A tight-fitting lid covering the interface of non-vented toilets prevents access for cockroaches.

POUR-FLUSH TOILET

This User Interface is designed to be used with water for flushing. Again, it is available for users that prefer to squat and for those who sit during defecation (Figure 13, Option 1 and 2, respectively). Its manner of functioning is like a Cistern Flush Toilet, with the difference that water is poured in by the users themselves (Tilley et al., 2014). The collection pan has a water trap which is filled with approximately 0.5L of water. Typologically, 'U' bend and 'gooseneck' style of traps are distinguished (Figure 13, upper and lower, respectively). The latter option is usually used for direct pits (Mara, 1985).

The amount of flushwater needed depends on the interface itself (i.e. seal depth and diameter) and whether the blackwater is discharged to a direct pit (no connection pipe), or an offset pit (e.g. length, diameter, roughness and slope of the pipe determines the volume). Direct pits need usually around 1L, offset pits roughly 2L for flushing (twin pits 2–4L) (Tilley et al., 2014).

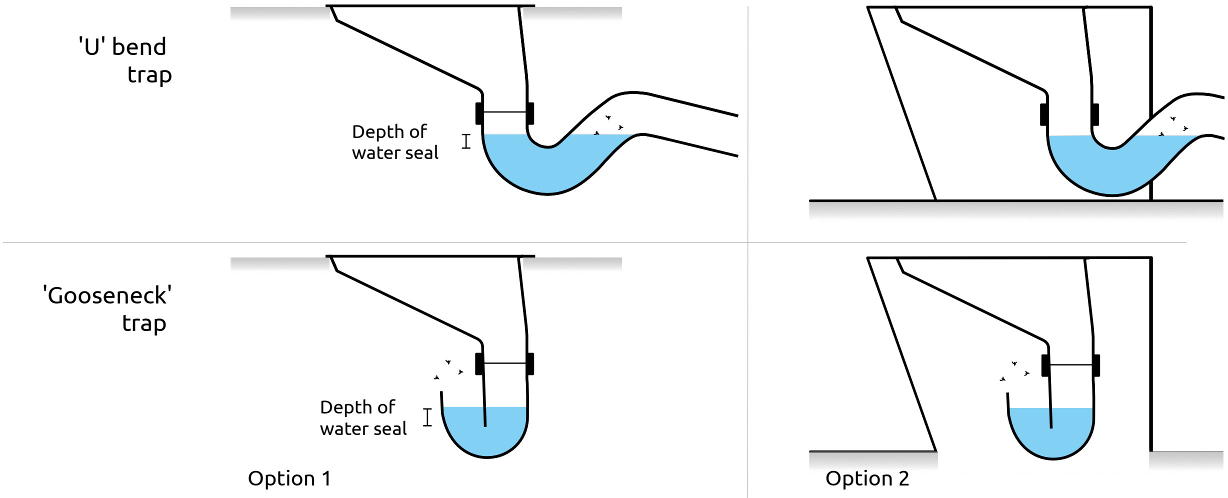


Figure 13: Schematic overview of a Pour-Flush User Interface. Option 1 shows a squatting toilet, Option 2 a pedestal or sitting toilet. Upper drawings show a 'U' bend type of trap, the lower type is called 'Gooseneck' trap (Reed & Shaw, 2012b, p. 3, adapted).

Situation in Vanuatu

Self-made Pour-Flush pedestals out of concrete are common, and sometimes Cistern Flush toilets out of porcelain are used in Pour-Flush mode.

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1 EP_2 EP_3 EP_4 EP_{Other}

(EP_1) Ingestion of excreta

This exposure pathway is similar to EP_1 of the Dry Toilet User Interface (p. 24). Besides, the obligatory handling of the flushing device (i.e. vessel) increases the contact with potentially soiled surfaces considerably.

Blockages involve a risk of pathogen transmission during removal. In the worst case, a blockage may cause a toilet to overflow, increasing the risk of pathogen transmission substantially (Stenström et al., 2011). Blockages occur more often as compared to Cistern Flush Toilets due to the smaller amount of water used for flushing (Tilley et al., 2014). The smaller trap diameters of Pour-Flush interfaces and coarse surfaces of self-made interfaces increase the risk of blockages additionally.

Risk mitigation

The vessel used to pour the water into the toilet should be properly cleaned on a regular basis to avoid pathogen transmission.

Regular cleaning of the User Interface is of high importance to minimize the risk of exposure to pathogens in-, and outside of the cubicle. Personal protective equipment (PPE) should be worn during cleaning procedures and when blockages are to be removed, followed by hygienic measures like hand washing (Stenström et al., 2011). Cracks and fissures in surfaces may '*harbor pathogens and nutrients for insects, cause odors and discourage hygienic and regular use*' (Mara, 1985, p. 7). Hence, a smooth surface of the User Interface is important for good cleanability. It is recommended to use water seals out of plastic or porcelain, as seals made out of concrete are prone for blockages due to a rough or textured surface. The traps should have a diameter of approximately 7cm (Tilley et al., 2014). Moreover, wetting the pan before defecation is recommended to prevent faeces from sticking to the pan (Reed & Shaw, 2012b). Dry cleansing material other than soft paper (e.g. newspaper, cardboard) should be collected separately in an extra bin to prevent blockages of the toilet (Stenström et al., 2011). Proper slabs significantly reduce *E. coli* points of hand contact in toilet superstructures. Slabs, walls, doors and roofs out of higher quality result in significant lower *E. coli* at these surfaces due to better cleanability and less hospitality to growth (Exley et al., 2015).

(EP_2) Dermal contact

See exposure pathway of Dry Toilet User Interface, EP_2 (p. 24).

Risk mitigation

See risk mitigation measures of Dry Toilet User Interface, EP_2 (p. 24).

(EP_3) Contact with flies/mosquitoes

The main benefit of a water-based User Interface is the water-seal which acts as a barrier for flies, mosquitoes and odours. Nonetheless, open containers used to store flushwater may become breeding sites for mosquitoes like *Aedes* (vectors for Dengue). Flies may be attracted by dry cleansing materials other than soft paper which should be disposed of separately to prevent blockages (Stenström et al., 2011). The water seal may break due to evaporation (e.g. hot climates, rare use) potentially enabling flies and mosquitoes to enter and exit the pit (Reed & Shaw, 2012b). Flies may feed and/or breed on soiled slabs (Reed & Shaw, 2012a).

Risk mitigation

Containers used to store the flushwater should be cleaned regularly to prevent mosquitoes from breeding in it. Bins used to separately collect dry cleansing materials other than soft paper should be closed with a tight fitting lid to prevent access for flies. Fixing the bin to the wall avoids the risk of spilling the contents (Rieck et al., 2012; Stenström et al., 2011). Menstrual hygiene materials should be collected separately too. Nevertheless, containers for separate disposal are only recommended if proper disinfection of the container and careful handling of the waste can be assured (Franceys et al., 1992).

Care has to be taken to prevent damages to the water seal during removal of blockages, especially if a gooseneck type of trap is used (Franceys et al., 1992; Mara, 1985). Sometimes traps are broken intentionally to avoid blockings (Brikke & Bredero, 2003). Broken traps allow unrestricted access to the pit.

The seal depth of the interface determines the amount of flushwater needed (Figure 13). A conventional Cistern Flush toilet has a seal depth of ~5 cm, resulting in several liters of flushwater needed to replace the water in the trap. For Pour-Flush Toilets, a seal depth of 2 – 3 cm is recommended to reduce the amount of water needed while still limiting the risk of a seal breakage due to evaporation (Reed & Shaw, 2012b). A smooth, easy to clean surface of the slab helps to prevent flies from breeding on it (Reed & Shaw, 2012a).

(EP$_4$) Inhalation of aerosols

Johnson et al. (2013, p. 262) state that '[c]*ontaminated* [Cistern Flush] *toilets have been clearly shown to produce large droplet and droplet nuclei bioaerosols during flushing, and research suggests that this toilet plume could play an important role in the transmission of infectious diseases for which the pathogen is shed in feces or vomit*'. Nevertheless, there are no studies that clearly proved or disproved an actual plume-related transmission of disease, caused by aerosols from flushing Cistern Flush toilets (Johnson et al., 2013). Pathogens in aerosols may be inhaled directly, or surface contamination by aerosols and subsequently ingestion via surface-to-hand-to-mouth transmission may occur (Barker & Jones, 2005). This may play a role in case of Pour-Flush toilets too, but studies concerning this pathway are lacking for this interface.

Risk mitigation

Closing the lid during flushing Cistern Toilets may have an influence in the number of emitted aerosols, but findings have been contradictory (Johnson et al., 2013; Barker & Jones, 2005). Nevertheless, this is not applicable to Pour-Flush Toilets anyway.

Cleaning and particularly disinfection is an important measure to control infection. Nonetheless, studies have shown that microbial surface contamination may be persistent despite cleaning. How the cleaning and disinfection is executed determines if a complete disinfection of surfaces is achieved, especially if the contamination level is high (Johnson et al., 2013).

(EP$_{other}$) Other exposure

Using contaminated water (e.g. untreated greywater) to flush the toilet involves a risk of pathogen transmission, determined by the actual quality (Tilley et al., 2014). Splashing of urine may occur, depending on the design (Mara, 1985).

Risk mitigation

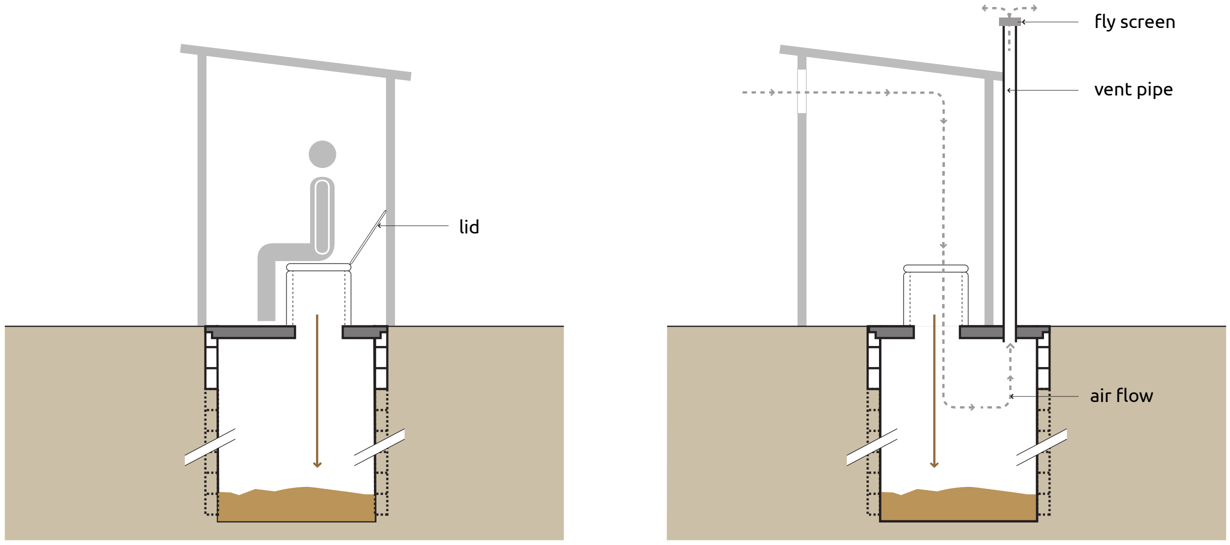
Using rainwater instead of greywater to flush the toilet lowers the risk of being exposed to pathogens. Flushwater should never be used for drinking (Stenström et al., 2011).

5.2.2. Collection and Storage/Treatment

SINGLE-PIT AND SINGLE VENTILATED IMPROVED PIT

The Collection and Storage/Treatment of excreta takes place either in a Single Pit or a Single Ventilated Improved Pit (VIP). Either way, the pit is a hole or shaft in the ground which may be lined (partly or fully) or left unlined (Tilley et al., 2014). Ring beams are often used to protect the pit head if the soil is not firm enough and no lining is applied (Morgan, 2004). The pit is covered with a slab featuring the User Interface (Tilley et al., 2014).

The actual dimensions of pits vary around the world. Pits are usually dug by hand, the depth ranges from shallow to very deep (e.g. 1m for rather short-term use up to 10 – 15m in parts of the world). The average depth of a pit is between 2.5 and 4m. The diameter is generally 1 – 1.5m (range from 0.5 to 3m) (Reed & Shaw, 2012c). Ventilated Improved Pits differ from Single Pits (often referred to as Simple Pits) by being equipped with a ventilation system. Figure 14 shows a Single Pit (Option 1), and a Single VIP (Option 2) schematically.



Option 1 Option 2

Figure 14: Schematic of a Single Pit (unventilated; Option 1) and a Single Ventilated Improved Pit (VIP) which includes a ventilation pipe covered with a fly screen (Option 2) (Tilley et al., 2014, p. 60ff, adapted).

Pits from water-based latrines can be also offset which allows the toilet to be installed inside a house. The toilet cubicle and the pits can be used permanently if desludging of pits is possible. Twin pits are used alternately, resting times of minimum 2 years per pit eases emptying and the material is considered to be safe to handle afterwards (Reed & Shaw, 2012b). This system includes direct and offset pits only, twin pits are classified as 'Pour-Flush Pit System without Sludge Production' according to Tilley et al. (2014).

VENTILATION PIPE

The ventilation pipe is a major upgrade of a Simple Pit to (i) reduce odours and (ii) control flies:

(i) Reduction of odours:

Dissipation of odours is based on the principle of the windshear effect (Franceys et al., 1992). The wind passing over the ventilation pipe creates a suction pressure in the pipe, leading to an air circulation (wind shear effect). Air is drawn into the superstructure, enters the pit via the User Interface and exits through the vent pipe. This minimizes odours in the cubicle (Tilley et al., 2014). Further, buoyancy occurs due to a stack effect of air, which is based on different air densities in and outside the pit caused by temperature and/or moisture differences (Mara, 1984).

Vent pipes of VIP toilets should be straight without bends, and protrude at least 0.5m vertically beyond the roof of the toilet and other adjacent obstacles (e.g. houses, trees) to prevent turbulences hampering the ventilation (Reed & Shaw, 2012f). Odourless conditions are obtained if an air flow rate of approximately 6 times the super-structure air volume is reached per hour (see p. 47 for more details) (Morgan et al., 1982). The vent pipe's diameter should be at least 150mm to reach sufficient air volumes greater than 20m^3/h for wind and stack effect independently. Pipes with a diameter of 100mm had about the half air volume exchange per hour as compared to 150mm (Ntabadde, 2004). In case the inner surface is not smooth, it is recommended to use wider diameters of 200 – 250mm. The door should face the prevailing wind direction for best results (Reed & Shaw, 2012f). The gap allowing fresh air to enter the toilet cubicle is usually above the door and should have an area of three times the area of the vent pipe (Franceys et al., 1992).

The air draught can be further improved by painting the pipe black which induces a thermal updraft due to the heat difference of the warmer pipe and the cooler pit (no shading of the pipe!) (Tilley et al., 2014). This may be improved by facing the ventilation pipe towards the equator (Franceys et al., 1992). Factors influencing the shearing action of wind (e.g. wind direction in relation to orientation of the door) are much more important than the stack effect (Mara, 1984). Harvey (2007) recommends a minimum distance of 30cm between drop hole and vent pipe to ensure an unobstructed air flow. It is further recommended to apply an air-tight seal with low strength mortar between slab and lining to ensure that there is no gap spoiling the aerodynamics of the ventilation and allow flies to access the pit (Morgan, 2009).

Spiders often settle in the ventilation pipe to feed from the flies. Their webs can have a substantial impact on the ventilation of a pit. Regular removal of webs is therefore crucial for a good ventilation of the toilet (Morgan, 2009).

The pits of Pour-Flush Latrines do not need to be ventilated because the emerging gas is absorbed by the surrounding soil and odours are prevented from escaping the pit by the water seal of the user interface (Reed & Shaw, 2012b; Mara, 1985).

(ii) Fly control:

Ventilation pipes are an important measure to control flies in the pit. The manner of functioning is based on the fact that flies are attracted by light (Franceys et al., 1992). By keeping the superstructure dark, they migrate towards the only light source at the end of the ventilation pipe. The fly screen at the end of the pipe hinders them from exiting, the flies keep trying to get out until they die and fall back into the vault (Tilley et al., 2014). Flies attracted by the smell cannot enter the pit via the vent pipe because of the fly screen (Franceys et al., 1992). Again, bends of the vent pipe are contra-productive because the incidental light is reduced, may causing flies to be attracted by the light coming trough the User Interface.

A fly screen out of aluminum is recommended from a cost-benefit point of view. From a durability perspective, screens out of stainless steel are almost ever lasting but more expensive (Morgan, 2009). A mesh size of 1.2 × 1.5mm has proven to allow a sufficient air flow while being narrow enough to stop flies from exiting. The effectiveness of the ventilation can easily be tested with the help of a cigarette (the air draught should suck in the smoke into the pit and leave the toilet via the vent pipe) (Tilley et al., 2014).

TREATMENT

The processes occurring in a pit may be subsumed in (i) accumulation, (ii) aerobic degradation, (iii) anaerobic degradation, (iv) leaching/draining, (v) compaction, and (vi) digestion by macro-invertebrates (Buckley et al., 2008a):

(i) Accumulation:

Non-degradable contents (or parts of it) which do not percolate into the surrounding or underlying ground will accumulate over time.

(ii) Aerobic degradation:

In case O_2 is available and aerobic micro-organisms are present, biodegradable material is decomposed into CO_2 and H_2O. A part of the material is utilized for cellular growth. Aerobic degradation is much faster than anaerobic degradation.

(iii) Anaerobic degradation:

Anaerobic digestion of biodegradable material takes place if O_2 is not available, anaerobic microorganisms are present and enabling conditions (e.g. pH, moisture) are met. This process results via intermediate products (e.g. soluble organic compounds, especially organic acids) in CO_2, CH_4, H_2O, non-biodegradable organic material, NH_4^+, phosphates and growth of microorganisms.

(iv) Leaching/draining:

Liquid and soluble components may percolate either from the pit into the surrounding ground, or from the ambient ground into the pit. Geological conditions (e.g. type of soil or rock, layers) are an important factor influencing the route. The former route is more likely and may causes soluble and/or suspended material to percolate either through the pit contents, and/or through the pit walls into the surrounding ground. This may cause the pit to be rather dry. The later route may occurs when the height of the water table is higher than the bottom of the pit, or when liquids from another source above the bottom (e.g. leaking tap near the pit, stagnant water after rainfall, surface waters) cause soluble and/or suspended components to be washed into the pit.

(v) Compaction:

The material in the pit is compacted at the bottom because material is constantly fed to the pit, and due to degradation of organic matter. Cells exude water when they break down over time, and the weight of upper layers also squeezes water out of underlying layers.

(vi) Digestion by macro-invertebrates:

Macro-invertebrates (e.g. fly larvae) in the pit have, as opposed to outside of the pit, beneficial influences in regard of stabilization and volume reduction of the material via digestion as well as aeration of the material through migration into upper layers.

Matter can neither be created nor destroyed, thus matter that enters the pit can only be diminished via evaporation into the atmosphere (or outgassing into the surrounding ground) or percolation of dissolved particles into the surrounding soil (Still & Foxon, 2012).

More than ¾ of the wet weight of faeces of a healthy individual is moisture. Besides, about 80% of the organic material contained in faeces is biodegradable. A significant amount of faecal matter consists of intact, semi-intact or dead microorganisms from the digestive system as well as partially digested plant and/or animal tissue that has been consumed by the individual. Approximately 30% (DM) of faecal matter are active microorganisms (Buckley et al., 2008a).

Decomposition of biodegradable components is undertaken by aerobic and anaerobic microorganisms in different layers of the pit. These microorganisms originate from the faecal material, soil, sand, leaves and, if applicable, residuals of faecal sludge from pit emptying. Addition of leaves and/or soil in the starting phase may enhance the availability of microorganisms (Buckley et al., 2008a). The degradation processes may be imagined in form of steps. Each step depends on populations of bacteria which are present under certain conditions to grow until they reach an environmental balance. Populations die and degrade after the biodegradable material that is available for the microorganisms is depleted (Still & Foxon, 2012).

Pit contents are considered to be stabilized if all biodegradable material is converted into biomass and gases (Buckley et al., 2008a). '*It is believed that stabilisation of unlined pits usually begins at the walls and gradually moves inward* [...], *indicating that contact with the soil walls provides good conditions for stable digestion. This may be attributed either to seeding from the walls, or the provision of micro-environments that shelter more sensitive micro-organisms from bulk conditions*' (Buckley et al., 2008a, p. 6). A thin aerobic layer in form of micro-environments between unsaturated soil (i.e. walls) and the pit contents in unlined pits may allow aerobic microorganisms to settle in this zones (Still & Foxon, 2012).

The treatment processes occurring in the pit will be different according to whether the system is operated with a Dry Toilet or a Pour-Flush User Interface. Since the latter option uses water to flush excreta, the water content in the pit will be comparatively higher. Within the scope of this thesis, it is assumed that the pit is unlined. The availability of oxygen in the upper layers is then determined by the actual geological conditions, height of water table, frequency of use, and volume of water needed per flushing. The upper layers of a pit operated with water may be therefore rather anaerobic, or partly/alternately anaerobic and aerobic, presumably leading to a slower degradation of biodegradable materials. This (partly) anaerobic conditions may cause foul odours from gases emerging during this process. Inspected Pour-Flush Toilets in Vanuatu often had problems with odours (e.g. due to an improper sealing between slabs and pit).

Buckley et al. (2008a) postulate a new theory of pit latrine processes which distinguishes four different categories of processes (i.e. layers) in a pit (Figure 15): (i) fast aerobic degradation of readily available components from fresh faeces on top of the pit contents, (ii) parts of the remaining biodegradable material undergoes aerobic degradation (more complex organic molecules to simpler compounds) before being covered with new faecal matter, resulting in an (iii) anaerobic degradation of remaining biodegradable components forming soluble products,

CH_4 and CO_2 in the layer below, and lastly, (iv) no further stabilization of mostly non-degradable material at the bottom of the pit occurs.

(i) Rapid aerobic degradation:

New faecal matter (and urine) accumulates on top of the pit contents, which is usually exposed to O_2 if normal conditions are present (no saturation e.g. due to high groundwater) and well-designed pit latrines are used (a steady, unobstructed air flow enters the pit via the User Interface and exits via the vent pipe).

The accumulation rate of fresh faeces is low as compared to the rate of degradation. Hence readily available biodegradable components of the faecal matter are likely to be consumed and degraded quickly in this uppermost layer by aerobic microorganisms already present in the faeces or in the top layer. Aerobic decomposition results mainly in CO_2, new cell matter and other chemical/biochemical by-products. The rate of degradation is influenced by the availability and amount of aerobic microorganisms, the time needed for hydrolysis of large molecules to smaller ones (since this biochemical process is the slowest), and the availability of oxygen at the location of interest.

This upper layer is hard to distinguish from the following layer because it is very small and usually not measurable in practice.

(ii) Limited aerobic degradation:

Decomposition of more complex molecules take place at a slower rate in this, still aerobic, layer. The remaining organic material comprises mostly out of inactive, semi-inactive or dead cell matter (e.g. cell walls, membranes) which are gradually covered by newly added faeces. This cell matter is more resistant to degradation and may persist for a long time.

(iii) Anaerobic digestion:

After the faecal matter is covered to an extent where O_2 becomes scarce (i.e. unavailable), anaerobic microorganisms utilize and decompose the residual organic material for cellular growth. Approximately 10% of the degradable material is used for that purpose, the remaining ~90% is converted to CO_2 and CH_4 as well as inert residuals.

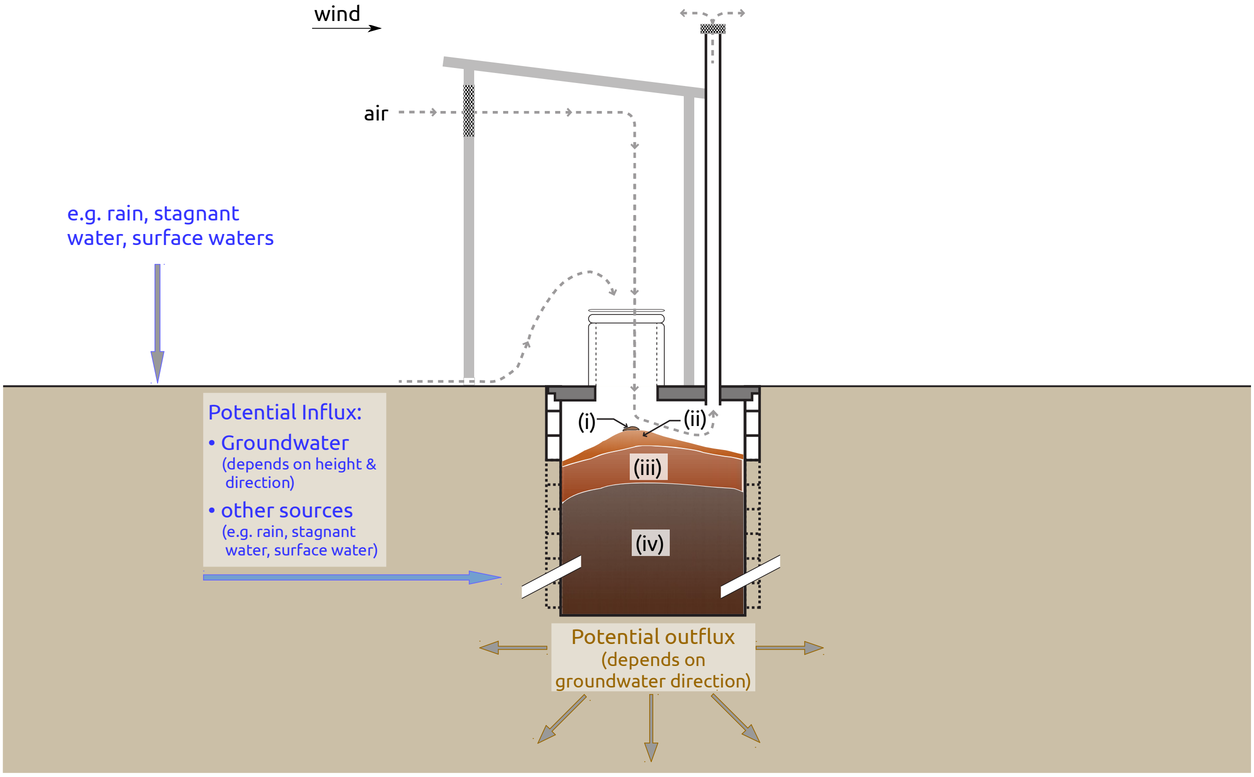


Figure 15: Categories (i.e. layers) in a pit latrine regarding dominant processes: (i) rapid aerobic degradation, (ii) limited aerobic degradation, (iii) anaerobic digestion, (iv) no further stabilization (Buckley et al., 2008a, p. 12, adapted).

Different species of anaerobic microorganisms are involved in an anaerobic digestion process, a stable mix of microorganisms is therefore necessary to complete each ‘step’ with its dominant species within this process. Since the still available organic matter is of a more complex nature and easily available biodegradable components have already been degraded in layer (i) to a large extent, the anaerobic processes in layer (iii) and (iv) decompose only small amounts of residual organic material, resulting in low CH_4 emissions. The moisture contained in the cells is released during this course of action. A combination of biological and physical processes result therefore in a slow dehydration of the pits contents.

(iv) No further stabilization:

‘*Once pit contents have resided for a sufficiently long period in the pit, they become fully stabilised, i.e.* [...] *degradation that will occur within their remaining residence time* [...] *is negligible; this is true of pit contents located deep in the pit*’ (Buckley et al., 2008a, p. 12).

‘*Aerobic processes proceed fairly rapidly in comparison to anaerobic processes, which are orders of magnitude slower*’ (Still & Foxon, 2012, p. 6). Approximately 0.05 – 0.10 g COD per g COD (5 – 10%) are converted into new biomass (i.e. cell growth) during anaerobic degradation as compared to aerobic conditions where 0.50 – 0.70 g COD per g COD (50 – 70%) are converted. It stands therefore to reason that the more material is degraded aerobically, the faster the material will be stabilized. About 64.5 and 34.3% of the feed is converted into biomass in case of aerobic and anaerobic degradation, respectively. Microorganisms are degraded after they die-off, leaving behind non-degradable organic as well as inorganic residuals. Since aerobic conditions cause higher yields of biomass, greater amounts of the aforesaid fractions will accumulate in the pit as compared to anaerobic conditions (Figure 16) (Still & Foxon, 2012).
This may be an explanation ‘*why it is reported in the practitioner’s literature that wet pit contents (which are predominantly anaerobic due to the occlusion of air by the water content) accumulate more slowly than dry pit latrines* [(27.2 and 20.7% of the end-product are non-degradable residuals in case of aerobic and anaerobic processes, respectively)]’ (Still & Foxon, 2012, p. 7).

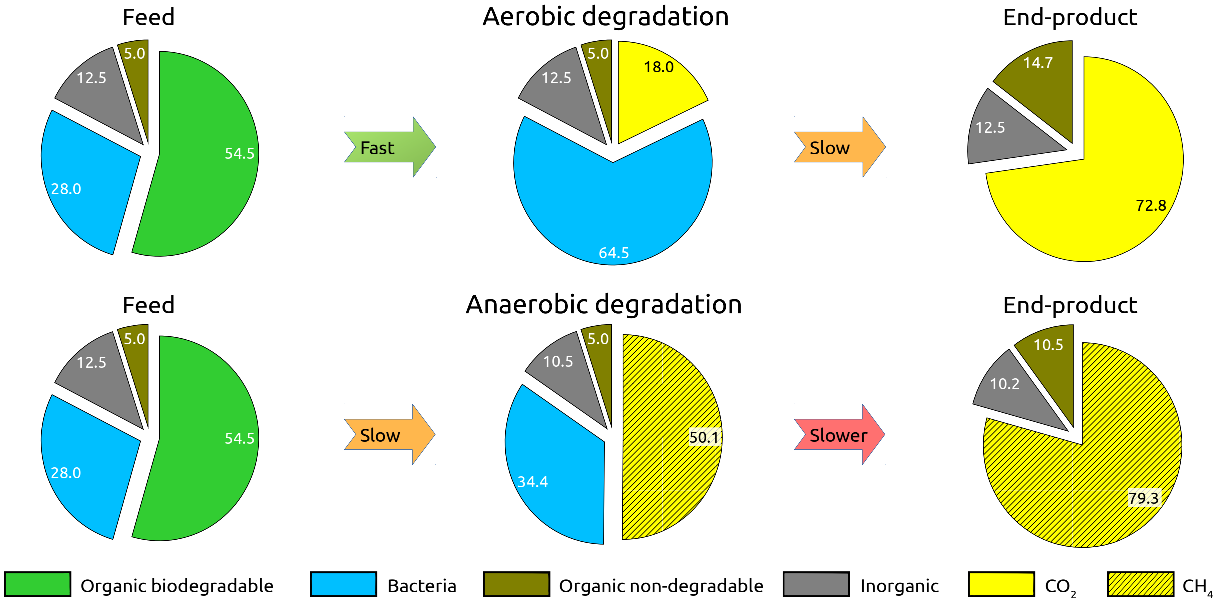


Figure 16: Simplified depiction of aerobic vs. anaerobic degradation of feed (i.e. faeces) into the resulting end-product (Still & Foxon, 2012, p. 8, adapted).

The theory by Buckley et al. (2008a) stands in contrast to the original concept that pit latrines behave like large, mixed and inefficient anaerobic digesters, may producing considerable amounts of CH_4. It rather conceives pit latrines as a form of a fed-batch accumulation system (i.e. slow accumulation of faeces, urine, water, anal cleansing material, and potentially other material like household waste) (Buckley et al., 2008a). Nevertheless, it has to be highlighted that '[t]*he theory* […] *has been suggested by the results obtained in this and other projects. Many aspects of it have not been scientifically proven, but make logical sense given the broader understanding of the nature of faeces and pit latrine contents, and observations of what is found at different depths within pit latrines*' (Buckley et al., 2008a, p. 13).

Furthermore, it is assumed that the moisture content in the pit has a significant influence on the rate of anaerobic degradation since research about the '*activity in the anaerobic digestion of wastewater treatment plant sludge cake showed that methanogenic activity dropped from 100% at a moisture content of 96% to 53% of the maximum activity when the moisture content was reduced to 90%*' (Lay et al., 1997 as cited in Buckley et al., 2008a, p. 7).

Table 9 lists further factors that may influence the performance of a pit latrine in regard of construction and location, operation and maintenance of the latrines.

Table 9: Factors potentially effecting the performance of a pit latrine (Buckley et al., 2008a, p. 15).

Construction and location	Operation	Maintenance
• Construction of walls & base • Permeability of the walls & base • Construction of slab, collar & superstructure • Height of water table (low/high) • Type of soil • Presence of bedrock / sandy aquifer • Proximity of other pits	• Age of the pit • addition of other material (e.g. household waste) • Ingress of non-urine liquid via the top of the pit • Rate of filling / number of users • anal cleansing material	• Frequency / history of emptying • Amount of seed material left after emptying • Additives used to enhance digestion • Ownership: Communal or private

Within the context of this thesis, it is assumed that toilets are abandoned after their end-of-lifetime. Hence, mid- and long-term effects of pit contents that remain in the ground are of main concern in regard of groundwater contamination (see EP$_5$).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP$_3$ EP$_5$ EP$_6$ EP$_7$ EP$_{Other}$

(EP$_3$) Contact with flies/mosquitoes

Flies and mosquitoes breed in wet pits (Stenström et al., 2011). Mosquitoes rely on water to breed. Some species of *Anopiteles* and *Culex pipiens* breed in polluted water of pits (Franceys et al., 1992). *Culex quinquefasciatus* are able to transmit bancroftian filariasis and proliferate in pits (Stenström et al., 2011). Furthermore, '[o]*pen pit latrines are ideal breeding places* [for flies]' (Franceys et al., 1992, p. 44). Blowflies and houseflies are attracted by food and faeces and are therefore vectors via the faecal-oral pathway. All three larval stages in the development of blowflies and houseflies are found in excreta of pit latrines. Houseflies prefer solid, moist and fermenting material, blowflies choose more liquid faeces (Franceys et al., 1992). VIP toilets may be ineffective in controlling flies due to bad maintenance of the ventilation pipe (e.g. hole in pipe, broken fly screen), or keeping the interior not dark enough.

Risk mitigation

To control flies in Simple Pit latrines, the User Interface should be kept clean and covered with a tight-fitting lid when not in use (see risk mitigation of EP$_3$, Dry toilet, p. 24). An effective measure to control flies in Simple Pit latrines is the upgrade to a VIP toilet (Stenström et al., 2011). A common reason for an ineffective fly control are broken fly screens, often due to improper materials (e.g. not UV-proof) (Brikke & Bredero, 2003). Broken vent pipes may hinder an effective air flow, and/or allow flies to escape through the damaged section. Regularly checking the pipe is therefore important to ensure its functionality. See above (p. 28) for more details about ventilation pipes. The gap above the door should be fitted with a fly screen.

Children and some adults may be afraid to use VIP toilets due to the darkness in the toilet superstructure. Bad sight in the toilet involves a risk of being harmed by animals (e.g. rats, snakes, scorpions, spiders). Besides, the lack of awareness for the need of (semi-) darkness may be another plausible reason why VIP toilets are sometimes not kept as dark as they are supposed to (e.g. doors are not closed, cubicle is too light) (Reed & Shaw, 2012f). It is important to educate users about the principle of fly control via vent pipes. This may raise awareness to ensure darkened superstructures. According to Morgan (2009, p. 15), VIPs should be semi-dark, which means '[i]*t should be possible to read a book inside a VIP toilet*'.

Care should be taken to avoid gaps between slab and foundation or lining. Such gaps may allow flies and vermin to enter the toilet (see EP_7) (Reed & Shaw, 2012a). Areas with shallow water tables or high seasonal fluctuations of the groundwater can cause Dry pits to be wet.

Wet pits may act as breeding sites for mosquitoes. Additives (e.g. soil, saw-dust) sprinkled in the pit are able to reduce the wetness (Stenström et al., 2011). This can help to reduce smell and breeding of mosquitoes (Brikke & Bredero, 2003; Franceys et al., 1992).

Polystyrene beads floating on the wet phase are effective in controlling *Culex quinquefasciatus* by blocking the access to the water (Curtis et al., 2002; Maxwell et al., 1990). A layer of 1 – 2cm is sufficient to prevent mosquitoes from breeding in the pit and further reduces odours emerging from the pit. Once the pit dries out, the beads are buried under the faeces. If it gets wet again, the beads will rise to the surface due to buoyancy (WHO, 1997).

(EP_5) Contaminated groundwater/surface water

Dry Pit latrines and especially Pour-Flush Toilets may cause groundwater and/or surface water contamination. Areas with high water tables and areas prone to floods present the greatest risk for groundwater pollution (Graham & Polizzotto, 2013). The risk of groundwater pollution by Dry Toilets is especially high in case the water table is as high or higher than the base of the pit (Barrett, 2002). Bacteria and viruses are of major concern due to their small size, and are therefore the most important pollutants together with nitrate (NO_3) which is especially important from a long-term perspective (Stenström et al., 2011; ARGOSS, 2002). Floods may cause pits to overflow, leading to potential surface water contamination and spread of pathogens in the environment (Stenström et al., 2011).

Risk mitigation

This technology for Collection & Storage/Treatment is generally not recommended for areas prone to floods and/or characterized by high water tables (Tilley et al., 2014; Gutterer et al., 2009). Werner et al. (2004) emphasize the fact that pit latrines and many other on-site sanitation systems hold back the solid fraction alone, while the aim is to infiltrate as much of the liquid into the ground as possible. Soluble elements including pathogens are washed out of the excreta and are transported with the liquid phase, which '*can be considered a highway to groundwater contamination*' (Werner et al., 2004, p. 26).

The vertical separation between the bottom of the pit and the saturated zone is most important in order to prevent groundwater contamination (Graham & Polizzotto, 2013). The hydraulic loading is a very important factor for the quantity of flow from a pit. If a system is operated with or without water is therefore critical (Krishnan, 2011). The British Geological Survey is distinguishing between low and high hydraulic loading, below and above 50mm/d, respectively. Simple pits, VIP latrines and Pour-Flush Toilets are all classified in the low hydraulic loading class (ARGOSS, 2001). Lewis et al. (1982) estimate that 1.3L of faecal fluids and 6L of flushwater accumulate per user and day, which sums up to a hydraulic loading of approximately 8mm/d for VIP toilets and 45mm/d for Pour-Flush Toilets when 5 users and a pit area of 0.8m² are assumed. Anyway, '[p]*our-flush latrines have a much higher hydraulic load than dry latrines and as a result have a greater pollution potential*' (Howard et al., 2006, p. 593). Sugden (2006, s.p.) deducts the general rule: '*The smaller the amount of liquid in the pit, the lower the risk of water point contamination*'. There may be still a significant risk that pathogens reach the groundwater even if hydraulic loadings are below 50mm per day, depending on the distance to the groundwater table (i.e. unsaturated zone) and on the grain size of the sediments (see groundwater contamination, p. 19). Thus, a minimum vertical distance of 5m is recommended for small grain sizes (silt and clay, fine sand with < 0.06, and 0.06 – 0.2mm, respectively) and > 10m for medium sand (0.2 – 0.6mm) in order to achieve a low to very low risk of groundwater contamination. Attenuation of pathogens in the unsaturated zone cannot be relied on in highly permeable unconsolidated sediments like coarse sand and gravels (0.6 – 2mm and > 2mm, respectively) and when sandstones, limestones or fractured rock is present (ARGOSS, 2001). Regarding vertical distances, '[c]*onditions at the end of the wet season should normally be used for design purposes as this is usually the time when the groundwater level is at its highest*' (Franceys et al., 1992, p. 38). Vertical distances are often not met in the field. Indeed it is common practice in the South Pacific region to dig pit toilets (Dry and Wet latrines) to the groundwater table. This leads to a direct contamination of the groundwater (Falkland, 2002). As a general rule, Dry latrines are better qualified to be implemented in areas with high water tables compared to Wet latrines. If Wet latrines are preferred, proper siting of the toilet is therefore critical (Howard et al., 2006).

Horizontal and vertical set back distances based on hydraulic loading and actual hydro-geological conditions are of high importance to protect the groundwater (Reed & Shaw, 2012d; Stenström et al., 2011; ARGOSS, 2001). See Table A.1 (Appendix, p. 111) for a literature review of recommended minimal horizontal distances between on-site sanitation and water supply facilities conducted by Lorentz et al. (2015). The suggested minimal lateral distance range from 6 to 90m, depending on the given conditions. The authors (p. 17) conclude that '*15.00 m, 30.00 m and 50.00 m are the most commonly accepted safe lateral spacings for on-site sanitation systems*'.

Another source of direct groundwater contamination may be seasonal fluctuations of the water table that cause water intruding into the pit. This can lead to saturated or partly saturated pit conditions (Mamani et al., 2014). A study in India has shown greater pollution travel distances of saturated Pour-Flush latrines (caused by a high groundwater level) in comparison to unsaturated latrines. The travel distances were further increased in sandy soils. The flow velocity of the groundwater was highest during the monsoon period (Banerjee, 2011).

Once pathogens reach the groundwater, they are transported with the groundwater flow. The travel distance is mainly dependent on the groundwater flow velocity and the ability of the pathogen to survive under the conditions (Krishnan, 2011). Bacteria and viruses have been observed of traveling up to several hundred meters in the groundwater (Lewis et al., 1982).

A common alternative for areas with a high groundwater table and/or flood-prone areas are raised pits, or technologies with watertight vaults above ground such as UDDTs or Composting Toilets (Stenström et al., 2011). Raised pits are usually more expensive in regard of construction and require additional maintenance to prevent seepage of effluent. Under certain circumstances (e.g. low permeability of soil) blackwater may seep through the sides of an earthen mound. The mound should be out of permeable soil with a stable, compacted side slope to prevent seepage percolating out of the sides (Franceys et al., 1992). Mbuligwe & Kaseva (2005) state that raised latrines even involve an increased risk of ground- and surfacewater contamination since the hydraulic gradient is increased by raising the pit. '*Also, the ponding that occurs around the pit latrine can raise the groundwater table to above the ground level. When it rains, the outcropping groundwater, which is essentially pit latrine effluent, is washed away with runoff* […]*, when it is not raining, the ponding around the latrine creates unsightly conditions* [… may] *attracting flies'* (Mbuligwe & Kaseva, 2005, p. 334). Furthermore, pits can be sealed to be apt under this conditions (ARGOSS, 2001; Graham & Polizzotto, 2013). Nevertheless, sealed pits require to be desludged and are therefore not a proper alternative for areas where this service is not available (e.g. rural areas of Vanuatu).

(EP$_6$) Contact with overflowing/leaking contents

Pits may overflow due to floods or heavy rainfall (Tilley et al., 2014). This can lead to the spread of pathogens in the surrounding area and the environment (Stenström et al., 2011). Flooded toilets are often prone to collapse (see EP$_7$, p. 36) and may be inaccessible during floods, which may lead to open defecation. Silt and/or debris transported with the floodwater may accumulate in the toilet, may causing the toilet to be permanently unusable (Uddin et al., 2013).

Risk mitigation

In case of squatting User Interfaces, the slab should be raised at least 0.15m above the surrounding surface level to prevent stormwater from entering the pit (Franceys et al., 1992). In case of pedestals, a watertight sealing between slab and the pedestal as well as slab and lining is important to impede stormwater intrusion.

Flood prone areas require specially adapted sanitation technologies to deal with this problem. Raised pit latrines are a common approach (Tilley et al., 2014; Stenström et al., 2011). UDDTs and Composting Toilets use watertight vaults built above ground and are therefore a viable alternative for flood prone areas (Sherpa et al., 2014; Rieck et al., 2012).

(EP$_7$) Falling into pit

Slabs may crack, break or topple, which can cause people falling into the pit (Reed & Shaw, 2012a; Stenström et al., 2011). A study of pit latrine slabs with 662 households in an urban setting (Dar es Salaam, Tanzania) revealed that 39.9% of the slabs were slightly cracked, 13.4% were badly cracked, and 6.2% had been collapsed already (Jenkins et al., 2014). '*In fact, one of the main causes of pit latrine failure is the collapse of the soil close to the surface causing the platform to fall into the pit*' (Reed & Shaw, 2012c, p. 3). Fluctuating groundwater levels can damage the walls of a pit, which may cause pits to collapse over time (Mamani et al., 2014).

Risk mitigation

Slabs out of concrete are most common. The slab should be either reinforced, or a dome design should be used to guarantee stability. Before mounting a newly constructed slab, a mechanical load test by having six people stand on the slab should be undertaken after a minimum curing time of seven days (CAWST, 2011).

The shape of the pit is either rectangular, square or circular (plan view). Pits with a circular shape have the best stability due to the natural arching effect. Furthermore, the surface is minimized, resulting in less consumption of materials in case a lining is applied (Reed & Shaw, 2012d). If a pit should be fully lined is determined by the diameter, depth, soil stability and whether it is planned to be used permanently. The top 0.5 – 1.0m of the pit should always be impermeably lined to support the weak soil layer near the surface, which is generally prone to collapse. The lining prevents animals from burrowing into the pit and provides a proper foundation for the slab and superstructure. A foundation prevents the lining from sinking in the ground (Reed & Shaw, 2012e).

Morgan (2009) recommends an airtight seal with low strength mortar between slab and lining. Another option is to seal potential gaps between slab, lining and surrounding ground with a mound out of soil (Reed & Shaw, 2012c). In doing so, it can '*reduce the risk of surface water infiltration to the pit, erosion and undercutting of the slab*' (CAWST, 2011, p. 29).

When a Pour-Flush User Interface is used, care about the orientation of the inlet pipe should be taken. The lining can be damaged over time if the pipe is oriented in a way that the discharged blackwater is hitting the wall (Reed & Shaw, 2012b). This is especially of concern in case of unlined pits because the earthen wall may erode quickly, which poses a major threat for pits to collapse.

Dry cleansing materials should not be used excessively, because this may cause pit walls to become clogged, leading to an improper infiltration rate of liquids (Stenström et al., 2011).

(EP$_{Other}$) Other exposure

Cracks in the slab may provide a habitat for parasites (Brikke & Bredero, 2003). Burrowing animals (e.g. rats, mice, rabbits) may enter the pit (Reed & Shaw, 2012e).

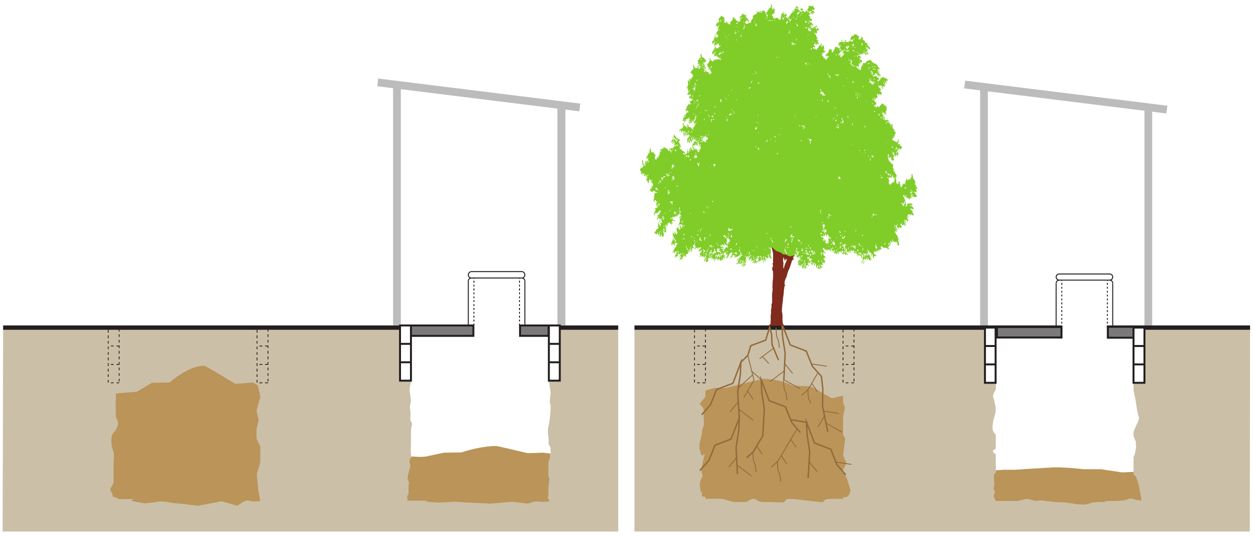
Risk mitigation

Checking the slab for cracks and repairing it if required should be part of the monthly inspection (Brikke, 2000). Lining the top 0.5m of the pit as recommended stops burrowing animals from entering the pit also (Reed & Shaw, 2012e). Sealing the gap between slab and lining with low strength mortar prevents rodents or cockroaches from possibly entering the pit via this way.

5.2.3. Use and/or Disposal

FILL AND COVER/ARBORLOO

When a pit reaches its end-of-life, it can be either emptied and the existing infrastructure is continued to be used, or it is abandoned and a new pit has to be dug. A pit is considered to be full when it is filled to approximately 0.5m below the slab (Pickford & Shaw, 1997). The pit is simply covered with soil after the superstructure, slab and ring beam is moved to the site where the new pit will be dug (Figure 17, left).
A special case of this simple Use and/or Disposal technique is called 'Arborloo' (tree toilet) and is used in some African countries (e.g. Ethiopia, Mozambique, Zimbabwe) (Figure 17, right).



Option 1

Option 2

Figure 17: This system is based on the simplest option for Use and/or Disposal, Fill and Cover/Arborloo. The Single Pit or Single VIP is covered with soil and a new one is dug. The abandoned pit is either simply left alone (Option 1) or a tree is planted (Option 2) which is also referred to as Arborloo (Tilley et al., 2014, p. 140, adapted).

Arborloos are based on shallow Dry pits that are used for approximately 6 to 12 months. After moving the toilet components (superstructure, slab, ring beam) and covering the pit, a tree or vegetables are planted. Similar to UDDTs or Composting Toilets, a cup of ash or soil is used after each bowel movement to cover the faeces. Before the pit is used the first time, leaves are put at the bottom of the pit and, if available, some leaves are added from time to time to increase the air content and porosity in the pile. The Fill and Cover/Arborloo option is only possible in areas with sufficient space to continuously dig new pits. The contents of an abandoned pit may pollute the groundwater as long as it is not completely decomposed (Tilley et al., 2014).

Situation in Vanuatu

Fill and Cover of full pit latrines is the prevalent technique of Use and/or Disposal of pit-based systems in Vanuatu (‘bush toilet’, Single Pit Dry Toilet, Single VIP Dry Toilet and Single Pit Pour-Flush) (Kassis, 2010).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1, EP_2, EP_3 EP_5

(EP_1, EP_2, EP_3) Ingestion of excreta; Dermal contact; Contact with flies/mosquitoes

The risk of pathogen transmission is generally low (especially in comparison to pit emptying), as the executer does not come into contact with the contents (Tilley et al., 2014). There is a risk of animals burrowing into, flies escaping of or people sinking in the backfilled pit (Reed & Shaw, 2012d). In the worst case, people may fall into un- or badly covered pits.
In case of an Arborloo, an additional risk during the planting of the tree may occur (Stenström et al., 2011). Pathogens may be transmitted during removal of the slab and the ring beam.

Backfilled pits include also the risk of being dug up during development of the site for new structures by people who are unaware about the abandoned pit (Still & Foxon, 2012). Moreover, a considerable amount of excessive liquid may be spilled during the decommissioning of wet pits, which may cause the surrounding area to be contaminated (Harvey, 2007).

Risk mitigation

It is important to stop using the toilet if the distance between the content and the slab is approximately 0.5m (Reed & Shaw, 2012d). After moving the superstructure, slab and ring beam (equipped with proper PPE), the pit has to be properly covered and compacted with a sufficient amount of soil. The volume of the contents is reduced over time as it is degrading slowly. Hence additional soil should be added from time to time (Stenström et al., 2011). By having the pit covered with a sufficient soil layer of approximately 0.5m, the area is safe to walk over, animals are prevented from burying into the pit and potential fly larvae in the pit are not able to escape. When the users continue to use the toilet despite reaching the recommended distance of 0.5m below the slab, the content may splash and soil the User Interface or the user itself, and flies and/or odours may increase significantly (Reed & Shaw, 2012d). In the case of wet pits, an overflow trench may be required to absorb abundant fluids when the pit is backfilled. The amount of fluid can be substantial, hence the trench has to be adequately sized and can be either implemented around the pit or in form of a single line drain. The favorable time for decommissioning is after the dry season, as the pit is likely to be drier compared to the wet season (Harvey, 2007). The area of the abandoned pit should be clearly marked (Tilley et al., 2014).

(EP_5) Contaminated groundwater/surface water

There may be an ongoing groundwater contamination by the pit contents. This risk is especially considerable in water logged areas (Tilley et al., 2014; Still & Foxon, 2012; Stenström et al., 2011).

Risk mitigation

Before backfilling the soil into the pit, lime can be added to aid inactivation of pathogens via high pH-values (UNHCR, 2014). Lime is the common name for either Calcium Oxide (CaO; quicklime) or Calcium Hydroxide ($Ca(OH)_2$; slaked or hydrated lime), an alkaline powder made by heating limestone (Tilley et al., 2014). Either highly acidic or alkaline conditions speeds up breakdown, because many microorganisms are well adapted for a neutral pH-value. It is recommended to add 15–20kg lime to the pit before backfilling (UNHCR, 2014).

Disinfectants should not be added to the pit because they may hamper the inactivation of pathogens. Besides, adding organic matter (e.g. wood chips) is beneficial for bacteria growth by providing carbon and increasing porosity. Bacterial growth can be further enhanced by increasing pH and surface area via admixing other materials like crushed cement blocks. These measures are recommendations for decommissioning pit latrines of (temporary) camps (UNHCR, 2014). Nevertheless, these measures could be practicable on household level too, especially to minimize potential groundwater pollution in areas with high water tables.

5.3. Double Vault Urine-Diverting Dry Toilet

This ‘Waterless System with Urine Diversion’ operates without water and is based on the separate collection of faeces and urine. Separate collection is achieved via the Urine Diverting Dry Toilet User Interface, a Urinal can be used optionally. Double Dehydration vaults are used alternately for the Collection, Storage and Treatment of faeces. Urine is either collected in a Urine Storage Tank to be reused or it is disposed of. Figure 18 gives an overview of the system.

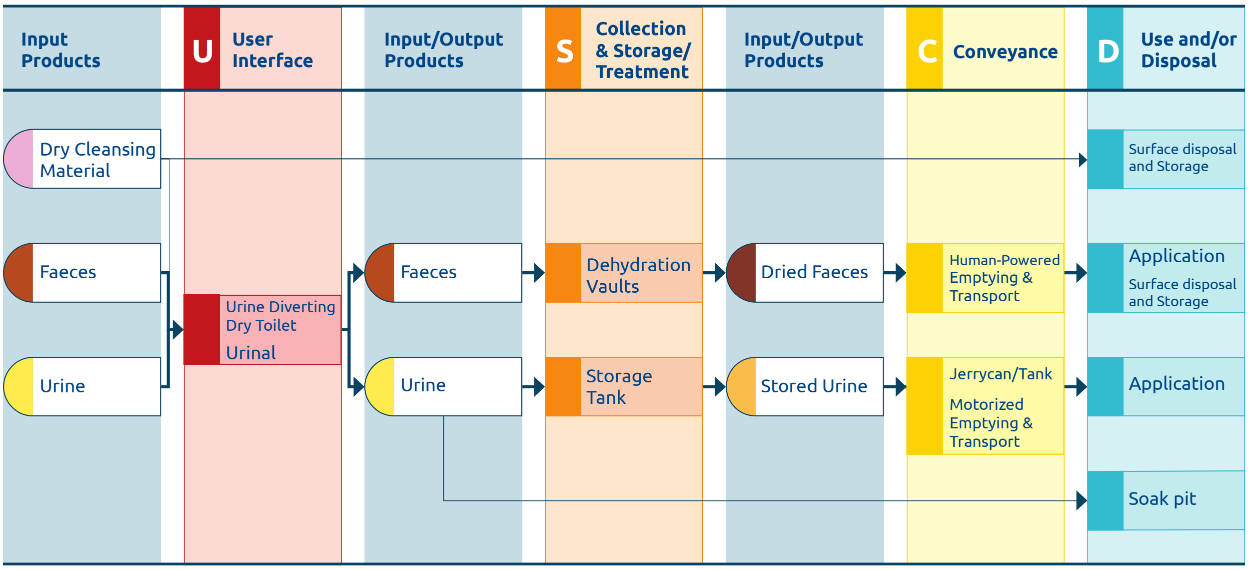


Figure 18: System overview of a Double Vault Urine-Diverting Dry Toilet (UDDT) (Tilley et al., 2014, p. 26, adapted).

The sanitization of faeces is based on desiccation. It is therefore of high importance to prevent additional water or urine from entering the vaults. Cover material (e.g. dry soil, sand, saw dust, lime, rice husks, leaves, compost, or wood/kitchen ash) is added after defecation to enhance dessication, prevent odours and act as a barrier against vectors. Some cover materials increase the pH-value which improves pathogen inactivation significantly. The ventilation pipes are primarily used to remove humidity, but also to prevent odours and to control vectors.

Since odours and vector infestation occur usually only in case of improper operation and maintenance, this system can be built inside or next to a house (Deegener et al., 2015).

Conveyance (Emptying and Transport) is usually human powered, but mechanical emptying (urine) and vehicular transport (urine, faeces) is possible. Urine and faeces can be either reintegrated in the metabolic cycle by reusing them, or they are disposed of (Use and/or Disposal).

A post-treatment of dehydrated and stored faeces is generally recommended but optional if the material is considered to be reused. The hygienic risk during consumption of produce can be reduced to acceptable levels if vaults are properly managed (moisture content; pH-value) and sufficient storage times, as well as proper application measures (e.g. application technique, crop restriction, withholding period) are adhered to (see Treatment, p. 46 and Application, p. 65). The simplest way to treat urine is by storing it in jerry cans or a tank. Cleansing materials are either thrown into the vault or collected separately, depending on the type of material and whether the faeces is to be reused or not (Tilley et al., 2014; Rieck et al., 2012).

Beside UDDTs with Double Dehydration Vaults, there are also designs with single vaults and interchangeable containers, which include a subsequent, external treatment. Further UDDTs using dedicated containers for faeces composting (i.e. Single Vault Composting Toilet with UD and interchangeable containers) and UDDTs with faeces mineralization in shallow pits (i.e. Urine-Diverting Ventilated Improved Pit; UD-VIP) can be distinguished. In the latter case, the substructure is moved to a new pit when the currently used pit is full, and a tree is planted (i.e. Fill and Cover, Arborloo, p. 37). UD-VIPs are recommended to be used primarily for areas with low water tables and a low risk of flooding (Rieck et al., 2012). Containerized systems (i.e. single vaults with interchangeable containers) have some advantages and some major drawbacks in comparison to double vault UDDTs (see Rieck et al., 2012, p. 5). This type of system has been excluded in this context due to multiple reasons: (i) there is no significant reduction of pathogens in the container, (ii) owners often do not want to handle fresh faeces (service providers are recommended), (iii) frequent emptying requires reliable and qualified handling of faeces and adequate treatment centers, (vi) costs for collection and treatment may be higher compared to double vault systems, and (v) emptying, treatment and disposal constitute a major health risk due to potential contact with fresh faeces (Rieck et al., 2012). Nonetheless, containerized systems may be a good option under other circumstances like in urban environments. An example for a successfully implemented single-vault system with centralized collection and treatment is documented from Haiti. The well managed centralized composting of the faecal material has proven to effectively inactivate *E. coli* and *Ascaris* within 4 months (Berendes et al., 2015).

5.3.1. User Interface

The centerpiece of this system is the Urine-Diverting Dry Toilet User Interface, a Urinal may be used optionally. The risk of infection relates to individual behaviour of the users, handling of anal cleansing material and the cleanliness of the toilet. The person who cleans and/or maintains the toilet is always at risk, which depends on the degree of contact, proper completion of the task and hygienic measures during and after the implementation (Stenström et al., 2011).

URINE-DIVERTING DRY TOILET

The Urine-Diverting Dry Toilet User Interface is operated without water and is designed to divert urine and faeces in two separate outlets (UD flush toilets are also available). A bowl in the front of the toilet or pan is capturing the urine, draining it off to a storage container or infiltrating it into the ground. The faeces drops directly in the collection vault through the drop hole in the back of the toilet or pan. Depending on the preferred posture of wipers during defecation, the interface can be either in form of a floor mounted Squatting toilet, or a floor mounted or wall hung Sitting toilet (Figure 19, Option 1 and 2, respectively) (Münch & Winker, 2011). Squatting pans can be adapted with an extra outlet for washers (Figure 19, Option 3; Figure 20, Squatting toilet, left) or a separate anal washbasin is implemented (Rieck et al., 2012). This option is not included in the analysis since anal washing is not common in Vanuatu. Single drop-hole squatting pans (one outlet for urine, one drop-hole for faeces) have to be moved when the vault is alternated, twin drop-hole versions (one urine outlet in the middle, two drop-holes for faeces, the hole of the unused vault is covered) can be mounted and sealed permanently. Further, UD inserts similar to squatting pans can be mounted on a bench to be used like a pedestal style interface (Figure 20, bench style). A tight-fitting lid is used to cover the interface (Hoffmann, 2012; Rieck et al., 2012).

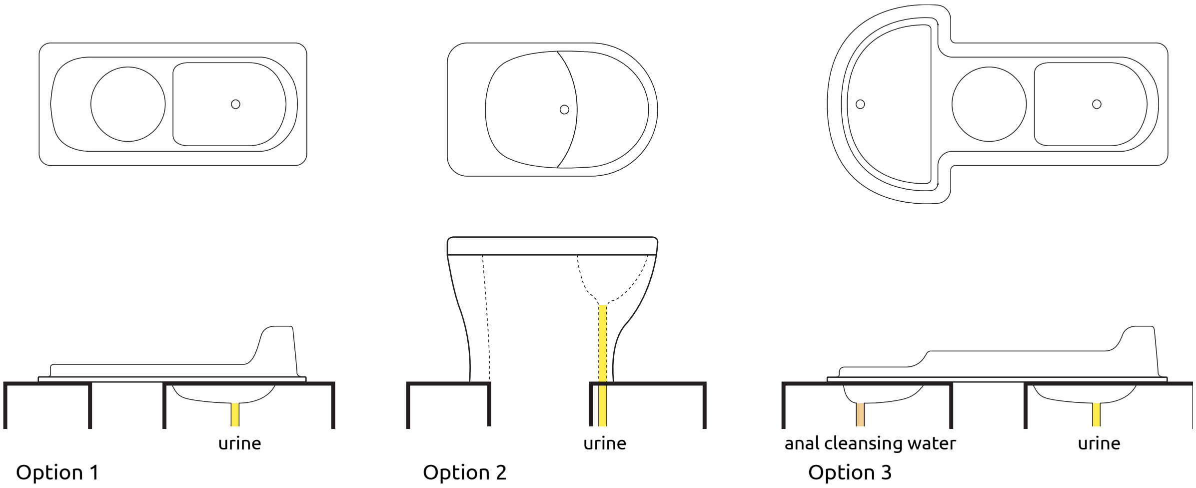


Figure 19: Schematic overview of the Urine-Diverting-Dry Toilet User Interface for wipers (Option 1: squatting toilet, Option 2: sitting toilet) and washers (Option 3: squatting toilet with anal washing basin) (Tilley et al., 2014, p. 46).

Figure 20: Overview of various designs of Sitting toilets (pedestal and bench style) and Squatting toilets (Rieck et al., 2012, p. 8, adapted).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1 EP_2 EP_3 EP_8 EP_{Other}

(EP_1) Ingestion of excreta

See exposure pathways of Dry Toilet User Interface, EP_1, p. 24 (except for VIP related pathway). Besides, faeces may be present in the urine section of the interface, exposing the person responsible for cleaning (usually the user) during removal (Stenström et al., 2011). Like the receptacle used to flush a Pour-Flush toilet, a vessel (scoop, cup) or garden trowel is used to cover the faeces with cover material after defecation. This presents an obligatory contact with a potentially soiled surface. Another potential point of exposure exists during the moving of the interface when the vaults are alternated.

Risk mitigation

Regular cleaning is important to mitigate exposure (Stenström et al., 2011). Therefore, the User Interface should be easy to clean, but also durable and resistant to malfunction, simple to use and aesthetically pleasing. Materials like plastic, fiber-glass, ceramic or sealed concrete are used to manufacture the interface (Rieck et al., 2012). Care should be taken that neither cleaning water, nor detergents or disinfectants enter the vaults during cleaning. Standard safety measures like using gloves, followed by hand washing should be applied during cleaning procedures (Stenström et al., 2011). The design of the interface should prevent faeces from falling into and clogging the urine collection bowl (Tilley et al., 2014). A moveable seat adapter for small children may be necessary to ensure a proper separation of faeces and urine in the designated sections of the interface. The toilet cubicle should have a minimum dimension of 90 × 120cm to minimize potential contact with soiled surfaces and allow the users to move freely. Additional space has to be calculated for disabled persons (e.g. wheelchair users). A minimum distance of 30cm between User Interface and walls as well as doors are recommended to prevent unintentional body contact with surfaces. The cubicle should be well lit during day hours (e.g. through windows or openings) and should be artificially illuminated at night ideally. Well lit cubicles reduce unwanted surface contact due to bad spatial orientation (Rieck et al., 2012). Research in Tanzania indicates significant lower

E. coli concentrations at slabs, walls, doors and roofs if materials of higher quality are used, due to improved cleanability and less hospitality for pathogens to grow (Exley et al., 2015).

It is important to properly clean the vessel used to apply the cover material during regular cleaning routines. Rieck et al. (2012) recommend heavy receptacles for the storage of the cover material, because these are less likely to slide or fall over, enabling a more hygienic, one-handed contact during application.

Standard PPE should be used when the interface is changed during vault alternation. This course of action offers further a good occasion to thoroughly clean the interface.

(EP$_2$) Dermal contact

See exposure pathways of Dry Toilet User Interface, EP$_2$ (p. 24).

Risk mitigation

See risk mitigation measures of Dry Toilet User Interface, EP$_2$ (p. 24).

(EP$_3$) Contact with flies/mosquitoes

Flies and mosquitoes may enter the vault via the User Interface (Rieck et al., 2012). There is also a low risk of exposure from flies or mosquitoes that are attracted by a badly maintained User Interface (Stenström et al., 2011). Misuse of the interface, either intentional (e.g. men refuse to sit on pedestals during urinating) or unintentional (e.g. visitors unfamiliar with this type of toilet), can lead to wet vaults causing vector infestation (Tilley et al., 2014; Münch & Winker, 2011; Muchiri & Mutua, 2010).

Risk mitigation

See risk mitigation, EP$_3$ of the Dry Toilet User Interface (p. 24). Although vectors are usually not of concern, it is recommended to cover the User Interface with a tight-fitting lid. This measure helps to prevent infestation from the outset and reduces potential odours (Rieck et al., 2012; ESF, 2007). Keeping the vaults dry is important in order to prevent infestation of vectors. Therefore the design of the interface should prevent splashing and spraying of urine into the faeces area (Tilley et al., 2014). Nevertheless, some urine may find its way into the vaults when women are urinating. This is usually only a small amount and does not affect dehydration (additional cover material may be applied in case of concerns) (Rieck et al., 2012). Squatting pans should be either raised approximately 2cm above floor level or have a rim to prevent water from entering the vault during cleaning the floor (ESF, 2007). Intentional misuse may occur when men refuse to sit during urination. A measure to prevent wetting of the faecal matter is to install a Urinal (p. 43) (Tilley et al., 2014). Instructions how to use the toilet displayed in or in front of the cubicle may reduce unintentional misuse by unfamiliar users.

(EP$_8$) Ingestion of urine

Splashing of urine from a UD interface may lead to the contamination of other surfaces (Stenström et al., 2011). Urine precipitates if it stands stagnant (see below and Equation 2 & 3, p. 53). By that way, urine stone and slimy, viscous residues can develop, which may cause urine pipes to become blocked (Rieck et al., 2012). This involves a risk for the person responsible for maintaining the pipe (Stenström et al., 2011). Blocked urine pipes, but also cover material, toilet paper or faeces clogging the urine drainage funnel may cause urine to accumulate in the UD section (Rieck et al., 2012). This exposes the removing person and users to untreated urine in the UD section. In the worst case, the urine spills over and wets the vault contents or soils the floor (depending on the interface design).

Risk mitigation

Urea from excreted urine is degraded by the enzyme urease (see Equation 2, p. 53), which increases the pH-value to 9 – 9.3 and leads to the precipitation of urine contained phosphate, magnesium, calcium and ammonium. Struvite ($MgNH_3PO_4$) and apatite ($Ca_{10}(PO_4)_6(OH)_2$) are formed (Jönsson et al., 2004). This results in either hard incrustations (urine stone; mainly found in inner walls of pipes and pipe bends) or soft, viscous precipitates (deposits in near-horizontal pipes; accumulation in tank in form of sludge). Waterless systems tend more to soft deposits and less to hard incrustations, water-based systems it is the other way around (Münch & Winker, 2011). Hence, it is important to design the piping in a way that blockages and the associated risk are minimized. Drangert (2010, p. 2) recommends to install the piping '*as vertical as possible* [… to prevent] *unnecessary problems with crystallization*'. A minimum slope of at least 4% should be satisfied, the total length of the piping should be kept as short as possible. The insides of the piping should be smooth, sharp bends of 90° angle should be substituted by two 45° bends to maximize the flow rate of urine and potential sediments (Kvarnström et al., 2006). The pipes should have minimal diameters of 25 – 35mm for vertical, and 45 – 70mm for all other sections (Drangert, 2010). Couplings with inspection ports are recommended to allow the piping to be inspected and cleaned. Ensuring watertight connections (e.g. glue, rubber grommet) is important to avoid leakage. Pipes out of metal should not be used, since urine is very corrosive. Rigid (preferred) or semi-rigid pipes out of (plasticized) polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) or unplasticized PVC (uPVC) can be used. Pipes may get brittle if exposed to the sun, hence it is recommended to coat them with UV resistant paint. Rods, wires or mechanical snakes are used to unblock pipes mechanically. A bottle cleaning brush can be used to clean precipitates, slime or scrub (Rieck et al., 2012). Persistent impurities can be removed by pouring hot water and caustic soda into the system (Drangert, 2010). It is obvious to remove objects clogging the urine drainage funnel by applying PPE followed by hand washing. The User Interface should be removed for this undertaking to allow thorough cleaning in order to minimize potential faecal contamination of the collected urine. Furthermore, the design of the interface should prevent splashing and spraying of urine to adjacent surfaces.

(EP_{Other}) Other exposure

Cross-contamination of urine by faecal matter may occur at the User Interface and involves a significant health hazard if the urine is applied as fertilizer (Stenström et al., 2011). A potential cross-contamination depends on the actual design of the interface, '*usage and maintenance patterns, and disposal processes, in addition to local cultural practices. For example, whether or not children use the UDDTs, especially during an active gastrointestinal infection, will influence the pathogen profile of the collected waste*' (Bischel et al., 2015, p. 61).

Risk mitigation

Education and information about the importance of preventing faecal contamination and the related risks may help to raise awareness to decrease cross-contamination due to misuse. Moveable seat adapters like stated in Rieck et al. (2012) may limit the risk of contamination by children. If urine is supposed to be utilized despite cross-contamination is likely, prolonged storage times, alternative treatment, disposal (infiltration, evapo-transpiration), or restricted reuse are options to mitigate the risk. In case there is a need for contamination-free urine, exclusive collection via urinals should prevent cross-contamination in the first place.

URINAL

Urinals are used to collect urine exclusively. This interface is mainly used by men, specially designed urinals for females are also available but its acceptance is rather low (e.g. different requirements on privacy due to the need to partially undress) (Münch & Dahm, 2009). Urinals are usually well accepted by men, especially because there is no need for behaviour change. Hence, urinals may contribute to a better acceptance of this system (Tilley et al., 2014).
Urinals can be operated with or without water for flushing (Figure 21). Using water to flush urinals is beneficial regarding cleanliness and limited odours (water seal) (Tilley et al., 2014). Nevertheless, the dilution of urine with water hampers pathogen die-off and should be therefore avoided (Schönning & Stenström, 2004). For the collection of undiluted urine, waterless urinals are necessary. Waterless urinals do not require much space since they are usually wall hung, and no additional piping for water supply or any flushing devices are needed. Squatting urinals installed on the floor (i.e. squatting toilet without a drop hole for faeces) are used in some parts of the world and are suitable to be used by women as well (Münch & Winker, 2011).

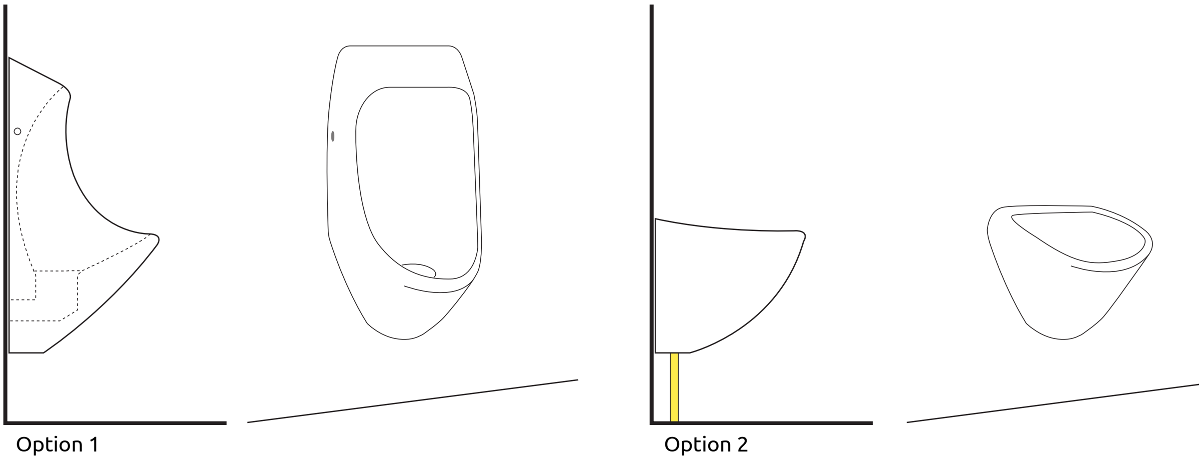


Figure 21: Urinals can be operated with or without water for flushing (Option 1 and 2, respectively). Beside the shown wall-mounted type, squatting version are used in some areas (Tilley et al., 2014, p. 48, adapted).

Waterless urinals require regular cleaning and a proper odour seal in poorly ventilated superstructures (especially indoor installations) (Rieck et al., 2012; Münch & Winker, 2011). A basic liquid seal to control odours is given by submerging the urine collection pipe close to the bottom of the urine tank (Tilley et al., 2014). By doing so, ammonia evaporation is minimised, resulting in a higher nitrogen content and thereby better fertilizer quality (Stenström et al., 2011). There are other low-cost measures to reduce or prevent odours like charcoal placed in the urine bowl, condoms attached to the pipe (primed with holes or cut apart; bad performance in warm climates), table tennis balls (floats when urine passes, otherwise seals underlying pipe with smaller diameter) or more complex options like liquid sealants (floats on top of urine in a trap) (Deegener et al., 2015; Rieck et al., 2012; Münch & Winker, 2011). A seal should be checked regularly if it is working properly (Tilley et al., 2014).

Low-cost urinals made out of e.g. recycled water buckets, to more expensive solutions out of fiber-glass reinforced polyester, stainless steel, acrylic or ceramic are available (if plastic is used, linear low density polypropylene plastic has very good characteristics) (Münch & Winker, 2011). Due to convenience, households prefer urinals installed inside of the toilet structure (Rieck et al., 2012).

Urinals are a measure to decrease the risk caused by intentional or unintentional misuse of UDDTs by men (see above, p. 42). Besides, it has been documented that men refused to use the toilet for urinating and continued to urinate outdoors (SOIL, 2011). It is therefore advisable to install urinals if this system is used in cultures where men do not like to sit while urinating (Deegener et al., 2006). Urinals can have a '*large impact on the well-being of a community. When men have access to a urinal, they may urinate less often in public, which reduces unwanted odours and makes women feel more comfortable*' (Tilley et al., 2014, p. 49). Research in South Africa has shown that 51% of men (n= 8101) use urinals when provided (Roma et al., 2013).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_8

(EP_8) Ingestion of urine

See EP_8 of UDDT User Interface, p. 42. The main pathway of urinals is the potential contamination of other areas through splashing of urine (Stenström et al., 2011). '*In waterless UD systems, more soft deposits tend to occur than hard incrustations, whereas for water-flushed UD systems it is the other way around*' (Münch & Winker, 2011, p. 11).

Risk mitigation

See measures for risk mitigation of UDDT User Interface, EP_8 (p. 42). Spraying and splashing of urine can be further reduced by placing a small target or painting a fly near the drain of the urinal (Tilley et al., 2014).

5.3.2. Collection and Storage/Treatment

The subsequent risk during handling and application of the faeces and/or urine relies on the pathogen removal achieved in the course of collection and storage. A focus of this section lies therefore on factors, conditions and technical details influencing pathogen removal and its efficiency.

DOUBLE DEHYDRATION VAULTS

Double Dehydration Vaults are used for collection, storage and sanitization of faeces. The vaults have to contain faeces safely to ensure a hygienic separation from human contact. The treatment is mainly achieved by desiccation, the watertight construction of the vaults is therefore of high importance to prevent the penetration of water and moisture. The volume of the vaults have to provide enough capacity to contain faeces, toilet paper and cover material from all users for a defined, minimum storage time. When the currently used vault is filled up, the User Interface is moved to the other one, which is used from then on. The drop hole of the inactive vault is covered and the faecal matter has time to undergo sanitization. When this vault is full as well, it is decommissioned, and the inactive vault is emptied and used from then on again. Handling of the dried faeces is easy, especially in comparison to faecal sludge. Depending on the intended use and the resting time, it is either disposed of or reused as soil conditioner (post-treatment is optional on household level; see Chapter 5.3.4, p. 59) (Tilley et al., 2014; Rieck et al., 2012; Stenström et al., 2011). Figure 22 shows a schematic of Double Dehydration Vaults.

The median value of excreted faecal wet mass in low income countries is 250 g/cap/day (range: 75 – 520 g/cap/day), corresponding to a median dry mass of 38 g/cap/day. Total food intake, body weight and diet are the major factors influencing the faecal mass. The median H_2O content of faeces is 75%, vegetarian diets have higher median values (78.9%) as compared to diets with less fibre and more protein (72.6%). Persons with diarrhea can excrete up to five times the wet faecal weight compared to healthy persons (Rose et al., 2015).

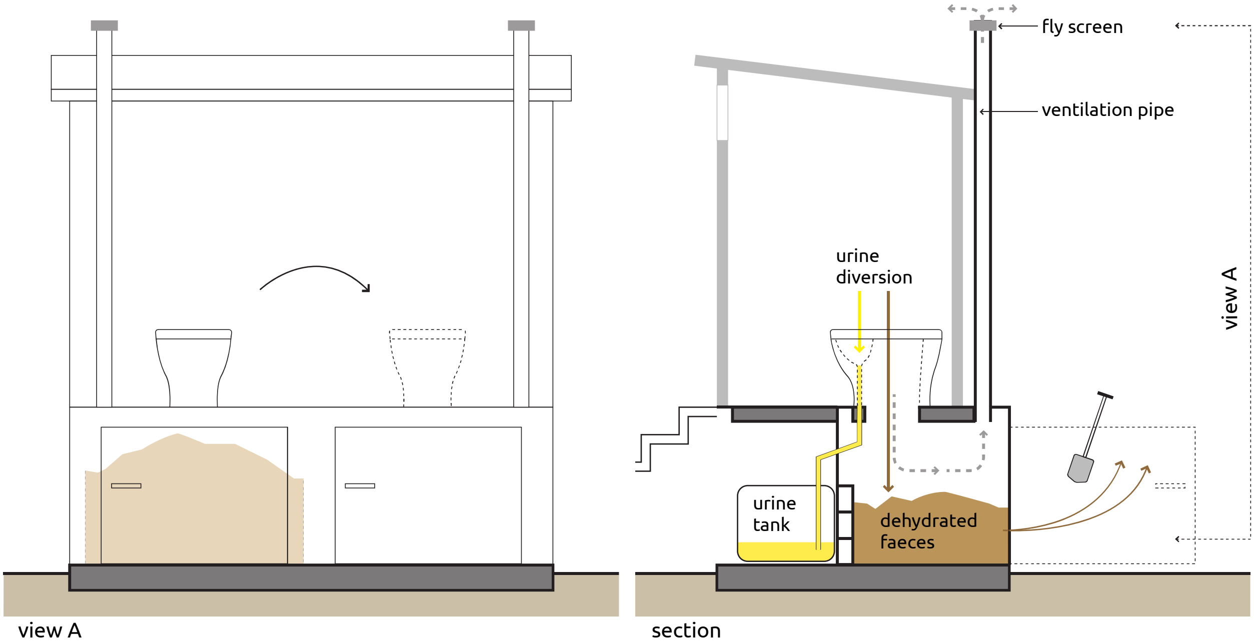


Figure 22: Schematic overview of Double Dehydration Vaults for Collection and Storage/Treatment (Tilley et al., 2014, p. 70, adapted).

TREATMENT

The primary treatment of faeces takes place in the vault during the collection period and is mainly based on desiccation and ideally high pH-values. Primary treatment fulfils three objectives, in particular to decrease (i) the hygienic risk, (ii) the risk of fly infestation, and (iii) odours. Secondary treatment occurs in the storage period, in case of Double Dehydration Vaults this happens in the vaults as well (e.g. versus single vaults with interchangeable containers where secondary treatment is off-site) (note: primary and secondary treatment in regard of UDDTs is sometimes used fuzzy; other sources may term primary and secondary treatment as primary, and post-treatment as secondary treatment). The objective of the secondary treatment is to get a (i) hygienically safe product in the end, which is (ii) free from odours, and (iii) visually non-repulsive (Jönsson et al., 2004). The effectiveness of the treatment is very important for the risk of pathogen transmission during obligatory emptying of the vaults and subsequent disposal or reuse of the material. Hence, this issue is going to be discussed in more detail, including technical recommendations to ensure proper conditions for the treatment.

It has to be made clear beforehand, that it '*is not the objective to achieve a complete pathogen removal in the faecal material, including inactivation of all helminth eggs, as literature suggests that this cannot be guaranteed under ordinary circumstances with any type of UDDT*' (Rieck et al., 2012, p. 4). Nonetheless, research indicates that well managed vaults achieving low moisture contents and the application of plant or kitchen ash as pH-elevating cover material may able to inactivate pathogens (including *Ascaris* ova) within a reasonable time in warm climates.

Four important factors determine the reliability of the treatment in Double Vaults to achieve a dry, safe to handle, sanitized and odourless product: (i) duration of storage, (ii) moisture content, (iii) pH-value, and (iv) temperature. The first two factors are easier to control in comparison to the latter two (Rieck et al., 2012).

(i) Duration of storage:

The storage period starts from the moment when the last faeces has been added to the vault (Deegener et al., 2015). Most of the pathogens are well adapted to, and die-off naturally over time without the conditions present in the human intestines (except helminth eggs) (Rieck et al., 2012). '*After defecation, the faecal pathogen load is naturally reduced through antagonism, competition and consumption by other microorganisms, as well as by the action of antibiotics*' (Niwagaba, 2009 as cited in Rieck et al., 2012, p. 15). The minimum storage time to limit the exposure risk cannot be determined as a rule of thumb, valid for all regions. Generally spoken: the longer the storage time, the higher the pathogen die-off due to a lower moisture content, potential beneficial temperatures and favourable pH-values (Rieck et al., 2012). Recommendations by WHO (2006a) regarding minimum storage times of dry excreta depend on temperature and alkalinity of the material (Table 10).

Table 10: Recommended minimum storage times of dry excreta and faecal sludge stemming from small-scale systems, before the product can be used at household or municipal level (WHO, 2006a, p. 56).

Treatment	Criteria	Comment
Storage; ambient temperature 2 – 20 °C	1.5 – 2 years	Will eliminate bacterial pathogens; regrowth of *E. coli* and *Salmonella* may need to be considered if rewetted; will reduce viruses and parasitic protozoa below risk levels. Some soil-borne ova may persist in low numbers.
Storage; ambient temperature > 20 – 35 °C	> 1 year	Substantial to total inactivation of viruses, bacteria and protozoa; inactivation of schistosome eggs (< 1 month); inactivation of nematode (roundworm) eggs, e.g. hookworm (*Ancylostoma/ Necator*) and whipworm (*Trichuris*); survival of a certain percent-age (10 – 30%) of *Ascaris* eggs (≥ 4 months), whereas a more or less complete inactivation of Ascaris eggs will occur within 1 year.
Alkaline treatment	pH > 9 during > 6 months	If temperature > 35 °C and moisture < 25%, lower pH and/or wetter material will prolong the time for absolute elimination.

The annual average temperatures in Vanuatu are between 23.5 and 27 °C (Australian Bureau of Meteorology & CSIRO, 2011a). A minimum storage time of more than one year is recommended for such mean ambient temperatures, before it may be reused directly without addtional post-treatment. The WHO guidelines state that even *Ascaris* eggs may be completely inactivated after this period of time (WHO, 2006a). The storage time is directly linked to the dimension of the vaults and the time needed until one vault is full. This in turn, depends on the number of users and the estimated faecal accumulation rate per person. Besides, regional factors such as diet and mean humidity, but also visitors, type and amount of cover material used, space for air flow and piling of faeces have to be considered when vaults are dimensioned (Tilley et al., 2014; Rieck et al., 2012; Franceys et al., 1992).
A greater size of the vaults allow longer storage times and will therefore increase the safety of the output material.

(ii) Moisture content:

Most of the pathogen die-off in UDDTs is due to desiccation (i.e. dehydration) (Endale et al., 2012). Without moisture, there is usually no or only little odour and no fly-breeding, organisms cannot grow, and pathogens die-off (Tilley et al., 2014). UDDTs with Double Dehydration Vaults are able to reach values below 25% moisture content like stipulated by the WHO guidelines (Table 10). The moisture content of fresh faeces is approximately 80%, separation of urine at the source enables the faeces to dry quickly. Dehydration starts as soon as the faeces drops into the vault and proceeds during the collection and storage phase until the vault is cleared. Dehydration takes place by vapour leaving through the vent pipe and due to cover material added after defecation (Rieck et al., 2012). Some cover materials are also able to increase the alkalinity of the vaults contents which improves sanitization significantly (see below). Beside its sanitizing effect, cover material is also able to control flies by blocking the access to the faecal material, and again, via moisture reduction (Austin, 2007).
Moisture contents < 30 – 40% lead to an increased die-off of microorganisms (except *Ascaris* ova survive levels up to 5%) (Feachem et al., 1983). Endale et al. (2012, p. 753) showed that '*a large number of Ascaris eggs were inactivated* [… at a moisture level of 3%]*, even in the absence of alkaline treatment*'. 54.8% of faecal coliforms and 80.8% of *Ascaris* eggs were inactivated after 40 days. Mixing faeces with wood ash or lime (1:3) resulted in a complete removal of faecal coliforms and *Ascaris* in the same period (Endale et al., 2012).
Disposal of toilet paper into the vault is likely to increase dehydration additionally (Rieck et al., 2012). Nonetheless, the toilet paper will not break down regardless of time, because decomposition of organic material is very limited when the humidity is (very) low. Moreover, organic waste or plants should not be thrown into the vaults because these increase the moisture input additionally (Water Aid, 2011).
Besides the central element of urine diversion, it is important to build the vaults above ground and to prevent the intrusion of rain- and floodwater (Rieck et al., 2012). Double vaults can be adapted to be suitable in regions prone to floods (see below, p. 51) (Tilley et al., 2014; Uddin et al., 2013; Rieck et al., 2012).
Ventilation of the vaults is important to dissipate humidity and omit odours. Either one or two vertical pipes are used for that purpose, but it is strongly recommended to use two independent pipes (Rieck et al., 2012). Pipes out of PVC, PE, metal or concrete can be used (Morgan & Shangwa, 2010). The piping should be straight without bends to minimize friction (Rieck et al., 2012). The end of the pipe(s) should protrude at least 50cm above the roof and adjacent obstacles (e.g. trees, roofs), and have a minimum diameter of 100 – 150mm. Areas with very high humidity may require even larger diameters up to 250mm (Winblad & Simpson-Herbert, 2004; Esrey et al., 1998). It is recommended to use pipes with a diameter of at least 150mm to reach sufficient air volumes greater than 20m³/h for wind and stack effect independently. Research has shown that pipes with 100mm had about half of the air volume exchange per hour as compared to pipes with 150mm. Moreover, a rotary vent turbine would be able to increase the rate of evaporation substantially (Ntabadde, 2004). The end of the pipe(s) should be finished with a cap or T-joint to prevent rainwater entering the vault(s),

a fly screen traps vectors in the vaults (screens should be resistant to corrosion, out of e.g. aluminium or stainless steel) (Hoffmann, 2012; Morgan, 2009). See Chapter 5.2.2 (p. 28) for more details about vent pipes, Figure 37 (p. 82) shows poor examples from ventilation systems of Composting Toilets in Vanuatu.

(iii) pH-value:

Most pathogens are adapted to neutral pH-values around 7. Adding alkaline cover material (e.g. ash, lime, urea) supports pathogen die-off by increasing the pH-value. Alkaline conditions above a pH of 9 are significantly reducing the pathogen load, values of 11 – 12 enable rapid inactivation (Schönning & Stenström, 2004). Alkaline conditions with pH-values > 12 are sufficient to inactivate Ascaris eggs within 3 months (Eriksen et al., 1996). Studies suggest that effective inactivation of *Ascaris* can be achieved in the field within reasonable storage times when high pH-values are met (see Table A.2, Appendix p. 112) (Endale et al., 2012; Jiayi & Junqi, 2001; Lan et al., 2001; Chien et al., 2001; Carlander & Westrell, 1999; Wang et al., 1999). Nevertheless, Schönning & Stenström (2004) conclude that the findings of some studies are contradictory to some extent. Rieck et al. (2012) remark that elevated pH-values > 9 are not reliably reached in practice throughout the whole pile, and sufficient amount of alkaline cover material is often lacking.

Niwagaba et al. (2009a) have shown that wood ash is superior compared to saw dust regarding the die-off rates of *E. coli* and *Enterococcus spp.* Research in China identified plant ash to be more effective concerning pathogen reduction (phages, *E. coli* and *Ascaris* eggs) and elevation of pH in comparison to other cover materials (coal ash, sawdust and loess; see Table 11) (Wang et al., 1999). This has been verified by Jiayi & Junqi (2001), who compared different cover materials (plant ash, coal ash, saw dust, corn husk, soil) in regard of their effectivity to reduce faecal coliforms, *Ascaris* eggs and phages too.

A further advantage of using plant ash, aside from its vast availability, is the high value of potassium, phosphor and calcium, increasing the fertility of the end-product additionally (Jönsson et al., 2004). WHO (2006a) recommends a minimum storage time of > 6 months for dry faeces, if pH-values > 9, moisture content < 25% and temperatures > 35 °C are achieved in the pile. Lower pH-values or higher moisture contents cause prolonged storage times (see Table 10, p. 46).

Lime is able to elevate the pH-value to levels of 11 – 12, allowing rapid inactivation of pathogens that way (Boost & Poon, 1998 as cited in Stenström et al., 2011). Calizaya et al. (2009) state short inactivation times when lime has been used as additive for UDDTs in Peru. People tended to use too much lime, which resulted in very hard material ('faecal rock') which had to be removed with pickaxes. Moreover costs for lime were considerable in this region (Hoffmann, 2014). Another study concluded that '[a]*sh appeared to be more effective for the removal of helminths egg whereas lime has a fast knockdown effect on bacterial organisms* (Endale et al., 2012, p. 753). Quick lime can be mixed with coal ash or soil to be as effective as plant ash. Despite, lime should only be used in disaster conditions

Table 11: Reduction of pathogens in faecal material from UDDTs, treated with different cover materials (Wang et al. 1999, p. 397f).

Absorbents/ Cover material	**pH**		**Retention time**	**Faecal coliforms**	**Phages**	**Viable *Ascaris* eggs**
	substrate	**mixed with faeces (1:3)**				
Plant ash	11	9 – 10	55 days	7 logs	6 logs	1.7 %
			3 months	> 7 logs	> 7 logs	0.95 %
Coal ash	8	7	3 months	5 logs	3 logs	28.3 %
			5.5 months	5 logs	5 logs	14.4 %
Sawdust/husk	7 – 8	7 – 8	3 months	4 logs	2 logs	32.2 %
			5.5 months	4 logs	4 logs	16.1 %
Loess	6 – 8	6 – 8	3 months	3 logs	2 logs	33.3 %
			5.5 months	3 logs	3 logs	20.2 %

(Jiayi & Junqi, 2001). Lime may cause the resulting material to be highly alkaline, which disqualifies it as suitable fertilizer for many crops (Peasey, 2000). Soil is not recommended to be used as viable treatment method (Endale et al., 2012; Jiayi & Junqi, 2001).
Schönning & Stenström (2004) recommend to separately dispose of toilet paper, for it to be handled as solid waste or incinerated, if alkaline treatment is applied. This is because only small biological degradation takes place when high pH-values in combination with fast desiccation is present (Jönsson et al., 2004).

(iv) Temperature:

Increased temperatures foster pathogen die-off, since most microorganisms die above 40 – 50 °C (see Figure 35, p. 77). It was initially common to use inclined and black painted vault doors oriented to the sun, assuming that this leads to increased temperatures in the vault. However, this measure did not prove to have a significant effect in increasing and maintaining temperatures high enough to foster pathogen die-off (Windberg & Otterpohl, 2016; Rieck et al., 2012). Experiences from China state slightly better performances of solar heated UDDTs as compared to unheated, but their operation is less convenient and the construction is more complex (Hua, 2000). It is therefore not recommended to use inclined vault doors ('solar latrines' or 'solar heated') since they are further more prone to vandalism and construction is more sophisticated as compared to vertical doors. Furthermore, the toilets are often not properly aligned to the sun and doors out of iron sheets are prone to corrosion. Potential gaps or holes may result in greater volumes of rainwater penetrating into the vaults as it would be the case when vertical doors are used instead (Windberg & Otterpohl, 2016; Rieck et al., 2012).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1, EP_2 EP_3 EP_{Other}

(EP_1 & EP_2) Ingestion of excreta, Dermal contact

- The user is largely unexposed because the vaults are effectively containing the contents (Stenström et al., 2011).
- The faeces simply drops down into the vault, forming a mound over time. Hence, it is necessary to level the pile occasionally (e.g. weekly), either through the User Interface or the vault door, and to mix additional cover material into the faecal material (Deegener et al., 2015).
- Potential dermal contact or ingestion of pathogenic material may occur when the User Interface is moved during the alternation of the two vaults (Stenström et al., 2011).
- Separate collection of used cleansing material includes a potential risk of transmission (Rieck et al., 2012).
- Improper designed and/or constructed vault doors may lead to direct exposure of children, or indirect exposure via animals soiling the surrounding environment (Rieck et al., 2012). Almost all inspected vault doors of Composting Toilets in Vanuatu were of bad quality (design, construction and/or maintenance) and exposed users to contents (Figure 23).
- '*Bad maintenance will not result in any enhanced security over single pits or double alternating dry pits*' (Stenström et al., 2011, p. 36).

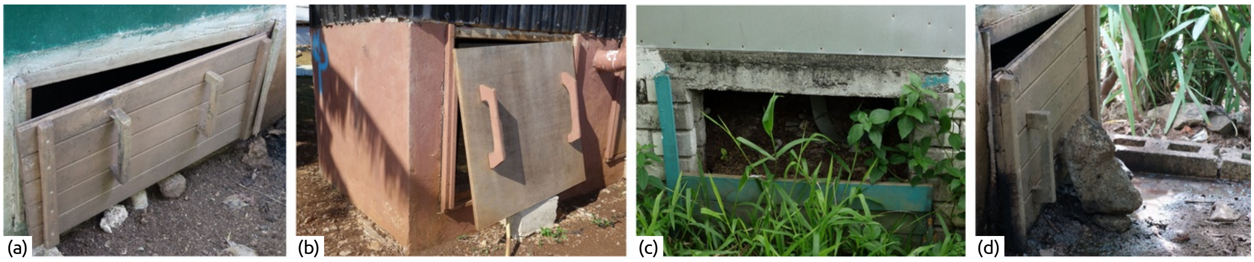


Figure 23: Examples of badly constructed and/or maintained vault doors of 'Composting' Toilets in Vanuatu. The doors are held in position with stones and bricks (a), (b) and (d), or are completely missing (c). Far right (d) shows excessive leaching with pooling due to inadequate usage of cover material in a 'Composting' Toilet.'Composting' Toilet

Risk mitigation

- The tool used to level the pile comes into contact with fresh faeces, it should therefore never be used for other purposes (e.g. handling already treated faeces, gardening). After the tool is cleaned thoroughly, it should be stored in a way that it is out of reach for children.
- PPE should be worn when the User Interface is moved from one vault to the other, followed by standard hygienic measures like hand washing.
- Disposal of soiled cleansing materials (e.g. toilet paper, newspaper, leaves) into the vault is highly recommended. The vaults can effectively contain the contaminated materials which include a risk of transmission if collected separately (Rieck et al., 2012). The disposal of toilet paper or leaves further enhances the aeration, affects the structure and absorbs moisture of the vault material. Moreover, these materials will be beneficial in case a post-treatment in form of composting is undertaken. Degradable sanitary napkins used by women during menstruation can be thrown into the vault too (Schönning & Stenström, 2004). Nonetheless, any non-degradable sanitary product should be disposed of separately into a bin with a tight fitting lid (ideally fixed to a wall to avoid potential spilling of contents) (Rieck et al. 2012). Bins used for separate collection should be suitable to be properly disinfected, and the waste should be carefully handled (Franceys et al., 1992). Bins need to be emptied and cleaned regularly (including proper PPE and hand washing), and the waste should be burned.
- The quality of design and construction, but also an ongoing maintenance of the vault doors is essential for long-term operation. Both vaults have to be sealed securely including a sufficient locking mechanism to prevent them from being opened by children or animals. Beside the increased health risk, light shining into the vault through broken doors may decrease acceptance by making faeces visible to users (Rieck et al., 2012).
- The users have to be well informed how to use and maintain the vaults. The vaults must be used alternately (Stenström et al., 2011). It is therefore important that the currently active vault can be clearly distinguished from the non-active vault. Emptying the vaults on time is critical to impede users defecating onto the already (partly) sanitized material in the inactive vault (Rieck et al., 2012).

(EP$_3$) Contact with flies/mosquitoes

Flies and other vectors are usually of no concern as long as the vaults are properly operated (Stenström et al., 2011). Flies may breed in vaults in case the moisture content is high enough and feacal matter is accessible (e.g. insufficient use of cover material; unfamiliar users; misuse by men; leaking pipes, vaults or doors) (Rieck et al., 2012).

Risk mitigation

The importance of preventing water and urine from entering the vault and some countermeasures have already been described in detail (see *(ii) moisture content*, p. 47).

Urine pipe connections should be absolutely tight to avoid wetting of the vaults (e.g. glued). When the UD interface is shifted, it has to be '*perfectly aligned over the fixed discharge pipe to avoid urine spillage into the faeces vault*' (Rieck et al., 2012, p. 36). If some water or urine is accidentally entering the vault, additional cover material should be added to compensate the extra moisture (Stenström et al., 2011). It is very important that a sufficient amount of cover material is available at all times (Rieck et al., 2012).

To reduce the risk of fly breeding in the vault, the additive should completely cover the faeces, so that fresh faecal surfaces are concealed (Jönsson et al., 2004). If watery diarrhea is common and lime or ash is used as cover material, other adsorbents like peat or soil may be necessary to effectively decrease the moisture content (Stenström et al., 2011).

Before a vault is used, it is recommended to cover the floor with 'prepared soil' (2:1 mix of soil and preferably ash, otherwise lime; sawdust optional) or a compost layer (3 – 5 cm) to aid moisture reduction. When the vault is full, covering the faeces with a dry soil layer is recommended before it is sealed for the storage period (Deegener, 2015). Spiders often settle in the vent pipe to feed from the flies. It is crucial to remove the webs regularly since they may have a substantial impact on the ventilation (i.e. dissipation of moisture) (Morgan, 2009).

(EP$_{other}$) Other exposure

'*It is important to eliminate pathogens as early as possible in the handling chain since risks are then minimized in subsequent steps*' (Schönning & Stenström, 2004, p. 8). The pathogen removal of the faecal material via storage in the vaults under dry conditions is very important to reduce the risk during further obligatory handling, disposal or reuse of the material.

A major advantage of this system is its applicability in flood-prone areas. This requires certain measures to ensure very high standards of water-tightness of the vaults (Rieck et al., 2012).

Risk mitigation

A sufficient storage time is essential to achieve acceptable pathogen levels, which in turn is linked to the available volume per vault (see *(i) Duration of storage*, p. 46) (Stenström et al., 2011). Beside additional moisture input via User Interface, urine piping or vent pipe, the base of the structure should be elevated for at least 10cm to lower the potential risk of water entering the vault during heavy rainfalls via potential gaps between vault doors and superstructure. The toilet should not be sited in a depression or sink to avoid the risk of water intrusion due to stagnant water pooling at this point during rain events (Rieck et al., 2012).

If this system is to be applied in flood-prone areas, the water-tightness of the vaults is of highest concern and require specific structural engineering. UDDTs without special precautions of ensuring water tightness should be able to cope with water levels of 10 to 20cm, depending on the actual height of the base (i.e. ground to lower edge of vault opening). In areas where higher flood levels are expected, it is usually necessary to raise the vault doors above this level and to plaster the interior walls of the vault (Rieck et al., 2012). By raising the doors up to a certain height, inclined doors are usually required. Delepiere (2011) reports about implemented UDDTs in flood-prone areas in Bangladesh, designed to withstand floods up to 0.9m (height from ground to floor). The vault was finished with a watertight plastering and raised, inclined vault doors were used. Covers out of galvanized steel have been replaced by concrete covers after rapid corrosion was detected, resulting in wet material in the vaults (Figure 24). The toilets proved to be working during a cyclone and subsequent flood (Delepiere, 2011). Other NGOs successfully implemented UDDTs with twin vaults in flood-prone areas in Bangladesh as well. The toilets have been functional during and after floods (Uddin, 2011; Morshed & Sobhan, 2010).

It is assumed that a fixed and watertight cover out of concrete, sealed with weak cement mortar, may be easier to construct and maintain, as well as better able to guarantee long-term tightness, in comparison to removable covers. Nevertheless, breaking and resealing the fixed cover for emptying the vault is less convenient. Properly refitting the cover depends furthermore on the users motivation and skills, which includes a risk of malfunction. Other types of tight doors (e.g. with rubber sealings) may be more complicated to repair and the procurement of specific materials and their replacement may be difficult in some countries.

Figure 24: This UDDTs have been successfully implemented in Bangladesh for flood heights up to 0.9 m. Vault doors out of concrete are used due to better corrosive resistance (a). The toilets proved to be working during cyclone Aila in May 2009 (b) (Delepiere, 2011. p. 4, 6).

URINE STORAGE TANKS

The diverted urine can be infiltrated on-site, discharged to a sewer or it is collected in a storage vessel (tank, container or jerry can, Figure 25) to be reused as fertilizer. Infiltration of urine should only be considered if the risk of groundwater pollution is proved to be insignificant or groundwater is not used for drinking purposes (see below, p. 70) (Rieck et al., 2012).

Figure 25: Urine is either directly discharged to an adequately sized storage tank or many smaller tanks for storage and treatment, or it is collected in a small tank (e.g. jerry can) which is then transported to a larger tank for further storage and treatment (Tilley et al., 2014, p. 58, 84).

If urine is to be reused on household level, it is either collected and stored directly in tank(s) (one tank of sufficient size or multiple small tanks, i.e. jerry cans which hold usually a volume of 20L), or collection and storage takes place separately in independent tanks (e.g. a jerry can is used for collection, and when filled up, to transport the urine to a larger tank) (Tilley et al., 2014). Storage tanks are available in a large variety of sizes and are mostly rigid (out of e.g. cement, PE, PP, PVC, fiber-glass), but expandable tanks out of rubber or plastic are also available for large-scale applications (Stenström et al., 2011; Münch & Winker, 2011).
If the tanks are to be carried manually, they should not exceed 20L (~20kg) (Münch & Winker, 2011). Tilley et al. (2014, p. 84) remark that '*jerrycans quickly fill up and need to be frequently exchanged or emptied,* [thus] *the use of a large Storage Tank/Container should be considered for primary collection of the urine*'. Large storage tanks have to be adequately sized according to the number of users and the minimum storage time (Tilley et al., 2014). Nonetheless, the size of the tank is also a matter of cost (the bigger, the more expensive), and a matter of comfort (the smaller, the easier to carry, but the shorter the emptying intervals) (Deegener et al., 2015).
'*In regions where there are definite cultivation periods followed by dry periods, storage of urine nutrients in soil is an alternative if the storage capacity is insufficient*' (Jönsson et al., 2004, p. 19). The urine is applied and worked into the soil during the dry season, the remaining nutrients are then utilized by the crops during the growing season. Although nitrogen losses are likely to be high, this may be an option for some regions (Jönsson et al., 2004).

To calculate the *total storage volume* ($V_{storage}$), the following factors have to be known: *number of users* (N_{users}), *specific urine production per person and day* (p_{urine}), *desired storage time in days* ($t_{storage}$) and *fraction of time person stays at the premises where the toilet is* ($f_{timefraction}$) (Münch & Winker 2011). The corresponding formula is shown in Equation 1.

$$V_{storage} = N_{users} \cdot p_{urine} \cdot t_{storage} \cdot f_{timefraction} \qquad \text{(Equation 1)}$$

An adult person exudes between 0.8 and 1.5L of urine per day (WHO, 2006b). This sums up to about 300 – 550L of urine per person and year (dependant on factors like liquid uptake, climate). If no specific data is available, 1.5L of urine per person (adult) and day is assumed, whereas this figure is halved for children (Münch & Winker, 2011). The amount of urine per person and year is sufficient to fertilize an agricultural area of 300 – 400m² (approx. 50 – 100kg N/ha) (Jönsson et al., 2004). The calculated $V_{storage}$ of a family with 3 children ($t_{storage}$ = 30d, $f_{timefraction} = \frac{2}{3}$) would result in a storage volume of 105L per month. It is further recommended to include a safety margin due to potential visitors, higher p_{urine} of children, higher $f_{timefraction}$ etc.

TREATMENT

The most common, simplest and most cost-effective treatment is to store the urine in a closed tank (Münch & Winker, 2011). Inactivation of microorganisms is mainly achieved by temperature, high pH-values (around 9) and ammonia concentration (Höglund, 2001). The total nitrogen concentration in urine is sufficient to achieve self-sanitization via subsequently formed ammonia and the corresponding elevation of pH if certain conditions are met (Nordin, 2010). The persistence of pathogens is further influenced by the storage time and dilution, as '*lower temperature and higher dilution result in longer survival of most bacteria*' (WHO 2006b, p. 39).

Nitrogen in fresh urine is mainly present in form of urea, which dissociates to ammonium, carbonate and hydroxide. This process relies on the enzym urease and leads to pH-values between 9 and 9.3 (Equation 2). The formed ammonium ($NH_{4\,(aq)}$) is in equilibrium with dissolved ammonia $NH_{3\,(aq)}$, which in turn is in equilibrium with gaseous $NH_{3\,(g)}$ (Equation 3) (Jönsson et al., 2004). Nordin (2010) notes that $NH_{3\,(g)}$ solute concentration is therefore influenced by ventilation and head space volume.

$$\overset{urea}{CO\left(NH_2\right)_2} + 3\,\overset{water}{H_2O} \overset{urease}{\rightarrow} \overset{ammonium}{2\,NH_4^+} + \overset{hydroxide}{OH^-} + \overset{carbonate}{HCO} \qquad \text{(Equation 2)}$$

$$NH_{3\,(g)} \leftrightarrow NH_{3\,(aq)} + H_2O_{\,(l)} \leftrightarrow NH^+_{4\,(aq)} + OH^-_{\,(aq)} \qquad \text{(Equation 3)}$$

'*To maximize its biocidal effect, NH_3 losses from stored urine should be minimized. Therefore, dilution of urine or the use of unsealed tanks or aeration during pumping of urine to transport facilities, which could lead to NH_3 volatilization, should be limited*' (Bischel et al., 2015). Dilution of urine decreases ammonia concentration, resulting in a lower effectiveness of sanitization (Makaya et al., 2014; Niwagaba, 2009; Vinneras et al., 2008). Undiluted urine is critical to achieve sufficient concentrations of NH_3 to inactivate *Ascaris* ova and viruses. Nonetheless, the pH-value is likely to remain at values of ≥ 8.9 regardless of dilution, in case the tank was used long enough to develop a urease-producing biofilm (Nordin, 2010). Dilution is also detrimental as it requires higher storage volumes and more frequent emptying, and facilitates the formation of urine precipitates (i.e. urine stone) that may cause blockages (Rieck et al., 2012).

The ammonium/ammonia equilibrium (Equation 3) is temperature and pH dependent (Nordin, 2010; Niwagaba, 2009). Higher temperatures cause higher ammonia concentrations, the combination of these factors lead to increased pathogen removal (Makaya et al., 2014; Nordin, 2010). '*Temperature proved to be a key factor for $NH_{3\,(aq)}$ toxicity on the viral models and Ascaris eggs*' (Nordin, 2010, p. 93). This is apparent in Table 12, which shows the relationship between temperature and formation of NH_3 at various constant temperatures (4, 14, 24 and 34°C) of undiluted urine, and the corresponding t_{90} for model organisms of bacteria, viruses (bacteriophages were used as indicator organism) and t_{99} for helminths. 90% (1 log) of bacteria were inactivated within seven days, regardless of temperature. High temperatures achieved reasonable inactivation times (t_{90}) for bacteriophages and *Ascaris* suum (t_{99}) in comparison to lower temperatures of 4°C and 14°C.

Table 12: Formation of NH_3 (concentration and fraction of total ammonia) in urine at different temperatures and including the mean time for 1 or 2 $\log_{10}$ reduction (t_{90}, t_{99}) given as mean values in days for bacteria (*Salmonella* Typhimurium, *Enterococcus* spp.), bacteriophages as model organism for viruses (MS2, Φx174, S. Typhimurium 28B) and *Ascaris* eggs (Nordin, 2010, p. 45, adapted).

Temp (°C)	NH_3 (mM)	NH_3 (%)	Bacteria		Bacteriophages			Helminths
			Salmonella (t_{90})	*Enterococcus* spp. (t_{90})	MS2 (t_{90})	Φx174 (t_{90})	28B (t_{90})	*Ascaris* eggs (t_{99})
34	232 – 236	54 – 55	< 0.1	< 1.1	1.6	< 5.7	2.2 [a]	3.4
24	141 – 156	33 – 37	0.6	< 2.3	15	12	17	48
14	94 – 109	22 – 26	< 1.1	6.4	71	79	56	240
4	57	13	2.1	6.3	160	120	140	480

[a] Performed at 37°C

Richert et al. (2010) confirm that the risk of a cross-contamination of separately collected urine from urinals is negligible. Nevertheless, direct contact with unstored and cross-contaminated urine results in a high infection risk for rotavirus (the risk for *Cryptosporidium*, *Campylobacter* and Hepatitis A was below the threshold). Since this data is derived from a study in Europe and the incidence rates of these pathogens is much higher in developing countries, the health risk for Hepatitis A and bacterial infections may be high in these countries. The infection risk of urine which has been stored between 1 and 6 months was generally low, except for rotavirus (Höglund, 2001).

Table 13 shows recommendations by WHO (2006a) regarding minimum storage times for urine treatment. Based on this guideline, urine does not have to be treated before it is applied as fertilizer if the crops are consumed on household level only (a withholding time of one month is recommended, see below, p. 64). '*The likelihood of household disease transmission attributable to the lack of hygiene is much higher than that of transmission through urine applied as a fertilizer*' (WHO, 2006a, p. 56). Richert et al. (2010) recommend a storage time of 1 – 2 weeks for urine produced and applied on household level and for urine collected by the means of urinals. They further state that this storage time should be prolonged if cross-contamination is likely. Urine has to be treated if the fertilized crops are '*consumed by individuals other than members of the household from whom the urine was collected*' (WHO, 2006a, p. 56).

The effectivity of urine treatment by means of storage to sanitize bacteria, viruses, protozoa and helminths has been subject to many studies since the publication of the WHO guidelines about ten years ago. Research by Nordin (2010) and Niwagaba (2009) suggest considerably shorter storage times to achieve 6 log reductions of viruses and bacteria, and > 3 log reduction of viable *Ascaris* eggs above 20°C and at 34°C if proper NH_3 contents are reached.
WHO guidelines (2006a) are based on research by Höglund (2001), which does not take ammonia concentration into account (Vinneras et al., 2008). It is further important to mention that the examined urine samples were diluted with flushwater (ratio urine:water ranged from 2:1 – 4:1) (Höglund, 2001). '*The dilution rate is an important factor regarding the reduction in pathogenic microorganisms in urine, especially at temperatures ≤ 24 °C, where low ammonia concentrations result in slow inactivation*' (Vinneras et al., 2008, p. 4073). Nordin (2010) has shown the significant effect of higher temperatures on the ammonia concentration and the resulting decrease in t_{90} for bacteria, bacteriophages as well as t_{99} for Ascaris (Table 12), whereas Höglund did not examine temperatures > 20°C. By considering these factors, Vinneras et al. (2008, p. 4073) conclude that '[f]*or safe, unrestricted, reuse of urine fulfilling the requirement of 40 mM*

Table 13: Recommended storage times for urine mixture[a] based on estimated pathogen content[b] and recommended crops for larger systems[c] (WHO, 2006a, p. 56).

Storage temperature (°C)	**Storage time** (months)	**Possible pathogens in the urine mixture after storage**	**Recommended crops**
4	≥ 1	Viruses, protozoa	Food and fodder crops that are to be processed
4	≥ 6	Viruses	Food and fodder crops that are to be processed[d]
20	≥ 1	Viruses	Food and fodder crops that are to be processed[d]
20	≥ 6	Probably none	All crops[e]

[a] Urine or urine and water. When diluted, it is assumed that the urine mixture has a pH of at least 8.8 and a nitrogen concentration of at least 1 g/L.

[b] Gram-positive bacteria and spore-forming bacteria are not included in the underlying risk assessments, but are not normally recognized as a cause of any infections of concern.

[c] A larger system in this case is a system where the urine mixture is used to fertilize crops that will be consumed by individuals other than members of the household from whom the urine was collected.

[d] Not grasslands for production of fodder.

[e] For food crops that are consumed raw, it is recommended that the urine be applied at least one month before harvesting and that it be incorporated into the ground if the edible parts grow above the soil surface.

uncharged ammonia above 20°C, the required storage time according to WHO guidelines could probably be shortened, especially for samples with high ammonia content and at temperatures well above 20°C'. Further, they point out the need for studies about animal viruses (e.g. rotavirus, adenovirus) and studies covering a wider range of temperatures and NH_3 concentration.

Stricter recommendations like those from Richert et al. (2010), who recommend to store urine for 1 – 2 weeks when applied on household level, may be justified via the precautionary principle. Considered from a different perspective '[l]*ess stringent guidelines for developing countries compared to the Swedish ones* [(i.e. WHO guidelines)] *are also justified by the generally higher health standard in developed countries, where the cautious interpretation of the precautionary principle and high safety requirements are applied*' (Schönning & Stenström, 2004, p. 15).
Table 14 gives a more differentiated picture about storage requirements in relation to type of crop.

Table 14: Strategies for a wide range of different types of crops including recommendations for storage and application to minimize the risk for involved persons and consumers (Richert et al., 2010, p. 26, adapted).

Crop	Example	Risk	People exposed	Time of application[a]	Urine storage[b]
Root crops					
eaten raw	Carrots	High	Consumers and workers	Until one month before harvest	Storage needed
processed/cooked	Cassava, potatoes	Low	Workers	Until one month before harvest	No storage needed
Leafy crops					
eaten raw	Lettuce, cabbage	High	Consumers and workers	Until one month before harvest	Storage needed
on the ground that are cooked	Spinach	Low	Workers	Until one month before harvest	No storage needed
Hanging plants					
partly or fully in contact with soil and eaten raw	Tomatoes	High	Consumers and workers	Until one month before harvest	Storage needed
not in direct contact with the ground and usually not eaten raw	Egg plant	Medium	Consumers and workers	Until one month before harvest	Storage needed
Slow growing crops	Pineapple	Low	Workers	In early stages	No storage needed
Grain crops processed before eating	Millet, Rice, Sorgum, Maize	Low	Workers	Until one month before harvest	No storage needed
High growing crops not picked from the ground and with “cover”	Banana	Low	Workers	Until one month before harvest	No storage needed
Fruits likely picked from the ground and eaten directly[c]	Mango, orange, passion fruit	Low	Workers	Outside the fruiting season[d]	No storage needed
Energy or fibre crops	Cotton, oil crops	Low	Workers	Until one month before harvest	No storage needed
Ornamental flowers, garden plants		Low	Workers	Until one month before harvest	No storage needed

[a] Urine application should take place considering crop needs and common practice in the region. Continuous application can take place where so noted, from a barrier point of view. A waiting period of one month should always be observed.

[b] The storage time for urine is not indicated, since this also depends on local factors such as temperature or design of collection system (degree of faecal contamination).

[c] If vegetables are grown under fruit trees then the measures of precaution or barriers for vegetables need to be observed.

[d] If application is close to the fruiting season, then precautionary measures or barriers need to be observed (e.g. storage).

Situation in Vanuatu

The concept of urine diversion is hardly known in Vanuatu. The response to the system in general, and to the possibility of using urine as fertilizer was very positive when it has been introduced to a number of communities at the island of Emae and during interviews at Efate, Espiritu Santo and Pele. Subsistence farming plays a major role in Vanuatu, and it is common to sell homegrown products on local markets.

For temperatures present in Vanuatu, a storage time of at least one month is recommended by WHO (2006a) before it can be used to fertilize crops that are to be processed before consumption. After a storage time of greater than six months, it can be applied to all crops (see Table 13). Nevertheless, it has been outlined beforehand that the recommended storage times may be shortened if certain conditions are met.

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1, EP_4, EP_6, EP_8 **EP_{Other}**

(EP$_6$, EP$_1$ & EP$_8$, EP$_4$) Contact with overflowing/leaking contents, Ingestion of excreta and/or urine, Inhalation of aerosols and particles

Tanks below the ground, self-built tanks (e.g. concrete) or tanks installed in areas prone to floods need special attention to prevent potential transmission of pathogens, or urine from leaking into the ground, which is likely to cause elevated nitrogen levels in the groundwater.

The risk of ingestion is directly linked to a potential cross-contamination of the urine with faecal matter, which is of major concern in regard of pathogens (see cross contamination, p. 43). The severity of this contamination is mainly influenced by the behaviour of the users (Stenström et al., 2011). It is therefore critical to '*adapt storage conditions to potential cross contamination at the user interface*' (Stenström et al., 2011, p. 41).

'*Storage does not result in health risks if the tank does not leak or overflow*' (Stenström et al., 2011, p. 41). The exposure for potential ingestion, inhalation or direct contact with urine may occur (i) during tank maintenance, (ii) at time of collection, or (iii) when storage tanks overflow:

(i) Tank maintenance:

Sludge and precipitated minerals will accumulate at the bottom of tanks and should be removed (Tilley et al., 2014).

(ii) Time of collection:

The exchange as well as the transport of jerry cans pose a low health risk for the handling person (Tilley et al., 2014).

(iii) Overflown storage tanks:

Overflowing tanks may lead to direct contact with untreated or partly sanitized urine (e.g. playing children) (Richert et al., 2010). Direct contact with unstored and cross-contaminated urine results in high infection risks for rotavirus, which is still of concern even if urine is stored between 1 and 6 months (Stenström et al., 2011).

Risk mitigation

Gloves should be used whenever tanks are handled, followed by proper hand-washing (Schönning & Stenström, 2004).

Urine tanks should be never used for other purposes (Richert et al., 2010).

If large tanks out of concrete are used, high standards of water-tightness are important (Münch & Winker, 2011). If tanks are buried in areas with high water tables, they have to be anchored to the ground to prevent the risk of floating tanks caused by lifting forces. Pipes below the ground should have diameters of minimum 110 mm due to higher stability. Connections below the ground have to be completely tight (welded or glued) or better avoided in the first place to avert potential groundwater intrusion. Metal corrodes easily in contact with urine and should not be used for the urine system in general (neither piping nor tank). Fitted taps of tanks should be well fixed, but at the same time easily replaceable (Stenström et al., 2011, Kvarnström et al., 2006).

ad (i) Tank maintenance:

Tilley et al. (2014) advise to regularly clean jerry cans and tanks to minimize bacterial growth, sludge accumulation and unpleasant odours. Schönning (n.d.) remarks, that sludge removal may be adverse in regard of urea degradation and therefore sanitization of the urine (the piping is designed to maximize the flow rate of urine to avoid the accumulation of urease and subsequent precipitation forming sludge or hard incrustations). But research by Udert et al. (2003) did not show any indication of sludge containing ureolysing bacteria, it is rather '*that urease-active bacteria primarily grow in the pipes*' (Udert et al., 2003, p. 2581).

There are recommendations to reuse the accumulated sludge at the bottom of tanks due to its nutrient content (e.g. phosphor). This may includes an increased risk since higher concentrations of sedimented pathogens may be found in the sludge (Höglund, 2001). This is true '*especially* [for] *Ascaris and other parasitic eggs and cysts, which sediment easily*' (Panicker & Krishnamoorthi, 1981 as cited in Nordin, 2010, p. 79).

ad (ii) Time of collection:

Tanks used to transport urine should have tight fitting lids to prevent spillage (Richert et al., 2010). Using jerry cans limits the risk because they seal very well (Tilley et al., 2014).

ad (iii) Overflown storage tanks:

Tanks should be designed with an overflow including a soak away (Richert et al., 2010). '*Smaller containers should be placed on top of a soak area in order to allow for the infiltration of any overflow and avoid odours*' (Rieck et al., 2010). In case a jerry can is used for collection, it should be preferably housed in the superstructure instead of next to the toilet to prevent potential contact with spilled urine.

(EP_{Other}) Other exposure

'*It is important to eliminate pathogens as early as possible in the handling chain since risks are then minimized in subsequent steps*' (Schönning & Stenström, 2004, p. 8). Treatment of urine reduces the risk during further handling and potential application. Besides, Richert et al. (2010) state a case where highly diluted urine in tanks with open lids led to mosquito breeding.

Risk mitigation

Urine should not be diluted because sanitization is hampered and more storage volume is needed that way (see p. 53 for more details) (Makaya et al., 2014; Rieck et al., 2012; Nordin, 2010; Niwagaba, 2009). Undiluted urine further prevents mosquitoes from breeding in the tank in case they get access to it (Schönning & Stenström, 2004). The top of small tanks (e.g. jerry cans) should be above ground level to avoid rainwater to enter the tank, diluting the urine (ESF & seecon, 2007). Lids should be closed to prevent access for mosquitoes.

Tanks should be always sealed to prevent ammonia volatilization, a small hole at the top of the tank is important to allow pressure equalization (Rieck et al., 2012). Thus NH_3 is retained in the receptacle which is important for the sanitization of the urine (see NH_3/NH_4 equilibrium, p. 53), the quality of the resulting fertilizer, and to prevent odours (Bischel et al., 2015; Nordin, 2010; Richert et al., 2010; Jönsson et al., 2004). The inlet of the urine pipe should end near the bottom of the tank to provide a liquid sealing. This minimizes NH_4 volatilization through the piping, prevents splashing of urine and limits odours (Stenström et al., 2011).

It is recommended to expose tanks to the sun if multiple jerry cans are used to collect and store the urine. This increases the temperature and the NH_3 concentration, leading to shorter inactivation times. Temperature is critical to remove viruses and *Ascaris*. Fluctuating temperatures during the day seem to enhance pathogen removal additionally. Besides external factors (e.g. ambient temperature, time of day), actual exposure to sun and the colour of the tank can be influenced by the user to increase the temperature. Thermal insulation of the tank may minimizes cooling effects of surfaces. Further, solar radiation may improves sanitization if small tanks are used (i.e. jerry cans; the higher the surface to volume ratio, the better) (Nordin et al., 2013).

Infiltration of the urine into the ground may be an option to mitigate some risks discussed above, but includes others such as groundwater nitrification (see Chapter 5.3.4, p. 70).

5.3.3. Conveyance

HUMAN POWERED EMPTYING AND TRANSPORT

The Human-Powered Emptying and Transport of a UDDT with Double Dehydration Vaults on household level comprises of the transportation of the urine (if not infiltrated or evaporated alternatively), and emptying and transporting of dehydrated faeces (Rieck et al., 2012). Emptying of dehydrated faeces from a double vault UDDT is shown schematically in Figure 26.

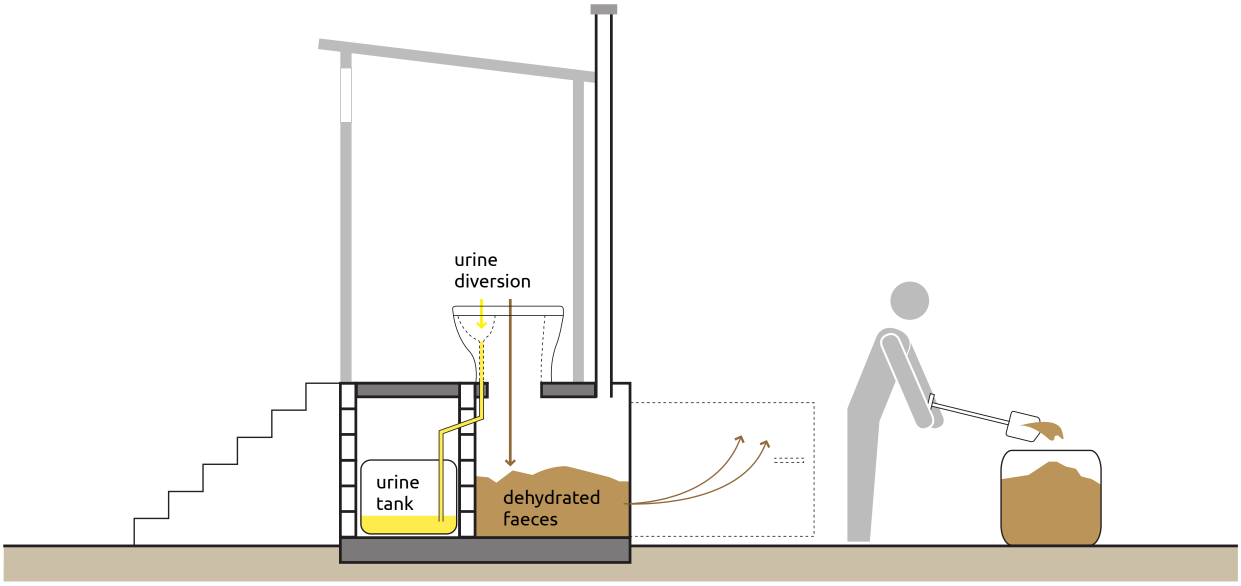


Figure 26: Human-powered emptying of dehydrated faeces via the vault access door (Tilley et al., 2014, p. 144).

Jerry cans with a volume of 20L are often used for urine transportation (and for collection and storage). The dehydration vaults are emptied via the vault access doors with the help of (long-handled) shovels. Buckets or wheelbarrows are used to transport the material to a designated disposal, reuse or post-treatment site (Rieck et al., 2012).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1, EP_2 EP_4, EP_8

(EP_1 & EP_2) Ingestion of dehydrated faeces, Dermal contact

The health risks of emptying a UDDT are generally high (Rieck et al., 2012). Nevertheless, the process is more pleasant and the risk of handling the material is lower compared to the removal of sludge from pit latrines (Stenström et al., 2011).

Research in South Africa identified the greatest risk of pathogen transmission along the whole system are posing helminths, which may be transmitted during handling of dehydrated faeces. There is an additional risk for the executing person and other community members (especially children) if the surrounding environment is contaminated during emptying of the vault or transport (mainly through spillage) (Stenström et al., 2011; Buckley et al., 2008b). A microbial assessment of hands from executors before and after emptying a vault manually (no use of gloves; 93% washed their hands afterwards, whereas 28% used soap, 3% soil and the rest water only) found significant differences for *Faecal streptococcus* levels. No differences of *Faecal coliforms* and *E. coli* levels have been observed (Moilwa & Wilkinson, 2006).

Risk mitigation

Wearing PPE during emptying and transport (boots, overall or clothing providing full body coverage, gloves, face mask), together with the availability of washing facilities and performing proper washing practices is important to limit the risks (Stenström et al., 2011). It is recommended to change and wash clothes after the undertaking is completed. Executers should wear shoes during the whole process to limit the risk of helminth infection.

People should also be encouraged not to smoke, eat or drink during the process (Austin, 2007; Germer et al., 2009a).

The equipment used to handle (e.g. shovel, rake) and transport (e.g. wheelbarrow) the treated faecal matter should minimize the user's contact with the material. It is further important to properly clean the equipment after utilization. Emptying and transport of faeces should only be undertaken by adults, never by children (EcosanRes, n.d.a; EcosanRes, n.d.b). It is generally recommended that children are not present during this process.

The area surrounding the vaults should be cleaned to be free from potentially contaminated material that may have been spilled during emptying or transport (Kvarnström et al., 2006).

Areas with high prevalence of *Ascaris* incidence rates may combine the implementation of UDDTs with a chemo-therapeutic campaign to possibly break the cycle of reinfection by reducing the load of ova in the environment (Buckley et al., 2008b).

(EP_4 & EP_8) Inhalation of aerosols and particles, Ingestion of urine

Persons emptying and transporting the dried faeces may be exposed to airborne particles from the dry, powder-like material (Stenström et al., 2011).

Emptying and transportation of urine tanks may cause an accidental contact and ingestion of small amounts of urine. Broken or leaking urine tanks represent an additional risk (Stenström et al., 2011). '*The health risk associated with the accidental ingestion of urine, compared to other exposure pathways is generally low; but may be of concern for viruses*' (i.e. rotavirus, norovirus) (Höglund, 2001 as cited in Stenström et al., 2011, p. 57).

The risk of ingestion or inhalation may be higher when multiple small tanks (i.e. jerry cans) are used as these have to be exchanged more frequently (usually within a range of days).

Risk mitigation

Emptying of the vaults should not be done on windy days to minimize potential exposure to aerosols. People should be further encouraged to wear a mask (e.g. bandana or handkerchief) to reduce the risk of particle inhalation (Stenström et al., 2011).

The jerry can should be cleaned before utilized for transportation in case it is soiled with urine. Adults should undertake the urine transport only (including proper PPE and handwashing after execution), as children may not adhere to hygienic behaviour.

Again, it should be refrained from smoking, eating or drinking during emptying and transport of urine to prevent hand-mouth contact with potentially contaminated hands.

5.3.4. Use and/or Disposal

At this point in the sanitation system, the (partly) sanitized faeces and/or urine are returned to the environment either in a sustainable way by making use of the contained resources, or they are simply disposed of. The former option means to utilize the macronutrients nitrogen (N), phosphorus (P) and Potassium (K), and micronutrients to fertilize plants. Table 15 shows examples of excreted nutrients per person and year for urine and faeces from Sweden.

Table 15: Annual excretion of nutrients per person and year as proposed for being used as norm values for Sweden (Vinneras, 2002, p. 42, adapted).

Parameter	Urine		Faeces		Total	
Mass [kg]	550	(91 %)	51.5	(9 %)	601.5	(100 %)
Nitrogen, N [g]	4000	(88 %)	550	(12 %)	4550	(100 %)
Phosphorus, P [g]	365	(67 %)	183	(33 %)	548	(100 %)
Potassium, K [g]	1000	(73 %)	365	(27 %)	1365	(100 %)
Total N+P+K [g]	5365	(83 %)	1098	(17 %)	6463	(100 %)

APPLICATION OF STORED URINE

Urine contains the majority of nutrients found in excreta. The example from Sweden shows that more than 85% of total nitrogen, 65% of total phosphorus and 70% of total potassium is excreted with urine (Table 15). The fertilizing effect of urine is equally compared to mineral fertilizer, as long as the same amount of nutrients is applied (Münch & Winker, 2011). Figure 27 shows a schematic of urine application in furrows next to maize.

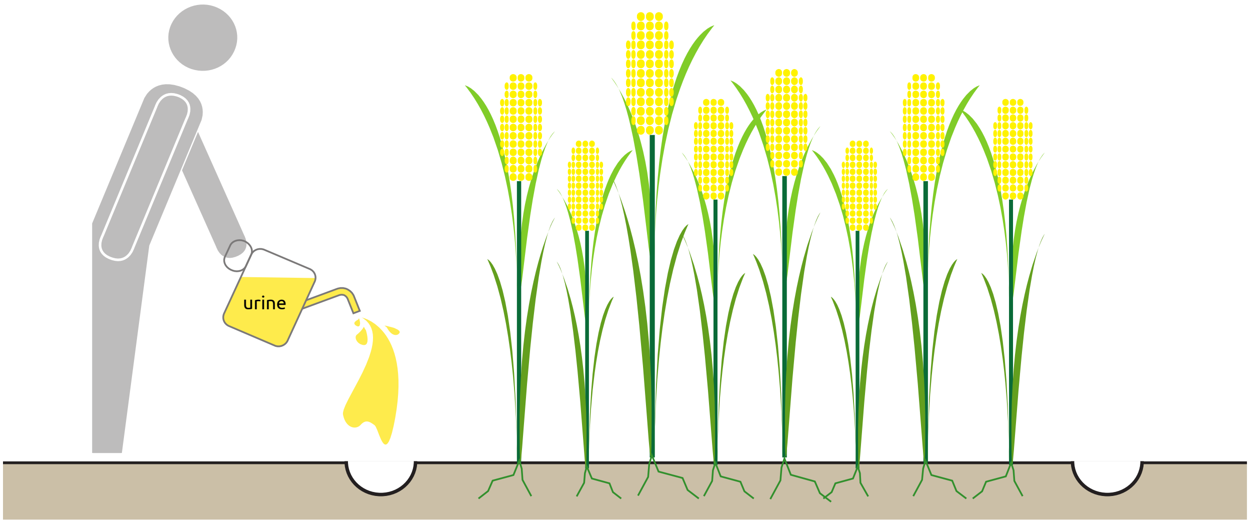


Figure 27: Application of Urine in furrows to fertilize crops or other plants (Tilley et al., 2014, p. 142).

The concentration of nutrients in urine depends on factors like diet, gender, climate and water intake (Stenström et al., 2011). Data from the Philippines underline variations due to these factors, as the average nutrient content excreted with urine per person and year was determined with 2.18kg of N, 0.20kg of P and 0.87kg of K (e.g. in relation to Table 15) (Gensch et al., 2011). Jönsson & Vinneras (2004 as cited in Richert et al., 2010) formulated two equations to estimate mean excreted amounts of nitrogen and phosphorus (Equation 4 and 5, respectively) from FAO available figures about protein intake.

$$N = 0.130 * (total\ food\ protein) \qquad \text{(Equation 4)}$$

$$P = 0.011 * (total\ food\ protein + vegetal\ food\ protein) \qquad \text{(Equation 5)}$$

Recent data for Vanuatu from FAO (2014) result in approximately 3.2kg/cap/a of nitrogen and 0.4kg/cap/a of phosphorus excreted with urine.

Urine is rich in nitrogen and is therefore especially suitable for N-demanding crops and leafy vegetables (e.g. maize, rice, millet, sorghum, wheat, chard, turnip, carrots, kale, cabbage, lettuce, bananas, paw-paw, oranges) (Tilley et al., 2014). The P/N and K/N ratio is lower compared to most mineral fertilizer used for vegetables (Jönsson et al., 2004). '*Urine's nutrient content – expressed with the international fertiliser convention of* $N:P_2O_5:K_2O$ *– is approximately 0.7:0.15:0.22 – compared to for example di-ammonium-phosphate* [... with a ratio] *of 21:46:0. This means that a huge volume of water is transported whenever urine fertiliser is transported*' (Münch & Winker, 2011, p. 14).

Small-scale trials by Morgan (2003) are stated exemplarily to show the fertilizing effect of urine application on the yield of vegetables, especially if the soil is poor (Table 16). Urine trials in the Philippines (Figure A.3, Appendix p. 113) demonstrated a significant fertilizing effect comparable to synthetic fertilizer, considerable differences in yields and plant heights depending on local site conditions (e.g. organic matter content, sunlight, water) were observed (Gensch et al., 2011).

'*As a general rule of thumb, one can assume that 1m² of cropland can receive 1.5 L of urine per growing season* [… corresponding] *to 40-110 kg N/ha*' (Tilley et al., 2014, p. 142). Approximately

Table 16: Small-scale plant trials from Zimbabwe, where various edible plants were planted in 10L containers out of cement (buckets[a] or basins[b]) and watered with water only, or a mix of water and urine (Morgan, 2003, s.p., adapted).

Plant	Urine:water	Amount	Application	Growth period	Yield (relative yield)
Lettuce[a]	Water only			1 month	230g
Lettuce[a]	3:1	0.5L	3 × per week	1 month	500g (2 fold increase)
Spinach[a]	Water only			1 month	52g
Spinach[a]	3:1	0.5L	3 × per week	1 month	350g (6 fold increase)
Tomato[a]	Water only			4 months	1680g (total of 9 plants)
Tomato[a]	3:1	0.5L	3 × per week	4 months	6084g (3.6 fold increase)
Maize[b]	Water only			3 months	6g / cob (average)
Maize[b]	10:1	0.5L	1 × per week	3 months	62g (10 fold increase)
Maize[b]	5:1	0.5L	1 × per week	3 months	138g (23 fold increase)
Maize[b]	3:1	0.5L	1 × per week	3 months	169g (28 fold increase)
Maize[b]	3:1	0.5L	3 × per week	3 months	211g (35 fold increase)

300 – 400m^2 can be fertilized per person and year that way. Increased yields via fertilization depend also on other factors like the soil condition. Low contents of organic substances in the soil are likely to result in reduced yields. Hence it is recommended to combine urine and faeces application (or another organic fertilizer) (Jönsson et al., 2004).

The health risks of urine used in plant production is generally low. The WHO guidelines (2006a) are based on a multi-barrier approach to manage the health risk when urine (or faeces) is used to fertilize crops, fruits or vegetables (Figure 28). Barrier I (source separation) is a major barrier since most pathogens are excreted with faeces. Preventing cross-contamination with faecal matter is therefore crucial (Richert et al., 2010). The treatment of urine via storage (barrier II) has already been discussed in Chapter 5.3.2, p. 52. The recommendations regarding urine storage primarily aim to reduce the health risk during consumption of fertilized crops. The person handling and applying the urine is benefiting from a reduced risk too (Schönning & Stenström, 2004). Barriers III to VII are important in this context and are included in the analysis below.

Official recommendations and guidelines have to be adapted to local conditions before this kind of a reuse-oriented system is implemented. A local guideline should cover all essential information for all involved stakeholders to be able to implement this system (Schönning & Stenström, 2004). Some or all of the following topics should be addressed: local site conditions (e.g. climate, water and soil conditions), plant requirements (e.g. type of crop, nutrient requirement), characteristics of urine (e.g. amount and nutrient content), recommendations for application (e.g. application technique, rates, time, dilution) and risk management (barriers relevant in local context) (for more information, see source p. 41ff) (Richert et al., 2010).

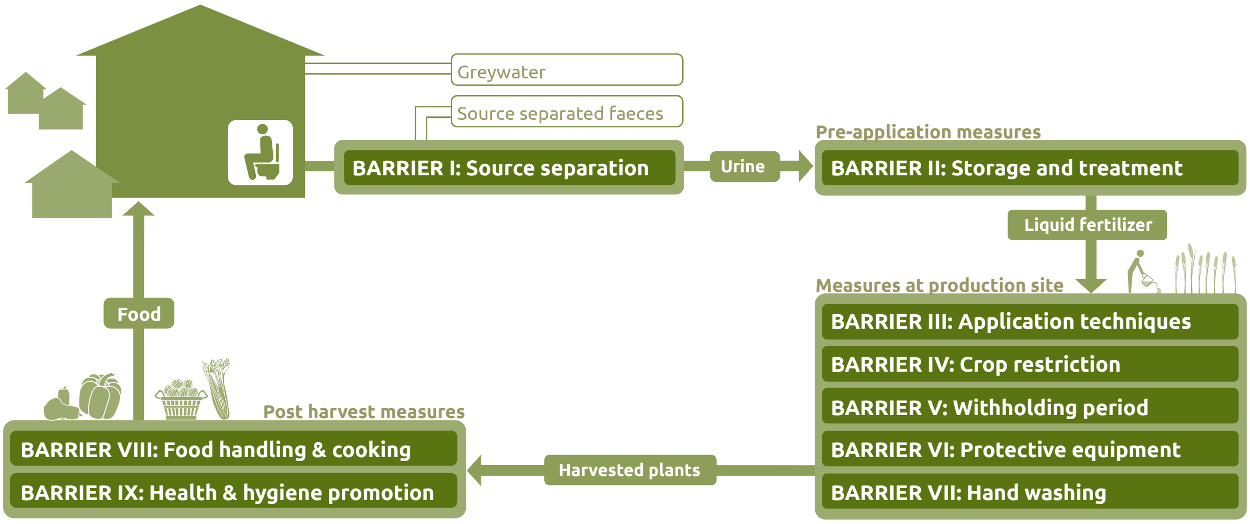


Figure 28: Representation of the multi-barrier approach for urine, based on the WHO Guidelines for the safe use of wastewater, excreta and greywater (2006a) (Richert et al. 2010, p. XI, adapted).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_4, EP_8, EP_9 EP_{Other}

(EP_8, EP_4 & EP_9) Ingestion of urine, Inhalation of aerosols and particles & Consumption of contaminated produce (vegetables)

Only few pathogenic bacteria, viruses and helminths are excreted with urine (see Chapter 5.1, p. 17). The person applying the urine in the garden or field may accidentally ingest urine from contaminated hands. Inhalation of aerosols is mainly considered to be a health concern in large scale applications when spray irrigation is used to apply the urine. Besides transmission by direct contact (especially of concern in regard of fresh urine), Schistosoma may be transmitted indirectly via an intermediate snail host if urine with viable eggs is applied near surface waters. Contact with unstored and cross-contaminated urine may results in high risks for rotavirus. *Cryptosporidium*, *Campylobacter* and Hepatitis A may be of concern as well (Stenström et al., 2011). Bischel et al. (2015) sampled unstored urine collected from UDDTs in South Africa. In regard of viruses, 100%, 34% and 31% of samples were positive for JC polyomavirus, rotavirus, and human adenovirus, respectively. Further *Aeromonas* spp. (94%) and *Shigella* spp., both gram negative bacteria, were found in 94% and 61% of the samples, respectively; 72% of the samples contained Clostridium perfringens (gram positive bacteria).

'*Consumers of crops fertilized with urine may also be exposed to pathogens if faecal cross-contamination has occurred and storage, application and withholding time practices are not adhered to*' (Stenström et al., 2011, p. 84).

Risk mitigation

The preceding storage of urine and the applied reuse practice (application technique, crop restriction, withholding period, protective equipment) determines the exposure to pathogens, especially if the urine is contaminated with faecal matter (Stenström et al., 2011).

Untreated urine should not be applied near surface waters in endemic areas of *Schistosoma haematobium*, to break the cycle of disease (Schönning & Stenström, 2004).

The sludge accumulating at the bottom of urine tanks during storage is rich in phosphor and can be either used for P-demanding plants or mixed with the urine to get an even dosage (Jönsson et al., 2004). Nordin (2010) advises against this recommendation because the sludge may contain viable *Ascaris* ova if sanitization is not sufficient (see above, p. 57).

Barrier III, Application techniques:

Application should be done during moderate temperatures in the morning or late afternoon hours to prevent nitrogen losses (Germer et al., 2009b). Moreover, urine should be applied close to the ground. This reduces the contact with edible parts, spreading of drops and avoids aerosol formation (WHO, 2006b). Close-to-the-ground-application further prevents foliar burning (Richert et al., 2010). It is generally recommended to rinse leaves in case they come into contact with (large amounts of) undiluted or diluted urine (Huuhtanen et al., 2009). Application close-to-the-ground further limits ammonia volatilization, which leads to a loss of nitrogen and therefore a reduced fertilizing quality. That is why the urine should be incorporated into the soil as soon as possible after application (e.g. application in shallow furrows which are backfilled afterwards, or washing urine into the soil by subsequent watering). This results in an approximately 1 log reduction of pathogens (Table 17) (Richert et al., 2010).

In case there is space in between plants, application in furrows in a distance of 10cm from the plant should always be applied, followed by watering (or it is applied after rainfall of ≥ 15mm). Point application of urine in quadratic furrows should be undertaken in case of densely planted crops. If this is not possible, urine should be mixed with water (at least 2:1), applied uniformly and followed by plenty watering. In case of fruit trees, the urine should be applied in a furrow, dug around the tree in a distance of the canopy line (based on a local guideline from Niger as cited in Richert et al., 2010).

Regions with heavy rainfall or areas with very sandy soils are prone to leaching. Applying more frequent, but smaller volumes may be better in these areas (Münch & Winker, 2011).

Höglund (2001) further states that '[f]*or crops growing under the surface it is* [...] *more beneficial not to work the urine into the ground since inactivation of potential pathogens by heat,*

Table 17: Achievable pathogen reductions by various health protection measures (WHO, 2006a, p. 32, adapted).

Control measure	Pathogen reduction (log units)	Notes
Excreta storage without fresh additions	6	The required pathogen reduction to be achieved by excreta treatment refers to stated storage times without addition of fresh untreated excreta.
Localized irrigation with urine (high-growing crops)	2 – 4	Crops where the harvested parts have not been in contact with the soil.
Material directly worked into soil	1	Should be done at the time when faeces or urine is applied as a fertilizer.
Pathogen die-off of applied urine (withholding time one month)	> 6	Risk levels for bacteria, viruses and parasitic protozoa was calculated far below 10^{-6} DALY. The log reduction depends on climate (temperature, sunlight intensity, humidity), time, crop type and other factors.
Produce washing with water	1	Washing salad crops, vegetables and fruit with clean water.
Produce disinfection	2	Washing salad crops, vegetables and fruit with a weak disinfectant solution and rinsing with clean water.
Produce peeling	2	Fruits, root crops.
Produce cooking	6 – 7	Immersion in boiling or close-to-boiling water until food is cooked ensures pathogen destruction.

UV-radiation and desiccation is faster on the surface'. Another option is to apply the urine '*before or during sowing/planting* [, hence] *a further die-off will occur of potential remaining pathogens (see withholding period* [below, p. 64]*) and thereby the risk will be reduced*' (Richert et al., 2010, p. 27).

Urine also contains chloride, which may be harmful to plants sensitive to it (e.g. tomatoes, potatoes). This is primarily a concern when the roots of small plants are exposed to urine. If such plants are cultivated, application of urine before sowing/planting or at a distance of e.g. 10cm from the plant is recommended (Münch & Winker, 2011; Jönsson et al., 2004).

Table A.4 (Appendix, p. 114) gives an example of recommended application periods and doses for various crops, vegetables and fruits from Niger. See Gensch et al. (2011, p. 20f) for recommendations of further plants.

To sum up, urine should be either (i) mixed into the soil before planting (undiluted), (ii) applied in shallow furrows which are backfilled with soil immediately, or (iii) diluted and used frequently around plants (e.g. twice a week) (Stenström, 2011).

Barrier IV, crop restriction:

The recommended storage times by WHO (2006a) are directly related to the choice of crop (see Table 13, p. 54). If urine has been treated according to the guidelines, it can be applied in compliance with the recommendations. If there are concerns about the safety of the product or to further reduce the potential health risk, additional crop restrictions may be applied. These restrictions include either (i) non-food crops (e.g. cotton), (ii) crops processed before consumption (e.g. wheat), (iii) crops cooked before consumption (e.g. potato), or (iv) crops or trees with an adequate distance between soil and harvested part (e.g. banana). The risk should be reduced to reasonable levels for all persons that may be affected by the application of urine (Richert et al., 2010).

Table 14 (p. 55) shows strategies for a wide range of crops in order to minimize the risk for involved persons and consumers. Crops that are eaten raw (e.g. carrots, lettuce) and hanging plants (e.g. tomatoes, egg plants) include elevated risks and are therefore of importance. The longer the withholding period (barrier V), the lower the risk. Hence, risks are generally higher for crops with short rotation times (e.g. spinach, lettuce) (Richert et al., 2010).

Barrier V, withholding period:
After the urine has been applied, environmental factors result in pathogen destruction in the soil and on crops (Schönning & Stenström, 2004). Examples of inactivating external factors are drying, temperature or UV-light at leafy plants. The destruction of pathogens is usually slower in soil (see Table 18, p. 67). The period between last application of excreta and harvest is called withholding period. A minimum withholding period of one month is generally recommended for all types of plants, whereas fruits, vegetables and root crops that are consumed raw should always adhere to a withholding period of minimum one month. Pathogen reductions of more than 6 log can be achieved with this measure (Table 17) (WHO, 2006b).
Generally spoken, nutrients are important during the early phase of growth, but neglectable when plants enter the reproductive phase. It is recommended to stop fertilization after ⅔ to ¾ of time between seeding and harvest (Richert et al., 2010).

Barrier VI, protective equipment:
Even though the health risk of treated urine is low, it is recommended that the person applying the urine wears proper PPE (gloves and shoes, or better boots). This is especially of importance if (heavy) faecal cross-contamination is likely, which includes a high risk of helminth transmission via bare skin (direct contact or indirect). Protective clothing is also important to avoid the spread and transport of pathogens (e.g. to the household) (Richert et al., 2010).

Barrier VII, hand washing:
'*Washing hands with soap after urine handling can be considered an additional barrier in the system. Self-evidently basic recommended health and hygiene practices like hand washing after toilet use and prior to meals should always be observed*' (Richert et al., 2010, p. 27).

The harvest and the subsequent steps include considerable risks for pathogen transmission (see below, p. 69). The post-harvest handling of plants eaten raw is especially of importance (barrier VIII). Generally, all crops should be washed before they are consumed (approximately 1 log pathogen reduction). Cooking and peeling of vegetables and fruits can reduce pathogens by an order of 2 – 6 log units and should always be applied (see Table 17) (Richert et al., 2010). See Table A.5, (Appendix, p. 115) for a comparison of different additives used for washing lettuce in regard of their efficiency to remove faecal coliform.

(EP_{other}) Other exposure

Urine contains more nitrogen than potassium and phosphorus in relation to plant requirements (Nordin, 2010). Leaching nitrogen due to over-application of urine can lead to elevated levels of nitrate in the groundwater. Groundwater with high levels of nitrate used for drinking purpose can cause methemoglobinemia in babies (Blue Baby Syndrome). Besides, excessive amounts of N and P can lead to eutrophication of surface waters (fresh and salt water). This may result in conditions causing an algae bloom and growth of cyanobacteria. The toxins produced by algae and cyanobacteria may lead to e.g. gastroenteritis, liver damage or nervous system impairment, in case contaminated drinking water is consumed. Further e.g. skin irritation may appear if affected surface waters are used for recreational purposes (WHO 2006a; WHO 2006b). Over-application of urine may also cause soil degradation due to high salinity (Richert et al., 2010).

Risk mitigation

In case urine is applied undiluted, it is important that the amount of urine is aligned to the N demand of the crops, fruits or vegetables to prevent over-application and therefore potential leaching of nitrogen and phosphor, as well as additional NaCl import. Local recommendations for mineral fertilizer can be used to calculate the urine equivalent. The N-demand can be further determined by back-calculating it from the amount of nutrients removed through the harvest. Otherwise experiments should be conducted to determine the actual demand (Richert et al., 2010). Applying urine in smaller amounts, but more frequent, may be a solution to prevent leaching of nutrients by (heavy) rainfall events or in sandy soils (Münch & Winker, 2011). Dilution of urine also reduces the risk of over-application. The amount of water used to dilute the urine should correspond to the water needs of the crops. A major disadvantage of urine dilution on household level is an increased effort due to higher volumes. There are no general recommendations for dilution of urine, common ratios are 1:1, 1:3 and 1:5 (Richert et al., 2010). Diluted urine applied in irrigation systems is referred to as *fertigation* (Tilley et al., 2014). The smell of urine may be unpleasant for some users and can be reduced via dilution. The ammonia formed during the storage (see Equation 2, p. 53) causes the characteristic odour of urine. It is therefore a good indicator for the quality of the fertilizer, i.e. amount of nitrogen (Gensch et al., 2011).

Ash or dehydrated faeces can be used to cover the residual nutrient requirements of phosphorus and potassium (Nordin, 2010).

High salinity of soils is mainly of concern in arid and semi-arid regions, where salts accumulate over time due to the absence of washing rainfall events. Besides, inefficient drainage, climate and type of soil is affecting the accumulation of NaCl as well (WHO, 2006b). Salt stress can cause substantial losses in crop production. The salt sensitivity of plants depends on the plant species and the temperature (Richert et al., 2010). Using fertilizers with high organic contents will act as a buffer to prevent high salinity of the soil (WHO, 2006b). Table A.6 (Appendix, p. 116) shows tolerance level of common plants in concern of salinity.

'*Regarding hormones and pharmaceuticals excreted with urine, the risk of negative effects to plants or human beings is low if urine is spread on agricultural land at levels corresponding to the plants needs*' (Richert et al., 2010, p. XI). Moreover, urine contains low contents of heavy metals (determined by the amount of heavy metals ingested via food) as opposed to artificial mineral fertilizer which may contain relatively high amounts (Münch & Winker, 2011).

APPLICATION OF DEHYDRATED FAECES

The concentration of pathogens in faeces is high in comparison to urine (WHO, 2006b). Hence faecal matter from UDDTs requires primary and secondary treatment. Both takes place in the vaults in case Double Dehydration Vaults are used (see above, p. 46) (Jönsson et al., 2004). '*Disposal of faecal material from UD toilets requires particular attention, as community and environmental health may be negatively affected by poor practices*' (Austin, 2007, p. 189). Figure 29 shows a schematic of a person applying dehydrated faeces to fertilize maize.

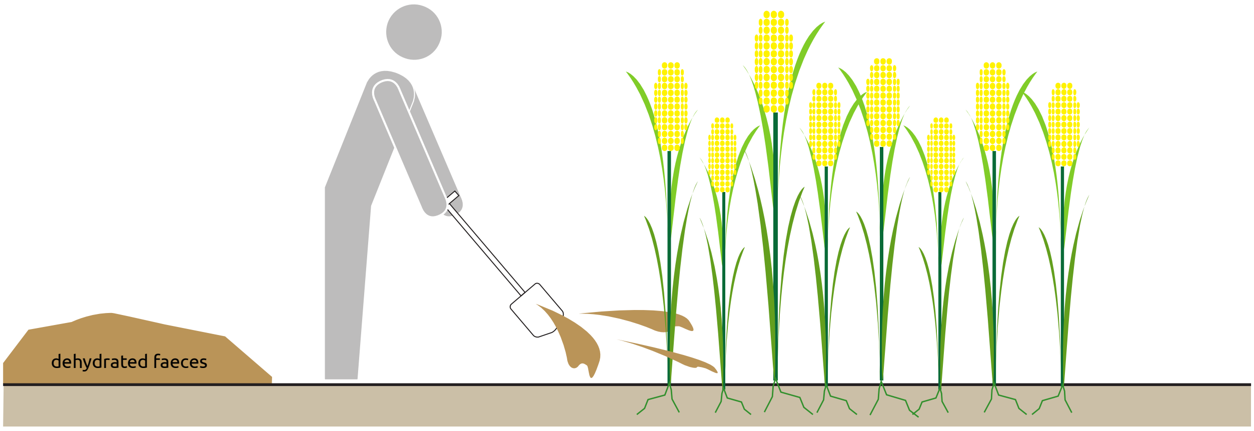


Figure 29: Application of Dehydrated Faeces to fertilize crops or other plants (Tilley et al., 2014, p. 146).

WHO guidelines (2006b) designate guideline values for large-scale systems only (< 1 helminth eggs per gram total solids and < 1000 *E. coli* per 100 ml contained in treated faeces). These values require usually a post-treatment of the faeces and is strictly required for large-scale systems (handling and application of dehydrated faecal matter, and/or consumption of fertilized products by third parties). No guideline values exist for handling and reuse of dehydrated faeces from UDDTs and consumption of fertilized products on household level. It is assumed that pathogen transmission from person-to-person (e.g. via handshakes, coughing, hugs) is more likely than through handling of the faecal matter and consumption of fertilized products (Rieck et al., 2012).

‘*It is however recommended to apply post-treatment for any case of reuse if possible in order to reduce the remaining infectious risk still prevalent after dehydration*’ (Rieck et al., 2012, p. 32). Methods for post-treatment of the faecal matter include composting, vermi-composting, drying, chemical sanitization and solar heat treatment (Rieck et al., 2012).
Research proved urea to be a promising treatment method for pathogen inactivation of (source-separated) faecal matter based on ammonia sanitization and elevated pH (Nordin, 2010; Vinneras, 2007; Vinneras, 2002). Urine is a natural source of urea, which is dissociated with the help of the enzym urease and ammonia is formed (Equation 2 & 3, p. 53). McKinley et al. (2012) achieved a log 2 reduction of *Ascaris suum* ova in a laboratory setting after 8 weeks of storing faecal matter (945g; including ash; constant storage temperature of 20°C in airtight containers) from UDDTs treated with stored urine (900ml).

Table 15 (p. 59) shows excreted nutrients per person and year exemplarily for Sweden. Rose et al. (2015, p. 1845) highlight that these values are very variable and depend mostly on the diet, '[t]*he intake of elements is therefore the most important variable*'. The nutrients are preserved during treatment, only nitrogen will be diminished due to ammonia losses. The organic matter is conserved for the most part, only the very easily degradable parts are lost in form of carbon dioxide (CO_2) and water (H_2O). Generally, the faster the desiccation, the smaller the losses of nitrogen and organic matter. This is based on the fact that decreasing moisture contents lead to slowed biological degradation (Jönsson et al., 2004). Fast desiccation results in nitrogen losses of approximately 50% (Trémolières et al., 1961 as cited in Jönsson et al., 2004).
The actual nutrient contents and the corresponding fertilizing effect after treatment is therefore more variable as compared to urine. The high contents of organic matter of faeces increases the water holding and ion-buffering capacity of the soil, leading to an improved soil texture and microbial activity. Faeces contain higher concentrations of phosphorus and potassium than urine, which may increase the yield significantly (WHO, 2006b). The potassium content will be increased additionally if ash is used as cover material. The nutrients are degraded by microbial activity in the soil and are therefore released slowly. Sieving of the material is necessary if non-degradable material (e.g. sanitary pads) has been disposed of in the vaults (Rieck et al., 2012). This usually applies to degradable material (e.g. toilet paper) too, since the decomposition under low moisture conditions is limited and will not degrade regardless of time (Water Aid, 2011).

Pathogens may be either (i) attached to the plant surface, (ii) taken up by roots, or (iii) internalized into plant tissue. The latter route is neglectable concerning the small amount of pathogens that may enter the tissue of healthy plants in comparison to the amount that is potentially deposited on the surface. Hence, pathogens attached at the plant surface are of major concern from a quantitative exposure point of view. Nevertheless, damaged or wounded plants and plants with a large surface area (e.g. leafy plants) are of higher risk to be contaminated. The pathogen survival is mainly affected by the initial dose, time and environmental factors (Drechsel et al., 2010). Table 18 lists factors influencing the survival of pathogens in the environment. Pathogens in the soil are less exposed to these factors as compared to pathogens deposited on the surface of crops (WHO, 1989). The survival time of *Ascaris*, bacteria, viruses and protozoa in soils is therefore significantly higher than on crops, as shown in Figure 30 (see Table A.7, Appendix, p. 117 for a more detailed observation).
The actual environmental conditions play a key role for the reduction of pathogens once they are present in the soil or on the crop surface. The time between last application and harvest (withholding time) is therefore a very important measure to minimize risks. Harvest practices are also an important factor to consider, as cut surfaces (or injury of plant tissues) are entry points for pathogens to find their way into deeper tissues where disinfection or washing is ineffective. The risk emanating from contaminated crops depends also whether the crops are consumed at household level, or e.g. sold and consumed by others. Studies have shown increasing pathogen concentrations of crops through contamination, recontamination and cross-contamination in case plants are not cooled on the way from harvest to final point of sale. Retaining pathogen levels or even further inactivation is only possible if crops are kept at controlled temperatures (Drechsel et al., 2010).

Table 18: Factors affecting pathogen survival in the environment (Drechsel et al., 2010, p. 244).

Factor	Comment
Humidity / precipitation	Humid environments favour pathogen survival. Dry environments facilitate pathogen die-off. Rainfall can result in splashing of contaminated soil on crops.
Temperature	Most important factor in pathogen die-off. The impact of temperature varies for different pathogens. High temperatures lead to rapid die-off, normal temperatures lead to prolonged survival. Freezing temperatures can also cause pathogen die-off.
Acidity / alkalinity (pH)	Some viruses survive longer in more acid, i.e. lower pH soils, while alkaline soils are associated with more rapid die-off of viruses. Neutral to slightly alkaline soils favour bacterial survival.
Sunlight (UV radiation)	Direct sunlight leads to rapid pathogen inactivation through desiccation and exposure to UV radiation.
Foliage / plant type	Certain vegetables have sticky surfaces (e.g. zucchini) or can absorb pathogens from the environment (e.g. lettuce, sprouts) leading to prolonged pathogen survival. Root crops are more prone to contamination and facilitate pathogen survival.
Competition with native flora and fauna	Antagonistic effects from bacteria or algae may enhance die-off. Bacteria may be preyed upon by protozoa.

If crops are supposed to be consumed by others than members of the household (give away, or sale), a post-treatment (e.g. composting, vermi-composting, chemical, solar heat, incineration) of dehydrated faeces is necessary (Rieck et al., 2012; WHO, 2006a).

As already highlighted before, the preceding treatment is important for the subsequent risk (i.e. during application and for consumption). The aim of the treatment in the vaults is to get a hygienically safe product in the end. Nevertheless, a complete inactivation of all pathogens cannot be assured (see Chapter 5.3.2, p. 45) (Schönning & Stenström, 2004). The already mentioned multi-barrier approach is therefore used to minimize the risk of infection to tolerable levels. This is achieved by introducing the following barriers: (I) source separation, (II) storage and treatment, (III) application technique, (IV) crop restriction, (V) withholding time, (VI) personal protection, (VII) hand washing, and (VIII) post-harvest measures (WHO, 2006b).

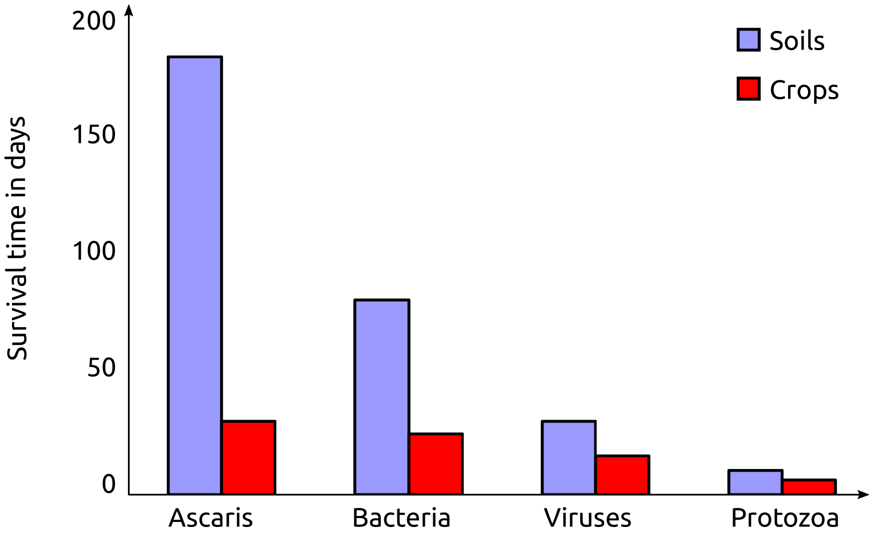


Figure 30: Survival time in days of *Ascaris*, bacteria, viruses and protozoa in soil and on crops from untreated faecal sludge applied to fields in warm climates (Strauss & Blumenthal, 1994 as cited in Austin, 2007, p. 104).

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1, EP_2, EP_4 EP_5 EP_9

(EP_1, EP_2 & EP_4) Ingestion of excreta, Dermal contact & Inhalation of aerosols, particles

The exposure risk is generally small as long as recommendations for storage and pre-treatment are adhered to. Especially dry vaults and storage times of a minimum of 12 months (for temperatures > 20°C, shorter retention times are possible if temperatures are higher and pH-values > 9 are achieved, see Table 10, p. 46) are important for a proper treatment and minimizes the risk of exposure to pathogens (see Chapter 5.3.2, p. 45). Neglecting recommended treatment measures can lead to substantial exposure to pathogens. Small amounts of dehydrated faecal matter may be ingested during application (Stenström et al., 2011). Especially children are of concern if burial is not done properly, as they may be exposed to potentially contaminated material during playing (Moilwa & Wilkinson, 2006). The risk of exposure to aerosols and particles from applying dehydrated faeces is normally low (Stenström et al., 2011). Sieving of the material (e.g. to separate toilet paper or sanitary pads) may increase the risk of inhaling aerosols or ingesting excreta. The risk for dermal contact with contaminated soil or dehydrated faeces is especially of concern in regard of helminth transmission.

Risk mitigation

Equipment that has been in contact with unsanitized or fresh faeces should not be used for handling sanitized material (e.g. stick used to flatten pile) (Schönning & Stenström, 2004).

Application of the dried material should not be undertaken on a windy day to prevent inhalation and ingestion of aerosols (Stenström et al., 2011). Wearing a mask during sieving may minimize the risk for inhalation of aerosols if the material is very dry.

Barrier III, Application techniques:

Treated faeces should not be distributed on the surface but rather worked into the soil as soon as possible and covered with a layer of soil of minimum 8cm (Rieck et al., 2012; Schönning & Stenström, 2004). Faeces should not be applied to fields which are prone to soil erosion or supposed to be plowed later on (Rieck et al., 2012). This reduces the risk for human and animal exposure (except for helminths) and potential contamination of surface waters (Schönning & Stenström, 2004).

Barrier VI, Protective equipment:

Gloves for personal protection should be used when handling treated faeces (Schönning & Stenström, 2004). It is further recommended to change clothes after the application (Stenström et al., 2011). See mitigation measures of conveyance, EP_1 and EP_2, p. 58 as well as EP_4 and EP_8, p. 59 for further recommendation to mitigate the associated risk.

Barrier VII, Hand washing:

'*Hand washing* [using a detergent (i.e. soap; if unavailable, ash or soil)] *should naturally be done*' (Schönning & Stenström, 2004, p. 29).

(EP_9) Consumption of contaminated produce

'*The main exposure, however, occurs after contact with the crops grown*' (Stenström et al., 2011, p. 86). Application of water for irrigation purposes may cause splashing of contaminated soil onto the crops (Drechsel et al., 2010). Contamination of products may also occur during harvest or in the subsequent steps on the way from the farm to the table (Drechsel et al., 2010).

Risk mitigation

Drechsel et al. (2010) state that there are hardly any studies about crop contamination in regard of traditional irrigation methods (e.g. buckets, watering cans). A simple measure to prevent splashing of potentially contaminated soils onto crops is to use an outflow rose (i.e. cap with holes) for watering cans from a height less than 0.5m. A study from Ghana has shown significant reductions of thermotolerant coliforms (2.5 log) and helminths (2.3 eggs per 100 g) for irrigation of lettuce by using this method as compared to watering without an outflow rose from a height of 1m (Keraita et al., 2007 as cited in Drechsel et al., 2010).

Barrier III, Application techniques:
Treated faeces should be worked into the soil and covered with a layer of soil with a minimum depth of 8cm (Rieck et al., 2012; Schönning & Stenström, 2004). It should be applied in the root zone of the soil before sowing or planting occurs. The high content and availability of phosphorus is advantageous especially during the development of roots and small plants (WHO, 2006b; Jönsson et al., 2004). '[T]*he faecal matter must be applied at a depth where the soil stays moist, because the P only becomes available to the plants at the rate that it dissolves in the soil liquid. Likewise, the water-holding and buffering capacity of the organic matter are fully utilized only in moist conditions*' (Jönsson et al., 2004, p. 26). For regions with a definable dry season and cultivation period, application is recommended during the dry season or at the end of the previous cultivation period. For application at a smaller scale, the product is normally applied in furrows or holes close where plants will be growing and are covered with unmixed soil afterwards. For details about application rates see source, p. 28f (Jönsson et al., 2004).

Barrier IV, Crop restriction:
'*Application of treated faeces is safest when applied to fruit trees, rather than vegetables or root crops. Crops that are processed further, such as coffee or cotton, are also low-risk crop options*' (Rieck et al., 2012, p. 32). Fertilization of vegetables, fruits or root crops which are to be consumed raw (e.g. salad or root crops like radish or onion; excl. fruit trees), or plants growing close-to-ground (e.g. pumpkin) include a higher risk. The longer the rotation time, the smaller the risk (Stenström et al., 2011; WHO, 2006b; Schönning & Stenström, 2004).

Barrier V, Withholding period:
Like in case of urine application, it is recommended to stick to a minimum withholding period of one month between last application and harvest of the plants. Microbial activity, desiccation and UV-radiation leads to additional pathogen reductions (EcoSanRes, 2005; Schönning & Stenström, 2004). The aim of the treatment is '*to fully or substantially eliminate pathogens before their application as fertilizer. Nevertheless, in practice, inactivation of pathogens in the soil may contribute importantly to overall risk reduction*' (WHO, 2006b, p. 42). Pathogen destruction in the soil or on crops is obviously higher for hot and sunny conditions as compared to cool, cloudy or rainy weather or climate. The surface of crops (e.g. hairy, rough, sticky, crevices) influence die-off of pathogens by shading from UV-radiation (WHO, 2006b). Ceasing the water application (irrigation) a few days before the plants are harvested results in adverse conditions for pathogen growth (increased temperature, desiccation and sunlight) (Shuval et al., 1986 as cited in Drechsel et al., 2010). Nevertheless, stopping the irrigation in hot climates can cause high yield losses (Drechsel et al., 2010).

Harvest, processing and marketing:
'*Harvest is a key step along the contamination pathway* [from farm to table] *as it involves the injury of plant tissues*' (Drechsel et al., 2010). The equipment used to harvest crops, fruits and vegetables is often in contact with bare hands, crops and the soil. It is therefore important to use properly cleaned and sanitized tools for that purpose. Using baskets or plastic sheets during harvest decrease the risk for cross-contamination of crops if they come into contact with the soil (or other agricultural inputs like manure). Internalized pathogens or pesticides on the surface of crops, vegetables or fruits cannot easily be removed with conventional washing or disinfection methods (e.g. 15% solution of trisodium phosphate completely removed *Salmonella* at the surface of tomatoes, and led to a 2 log reduction of internalized pathogens). Elevated temperatures, together with the initial microbial load and time, are the main determinants for microbial growth during transportation (to the final point of sale or to the site where it is processed and marketed). Vegetables are exposed to high temperatures if they are packed in closed plastic bags, thus this should be avoided. Cool storage during transportation is often not available, storing the crops in the shade is then a simple measure to keep temperatures at a lower level. See source (p. 247ff) for more recommendations during processing and marketing (e.g. provision of handwashing facilities, avoid ill individuals

harvesting or handling produce) and final point of sale. Markets, transportation and retail traders can (theoretically) be influenced and/or regulated with the help of governmental guidelines and control measures. Nevertheless, formal regulations will not be suitable to induce a change in the consumer behaviour. Raising awareness for the risk and promote safe food-handling behaviours should be undertaken instead. Education should target different audiences like schoolchildren, women or households (Drechsel et al., 2010).

Barrier VIII, Food handling and cooking:
Proper handling of plants before consumption is important, especially for those eaten raw. Produce should always be washed with water before consumption to reduce pathogen and, if present, pesticide levels. Depending on the surface of the crop, pathogen reductions of 1 – 2 logs can be achieved (WHO, 2006b). '*Helminth eggs were most effectively removed from lettuce by washing with water under an open tap; this achieved a reduction from nine eggs per 100g to one egg per 100g* [~ 1 log reduction]' (Drechsel et al., 2010, p. 97). Additives like salt, lemon, soap, vinegar or bleach enhance pathogen and pesticide removal. The reduction of pathogens is determined by the contact time, used sanitizer and water temperature. Faecal coliform can be reduced by up to 4.7 log units with this measure (see Table A.5, Appendix, p. 115) (Drechsel et al., 2010).
Cooking and peeling of vegetables and fruits can reduce pathogens by an order of 2 – 7 log units (see Table 17, p. 63) (WHO, 2006b; WHO, 2006c). Cooking may be also '[...] *contra-effective when the melting point of the pesticide is over 100°C, like in the case of Lindane analysed on tomatoes in Ghana. In this case, the tomato skin cracks when boiled and the pesticide can enter the fruit body*' (Obuobie et al., 2006 as cited in Drechsel et al., 2010, p. 251).

(EP$_5$) Contaminated groundwater/surfacewater

Over-application of treated faeces can lead to eutrophication of surface water. Post-treatment with low N losses (or even an increase due to urea treatment) can cause elevated levels of nitrate in groundwater if applied in excess. This can have serious environmental as well as health impacts (see above, p. 64 for more details) (WHO 2006a; WHO 2006b; Nordin, 2010).

Risk mitigation

The nitrogen content of faeces depends on the treatment (see above, p. 66). High pH-values (e.g. using wood ash or lime as cover material) result in significant losses of NH_3 by volatilization. Ash is rich in K and P, ash and lime are able to increase the soil buffering capacity and pH. Many post-treatment methods result in large losses of mineralised nitrogen also (N in its organic form is less plant-available). It is therefore recommended to apply faeces according to the phosphorus or organic material demand of the crops. If N losses are kept at a minimum or the N content is even elevated (e.g. via urea treatment), the application rate of faeces has to be related to the N demand of the crops to prevent leaching and volatilization (Nordin, 2010)

INFILTRATION OF URINE INTO THE GROUND

The on-site infiltration of urine via a soak pit or subsurface infiltration trench (see Figure 31) obviate the need for storage, treatment and transportation of urine and is therefore the simplest method to manage urine from UDDTs. Besides this apparent advantage, it can have negative impacts to the groundwater. The risk of direct exposure to humans or animals can be neglected because both options are below the surface. Furthermore the nutrients (nitrogen, phosphorus, potassium, sulphur and micronutrients) are not utilized that way and simply lost. Soak pits can be lined or unlined, the latter option requires to be filled with coarse gravel (or e.g. coral) for stability. A slightly raised ring beam with a lid demarcates the pit, allows access for maintenance and prevents objects falling into it (potential source of clogging). Infiltration trenches consist of a punched pipe (e.g. 5cm diameter) placed in a gravel lined trench in a depth of 0.5 – 1m (or shallower) and allow urine to be dispersed over the length of the diffuser. Plants planted next to the trench can make use of the nutrients if their roots reach this depth. Evaporation and capillary

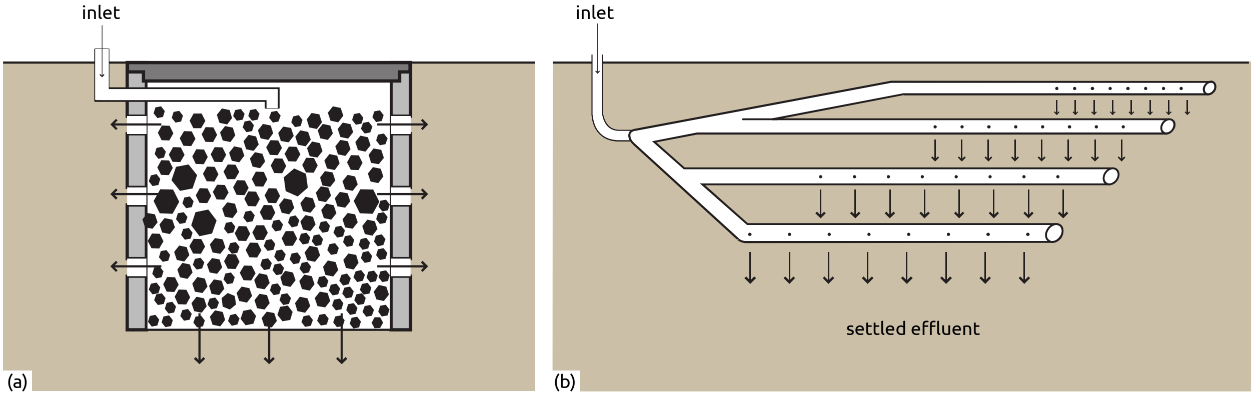


Figure 31: A soak pit (a), or a subsurface infiltration trench (b) can be used to infiltrate urine into the ground (Tilley et al., 2014, p. 152, p. 154, adapted).

rise can lead to increased uptake of nutrients, lowering the risk for groundwater contamination that way. Salinity may be a problem (Tilley et al., 2014; Rieck et al., 2012). '*The fate of the infiltrated urine depends on the quantity, infiltration basin size, as well as soil and climatic conditions*' (Rieck et al., 2012, p. 33). See Tilley et al. (2014, p. 152ff) for technical details of soak pits and leach fields. The stated dimensions of the pit and the leach field are for infiltrating greywater or primary treated blackwater. The pit or trench used for infiltrating urine on household level can be dimensioned smaller.

The infiltration of urine presuppose good absorptive properties of the soil. Harvey (2007, p. 193) notes a simple way to measure the soil infiltration rate by forcing '*an open steel cylinder (i.e. without ends)* [...] *a few centimetres into the soil so that it stands upright* [..., fill it] *with clean water and measure the fall in water level at convenient intervals (5, 10, 20, 30 minutes)*' and calculate the rate for each interval and the mean for the total time. This test should be undertaken at the same depth as the bottom of the soak pit or trench is supposed to be.

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_5

(EP_5) Contaminated groundwater

The risk of pathogen transmission to groundwater from urine infiltrated into the ground is insignificant. This may only be of concern if heavy cross-contamination with faeces occurs. The main problem of urine infiltration are potentially elevated levels of nitrate (NO_3) in the groundwater which can cause the 'Blue Baby Syndrome' if the water is consumed by infants (Rieck et al., 2012). When urea comes into contact with water in the ground, it quickly dissociates to ammonia (NH_4) (see Equation 2, p. 53) and forms nitrate by bacterially-mediated oxidation ($NH_4^+ + 2\ OH^- + 3\ O_2 \rightarrow 2\ NO_2 + 4\ H_2O$; $2\ NO_2^- + O_2 \rightarrow 2\ NO_3$) (ARGOSS, 2002). NO_3 is further reduced to nitrogen gas (N_2) under anaerobic conditions which is stable and may outgas to the atmosphere (Nick et al., 2012). Under aerobic conditions, nitrate is stable (rarely combining with other compounds), does not bind to soil particles (like other contaminants) and is soluble in water. It is therefore easily transported to the aquifer via percolating rain or irrigation water and can potentially cause problems kilometers away from the source (Odong, 2007). '*The actual problem with nitrate in groundwater used as drinking water is its persistence under aerobic conditions; it takes advanced, high cost treatment processes to remove nitrate from contaminated drinking water. Thus long term accumulation should be prevented*' (Nick et al., 2012, p. 4). Nitrate values above the WHO guideline value of 50mg/L (corresponding to 11.3mg NO_3-N/L) can be harmful to infants (Nick et al., 2012; ARGOSS, 2002).

Risk mitigation

Infiltration may be a viable option if the groundwater is not used as a drinking source and if there are no plans to do so in the future. In case groundwater is used for drinking purposes, a risk assessment of potential impacts from urine infiltration is necessary. This assessment includes considerations concerning groundwater level, soil conditions and evapo-transpiration of the surrounding vegetation (Rieck et al., 2012). If a proper assessment is not possible, general siting recommendations of pit latrines should be followed (see Chapter 5.2.2, p. 34) (Tilley et al., 2014). '*In areas with a high risk of groundwater contamination (highly conductive soils, high water table, heavy precipitation) and where groundwater is the sole source of water, soak pits should not be used. In such scenarios, reuse of urine in gardening and agriculture should be promoted instead*' (Rieck et al., 2012, p. 33).

Causes and potential measures to prevent cross-contamination of urine have been discussed already (see above, p. 43).

A further option to reduce NO_3 input to groundwater is to infiltrate the urine close to fruit trees, bushes or other plants which make use of and absorb the nutrients (Rieck et al., 2012).

Discharging the urine to an evapo-transpiration bed including a subsurface overflow may be another option to reduce the nitrate input to the groundwater (see Chapter 5.4.2).

BURIAL OF DEHYDRATED FAECES IN THE SOIL

Burial of dehydrated faeces in the soil is the '*simplest and most effective method for the disposal of faecal matter from UDDTs*' (Rieck et al., 2012, p. 29). It requires sufficient space and is therefore more appropriate for peri-urban or rural areas. The nutrients and the organic matter of the faeces can be utilized if it is buried close to fruit trees, cash crops or other plants. Dehydrated faeces from double vault systems do not require post-treatment for disposal via burial in the soil (Rieck et al., 2012). Figure 32 shows a schematic of a person in action applying dehydrated faeces close to a tree.

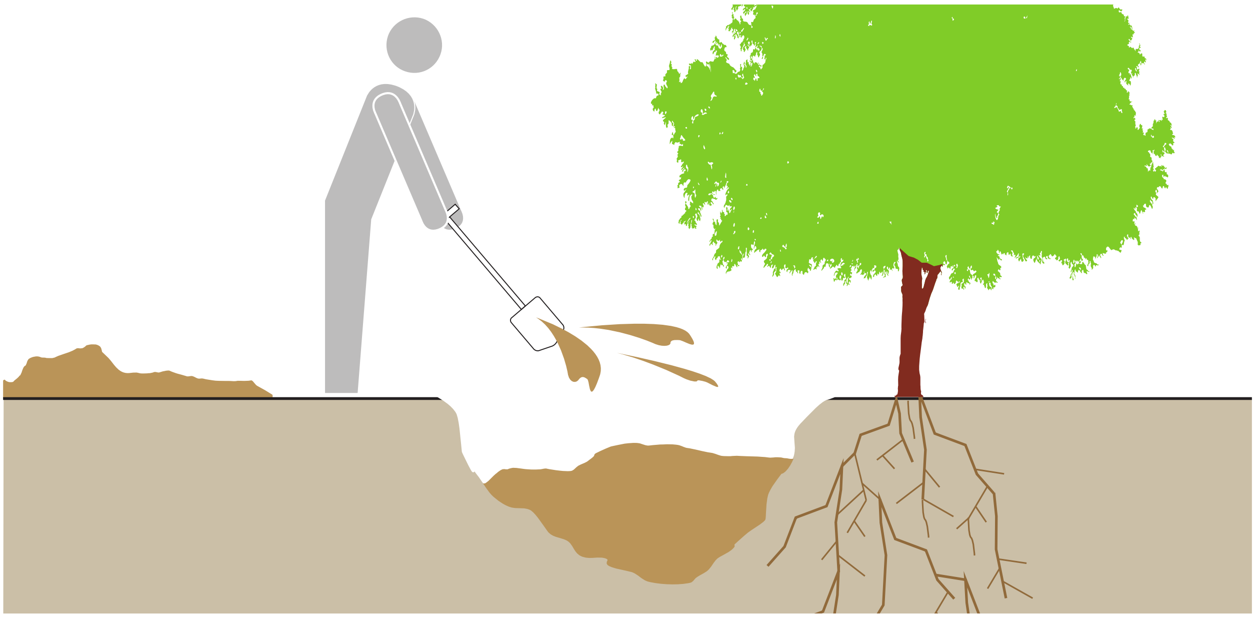


Figure 32: Burial of Dehydrated Faeces in the Soil. Application next to a tree minimizes the risk of human contact and pathogens to be resurfaced or discharged to groundwater (Tilley et al., 2014, p. 146, 140, adapted).

Exposure Pathways and Risk Mitigation

EP_1, EP_2, EP_4 EP_5

(EP_1, EP_2 & EP_4) Ingestion of excreta, Dermal contact & Inhalation of aerosols, particles

Similar to exposure during emptying of the vault (see Chapter 5.3.3, p. 58) and application of dehydrated faeces (see Chapter 5.3.4, p. 68). Besides the exposure pathways mentioned in these chapters, the buried material may be also resurfaced due to erosion (rain, wind), burrowing animals or humans (e.g. playing kids, excavation work).

'*Under ordinary circumstances, faecal material buried at sufficient depth does not pose a significant risk to human health*' (Rieck et al., 2012, p. 29). Research in El Salvador revealed that households which buried dehydrated faeces from UDDTs in their gardens were more likely to be infected with *Ascaris* and *Trichuris* in comparison to pit latrine users (8.3 and 3.7 times, respectively). Nonetheless, hookworm, *Girardia* and *E. histolytica* infections were significantly lower for households burying their faeces. Children were 11.5 times more infested by *Ascaris* than people of the highest age category. Storage times of the faeces were between weeks to months (Corrales et al., 2006). Short storage times may be the reason for the high prevalence of helminths. Besides, the authors (2006, p. 1828) remark that '[t]*he transmission of these infections is due not only to environmental sanitation conditions, but also to the interaction of various socioeconomic and cultural factors*'.

Risk mitigation

See risk mitigation measures during emptying of vaults (EP_1 & EP_2, p. 58 and EP_4, p. 59) and application of faeces (EP_1, EP_2 & EP_4, p. 68).

Faeces should be buried and covered with a soil layer with a minimum depth of 25cm (WHO, 1989). This prevents potential exposure of faeces due to heavy rainfall, burrowing animals or digging humans (Rieck et al., 2012). '*Children are more likely than adults to* [be exposed because they may ...] *play in areas where excreta are dispersed*' (Corrales, 2006, p. 1828). Disposal sites should be therefore clearly demarcated (Rieck et al., 2012). Burial next to a tree or bushes (see EP_5) may prevent the material from being dug up again, or children being exposed to the material by acting as a physical barrier (Niwagaba, 2009). Root crops should not be planted directly on top of the burial site (WHO, 1989). The buried faeces mineralises gradually and becomes pathogen free eventually, but pathogens with high persistence (e.g. helminths) are of concern (O'Lorcain & Holland, 2000).

(EP_5) Contaminated groundwater

'*Clearly, the lower pathogen loads in dehydrated faecal matter from double vault UDDTs reduce the risk of contamination of groundwater*' (Rieck et al., 2012, p. 29). Nevertheless, research has shown significantly elevated levels of *E. coli* and *Staphylococci* in the leachate of buried faeces from UDDTs which may percolate to and contaminate the groundwater (Guness et al., 2006).

Risk mitigation

Burial next to trees or bushes reduces the risk of groundwater contamination or resurfacing of the material due to the interception of rain by leaves, twigs and the stem as well as reduced water infiltration to groundwater caused by plant uptake. The distance from the bottom of the burial site (i.e. pit) and groundwater table should be > 1.5m and not adjacent to water sources (> 30 m apart) (Niwagaba, 2009). '*In order to make the right decision about appropriateness of burial an assessment of groundwater pollution should be carried out*' (Rieck et al., 2012, p. 29). Another measure to minimize potential groundwater contamination could be to bury the dehydrated faeces at multiple points (more than one).

It has to be highlighted that '[b]*oth field and laboratory scale studies clearly showed that buried UD waste cannot be considered an 'out of sight, out of mind' waste management option. Microbial processes continue to occur after burial, even after the waste has undergone a one year standing period. Some of theses processes concern health-related microbes*' (Guness et al., 2006).

5.4. Double Vault non-Urine-Diverting Toilet (Composting Toilet)

Composting Toilets are numbered among dry toilets and are classified as improved toilets according to the JMP (WHO & UNICEF, 2014b). Composting Toilets (see Box 2) differ from UDDTs in regard of the underlying treatment process: UDDTs rely mainly on desiccation (and high pH) for pathogen inactivation, whereas Composting Toilets are supposed to reach sanitization via a composting process. Figure 33 shows an overview of the system.

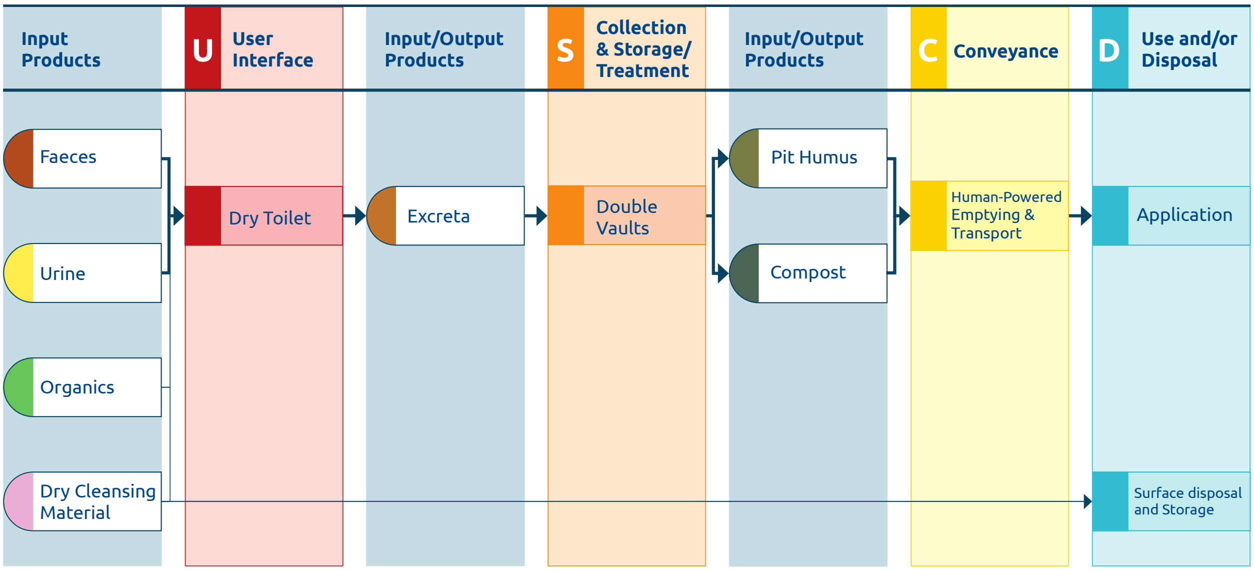


Figure 33: System overview of a Double Vault non-Urine-Diverting Toilet (Tilley et al., 2014, p. 22, adapted).

The Dry Toilet is the standard User Interface of this ‘Waterless System without Sludge Production’, but a Urine Diverting Dry Toilet or a Urinal can be installed optionally. Similar to UDDTs, Composting Toilets can be operated continuously (i.e. Single-Vault) or in batch mode (i.e. Multiple-Vaults). The latter includes either two vaults (i.e. Double-Vault Composting Toilet) or more vaults (e.g. in form of a carousel) for Collection, Storage and Treatment of excreta. Other batch designs use multiple interchangeable containers (e.g. mobile buckets or bins) for collection and transport, the treatment takes place off-site (Berger, 2011). There are also more sophisticated, commercial toilets available (e.g. Clivus multrum, a Single-Vault system).

This thesis focuses on alternated double vaults without UD only, because this type of Composting Toilet is promoted by NGOs in Vanuatu. The inspected Composting Toilets (Blacksands & Salvabay, Efate; Tangovawia, Pele; Pepsi & Solway, Espiritu Santo) seem to be influenced by the design introduced in the context of an 'Eco-Sanitation Workshop' (Crennan & Booth, 2007) held in Port Vila in 2004. The design is similar to the advanced Vietnamese double vaults by Nimpuno (1977, as cited in Rybczynski et al., 1978), urine is not diverted, excess urine and leachate is discharged via a false floor to a soak pit.

The ventilated, alternately used vaults receive faeces, urine as well as wiping and bulking materials (e.g. wood or bark chips, saw dust, ash, paper). It is further beneficial to discard biodegradable household waste into the vaults. The vaults are equipped with a collection system to handle, treat and discharge excess leachate. The ventilation system should enable a good aeration of the compost pile, remove gases and water vapour, and limit odours (Berger, 2011).

The term *composting* was and is still used inflationary for a range of different *eco-san* systems (i.e. ecological sanitation; a often used, ambiguous term also). Many systems containing composting in its name do not achieve a well-working or even no composting process (Schönning & Stenström, 2004). UDDTs are also often referred to as Composting Toilets although no composting process takes place. Rybczynski et al. (1978, p. 16) states '[t]*he term "composting privies" refers to household composting systems, which may be either aerobic or anaerobic*'. Today, composting is primarily defined as aerobic decomposition (aerobic digestion), but anaerobic digestion (anaerobic decomposition or anaerobic fermentation) is continued to be called anaerobic composting especially in North America.

Box 2: Inflationary use of the term *composting.*

The design applied in Vanuatu makes use of a 'false floor' to allow the leachate to be drained to an evapo-transpiration bed next to the toilet and to improve aeration of the compost pile (see Chapter 5.4.2) (Crennan, 2007).

The composting process is a biological degradation of organic matter which continually consumes carbon, oxygen and water. Optimal conditions of these factors lead to temperatures around 50 – 70°C, necessary for biological activity of thermophilic bacteria to enable a fast and substantial pathogen reduction (Rieck et al., 2012; Berger, 2011). '*In practice, these optimal conditions are difficult to maintain. As a result, the output product is often not sufficiently stabilized and sanitized, and requires further treatment*' (Tilley et al., 2014, p. 72).
After the compost had enough time to maturate, Emptying and Transport is usually done Human-Powered (*Conveyance*). The compost is then either applied as soil conditioner, further treated due to potential concerns about the hygienic safety, temporarily stored for later use, or simply disposed of (*Use and/or Disposal*) (Tilley et al., 2014). If urine is diverted, it can be either infiltrated into the ground or collected in container(s) to make use of its nutrients (Berger, 2011).

5.4.1. User Interface

The system in Vanuatu relies on a Dry Toilet User Interface (Chapter 5.2.1, p. 23). Urine diversion via Urine-Diverting Dry Toilet interface (Chapter 5.3.1, p. 40), or a Urinal is optional (Chapter 5.3.1, p. 43). Berger (2011) recommends UD to prevent potential anaerobic conditions in the pile and to minimize the amount of leachate produced (see *(ii) moisture content*, p. 79).

5.4.2. Collection & Storage/Treatment – Double vaults

Two watertight vaults above the ground are used alternately for collection & storage of the excreta, only one vault is used at a time. When the currently used vault becomes full, it is taken out of service and the other one is used from then on instead (after being emptied). Urine and faeces is collected together with cleansing and bulking material in the active vault below the User Interface (Figure 34). Batch systems with multiple vaults offer increased hygienic safety as compared to continuously operated single-vault systems. This is due to the fact that continuously operated single-vault systems include a risk of recontaminating already sanitized material with fresh excreta. Multiple-vault systems on the other hand prevent potential reinfection of mature compost through alternation of the vaults (Berger, 2011; Esrey, 1998).

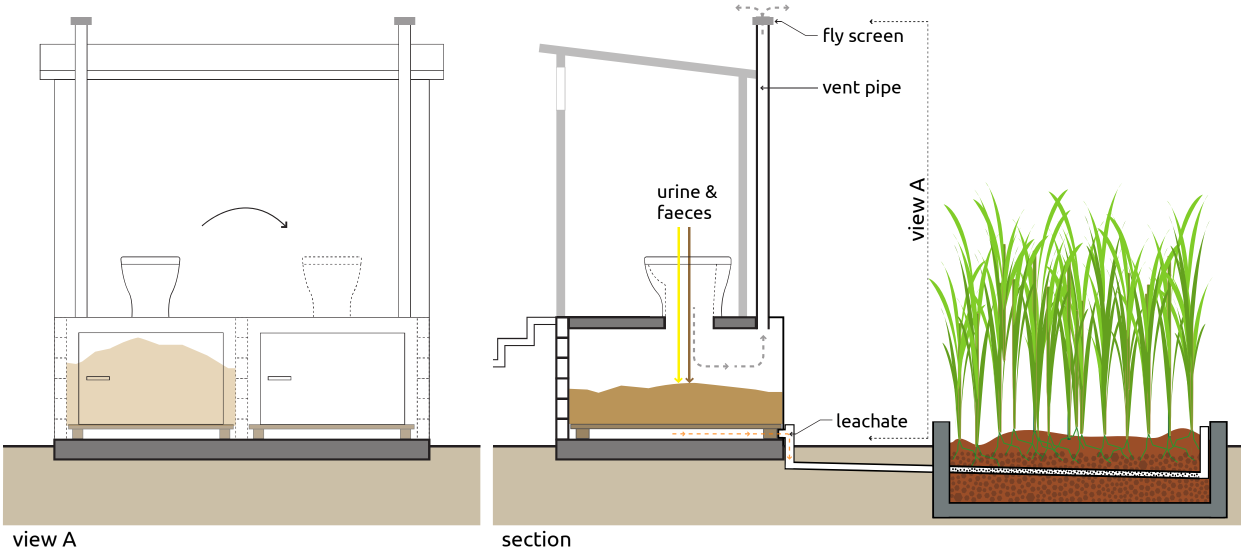


Figure 34: Double Vault Composting Toilet used in Vanuatu. A false floor enhances the aeration of the pile, leachate is drained into an evapo-transpiration bed (can be sited on either side of the cubicle) (Tilley et al., 2014, p. 70, adapted).

The system introduced in Vanuatu seems to be similar to a design proposed by Nimpuno (1977, as cited in Rybczynski et al., 1978), which in turn is based on the Vietnamese double-vault UD Composting Toilet. The Vietnamese double-vault Urine-Diverting Composting Toilet did not include a ventilation pipe when it was introduced to Vietnam in 1956 (Rybczynski et al., 1978). The composting process after the vault is filled up and sealed is therefore anaerobic (Gutterer et al., 2009; Polprasert, 2007; Harvey, 2007; Franceys et al., 1992; Feachem et al., 1983; Kalbermatten et al., 1982). '*It is certain that double-vault* [non-Urine-Diverting] *composters* [without ventilation] *will be anaerobic* […]. *Anaerobicity and ambient temperature certainly are the correct, conservative assumptions to make where pathogen removal is the concern. Pathogen removal then depends on the retention time in the unit*' (Feachem et al., 1983, p. 71ff).
The design from Nimpuno did not divert urine, but included the addition of organic wastes to increase the C:N ratio, a ventilation pipe to improve odours and dehydration, and a perforated bottom to discharge excessive urine or leachate via a 'filter' (layers: coarse sand, charcoal, crushed limestone, ashes, leaves, coarse sand) to a soak-away (Rybczynski et al., 1978).

The applied design of Composting Toilets in Vanuatu are vented via a ventilation pipe (including a fly screen) to improve the air flow into the vault and enable gases to escape (evaporation of excess moisture, CO_2; see Chapter 5.3.2, p. 47 for more details about vent pipes) (Berger, 2011). A false floor helps to improve the air supply of the heap and allows excessive urine and leachate to be drained to an evapo-transpiration (ET) bed. The floor of the superstructure (drainage floor) is slightly inclined for that purpose (e.g. 25mm from one end to the other). A pipe with a diameter between 75 – 100mm connects the vault with the adjacent ET bed (each vault has its own, independent drainage system). The false floor consists of hardwood timber slats (e.g. 50 × 25mm) and is removable. The slats are fixed to a frame (gaps in between should be 15 – 20mm) which is held in position approximately 10cm above the drainage floor (e.g. by concrete blocks). The ET bed (500 × 1400 × 750mm) is either lined with concrete or with plastic (e.g. HDPE). Capped inspection points at both ends of the drainage pipe are important to allow maintenance (e.g. regular cleaning; blockages). The bed is backfilled with large and small aggregate, sand and soil. Afterwards, appropriate vegetation is planted (e.g. banana, papaya) to improve evapo-transpiration and make use of the nutrients. The ET bed can be sited on either side of the toilet cubicle as long as the drainage floor is sloped in that direction (Crennan, 2007).

Before the vaults are fed with excreta, a '*large amount*' of bulking material (e.g. leaves, grass clippings, sawdust, weeds, straw, husks, sawdust) should be applied in the vault to absorb moisture and provide a carbon source. Some authors recommend to add a layer of approximately 10cm of an absorbent (e.g. soil) instead, and some advise to apply both additives. When the vault is about ⅔ to ¾ full, the pile is leveled with a stick and the remaining volume is topped up with dry powdered earth or dry leaves. Some sources further recommend to add ash and organic materials (Crennan, 2007; Harvey, 2007; Franceys et al. 1992; Winblad & Kilama, 1985; WHO, n.d.).

TREATMENT

Composting is a managed aerobic decomposition and stabilization of organic matter by bacteria, fungi and actinomycetes. Pathogen reduction is based on high temperatures caused by thermophilic bacteria (active from 45 – 80°C). These heat affine bacteria cause temperatures above 50°C under optimal conditions (Berger, 2011). Heat treatment is an effective way for pathogen inactivation, high temperatures are considered the most important factor to achieve sanitization during composting (Schönning & Stenström, 2004). Figure 35 shows the relationship between temperature and time in regard of pathogen inactivation. '*If the corresponding temperature-time relationship is achieved in all of the exposed material, it may be considered microbiologically safe for handling and use*' (Schönning & Stenström, 2004, p. 21).

The composting process is classified into three main phases of temperature levels, named corresponding to the type of microorganisms dominating the particular phase: (i) psychrophilic (below 10°C), (ii) mesophilic (10 – 40°C), and (iii) thermophilic (above 40°C) (Figure 36). This classi-

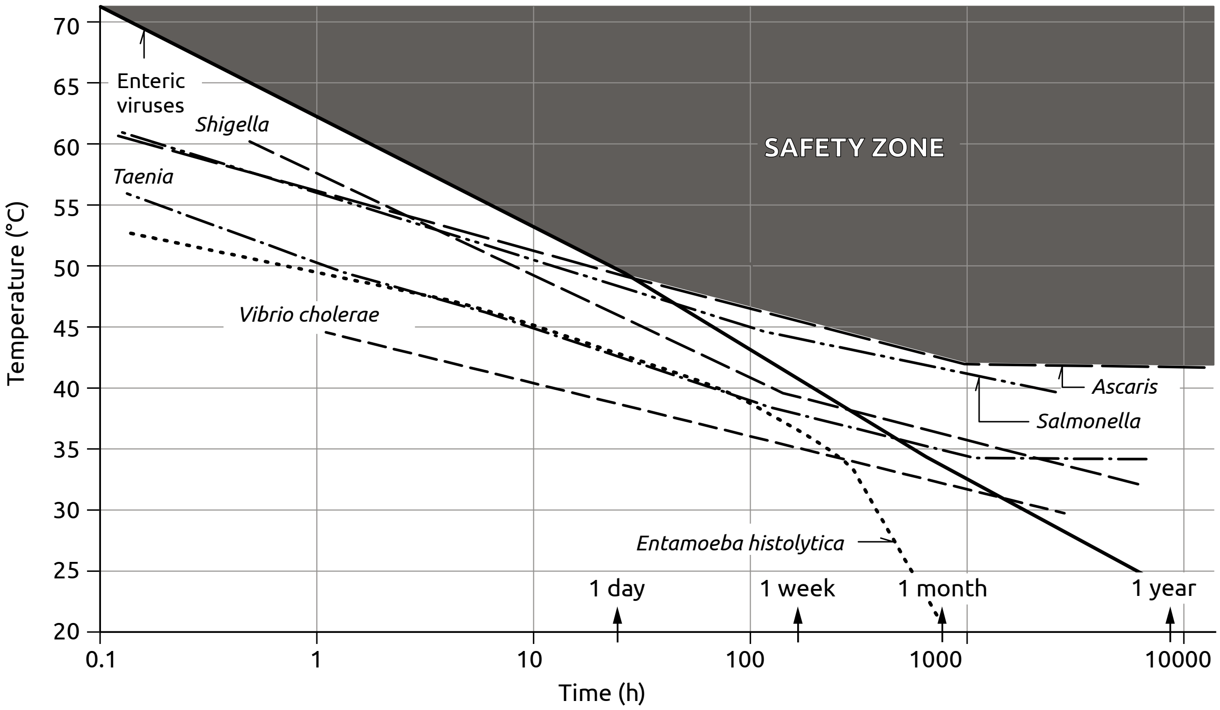


Figure 35: Pathogen reduction in relation to time and temperature (Vögeli et al., 2014, p. 68 after Feachem et al., 1983, adapted).

fication is a rough demarcation of temperature ranges deducted from the prevalent, dominating type of microorganism, having the best growth rates and efficiencies under these conditions. At the beginning of the composting process, microorganisms break down the most readily degradable material. During this process, heat is generated and trapped in the pile causing temperatures to rise. The heat may also be lost due to conduction, convection, radiation or gas emissions. Minimizing these losses is important to facilitate a continuous rise of the temperature, leading to a diversification of the microbial composition. Temperatures reach thermophilic levels usually after a few days. During this phase, intensive microbial activity enable the decomposition of more complex, decay resistant material (e.g. cellulose). In a well managed composting process, temperatures peak around 55 – 70°C. Microbial activity decreases over time due to consumption of readily degradable matter and depletion of oxygen, very high tempera-

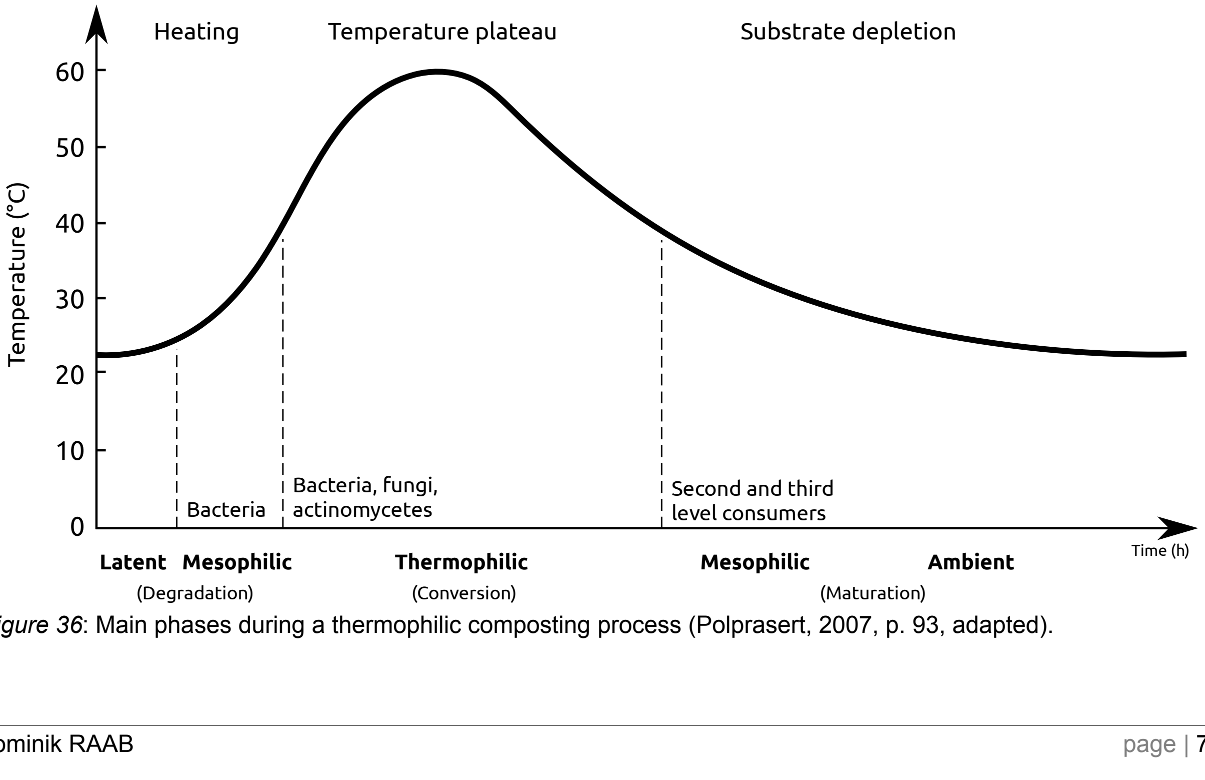


Figure 36: Main phases during a thermophilic composting process (Polprasert, 2007, p. 93, adapted).

tures may harm the organisms too. In this stage, the pile begins to cool as more heat is lost than generated by the microbes. The curing period starts when the mark of 40°C is undershot and is important for the stabilization of the material (USDA, 2010).

The thermophilic phase can only be reached with an aerobic composting process, requiring (i) an appropriate C:N ratio, (ii) a proper moisture content, and (iii) a sufficient supply of air. The inactivation of pathogens depends mainly on the achieved temperatures for a certain period of time during the process (Berger, 2011).

Aforesaid factors are crucial for an effective treatment to reduce the risk of pathogen exposure during emptying, disposal/reuse and consumption. Thus, these factors are discussed in detail:

(i) C:N ratio:

Fresh faeces have a C:N ratio of approximately 6 – 10:1, as compared to urine with a ratio of 0.8:1. Adding urine to faecal material decreases the C:N ratio by increasing the total N input 3 to 8 times (Polprasert, 2007; Jenkins, 2005; Jönsson et al., 2004). The C:N ratio of urine and faeces together is around 7 – 8 (WHO, 2006b).

Microorganisms utilize C as a source of energy and for cellular growth, N is required for cell synthesis. The C:N balance for aerobic microorganisms should be between 15:1 and 30:1. This way, sufficient N is available to allow unobstructed metabolism (Haug, 1993). Polprasert (2007) recommends a C:N ratio of 20 – 40:1, Berger (2011) suggests 30 – 40:1. It is therefore necessary to increase the C content by adding carbonaceous bulking material after defecation (e.g. sawdust, kitchen refuse, toilet paper, weeds, grass) (Redlinger et al., 2001; Esrey et al., 1998).

A higher C:N balance slows the process as it requires the microbes to oxidise the excess C first to reach a proper ratio. A lower balance causes the excess N to be lost additionally to regular losses (USDA, 2010). Regular N losses during the composting process are significant and occur in form of gaseous emissions, leaching and denitrification (USDA, 2010). These losses are usually between 10 – 50%, presumed a proper C:N ratio is given (Eklind & Kirchmann, 2000 and Jönsson et al., 2003 as cited in Jönsson et al., 2004).

Moreover, the high N contents of urine may be lost almost completely during composting through ammonia volatilization (Nordin, 2010; Jönsson et al., 2004; Vinneras et al., 2003). A measure to avoid gaseous ammonia losses are closed containers for composting (Vinneras, 2007). Wood ash used as cover material results in additional N losses during composting (Schönning & Stenström, 2004). This is because a pH > 8 fosters the conversion from ammonium to ammonia. High temperatures favour ammonia volatilization additionally (USDA, 2010). Winker et al. (2009) note that the low levels of N in compost from source-separated faecal matter is therefore rather used as soil conditioner instead of a fertilizer.

Under aerobic conditions, approximately 30 – 50% of the carbon is released in form of CO_2 during the metabolism, whereas N is used non-consumptively and becomes available again when the microorganism dies. Hence the C:N ratio is decreasing over time, as long as there are no excessive N losses. Availability of nutrients is a considerable factor, as there are materials more difficult to decompose (e.g. wood due to resistant lignin) compared to e.g. simple sugars from fruit waste which are degraded rapidly. Except for keratin (e.g. horns, hair, wool, feathers), most N sources decompose rather easily (USDA, 2010).

Easily degradable parts of the matter are likely to be already decomposed if the material is collected over a long period of time, resulting in an additional reduction of the energy content available for the composting process. It is therefore important to compensate this loss of energy by means of co-composting (i.e. using more than one type of feedstock) to provide both, easily available as well as more complex carbon sources to trigger a (thermophilic) composting process (Nordin, 2010; Vinneras et al., 2003). Using inert bulking materials (e.g. ash or soil) leads to a reduced energy concentration in the pile which has to be accounted for by additionally adding '*energy rich materials, such as kitchen waste, and acidic material* [...] *for good compost*' (Schönning & Stenström, 2004, p. 22). A mix of garden and kitchen waste increases the amount of easily available energy (Berger, 2011). Table A.8 (Appendix, p. 118) gives examples of C:N ratios of different materials.

(ii) Moisture content:

A sufficient water content in the heap is important for the transport of nutrients, movement of the microorganisms and as medium for chemical reactions (USDA, 2010). Besides, a proper composting process requires a sufficient supply of oxygen for aerobic microbes at the same time (see below). The optimal water content is therefore between 45 – 65% (water content of fresh faeces is around 65 – 80%). A moisture level below 25% leads to significant decreases in microbial activity (Berger, 2011). Microbial activity stops when the moisture level drops below 15% (USDA, 2010). The wet weight (WW) of urine compared to faeces is about 10:1, corresponding to a dry matter (DM) content of approximately 2:3 (Vinneras et al., 2003).

Amendment and bulking material account between 2 and 5 times the volume of faeces (Franceys et al., 1992). This is because large amounts of amendments are needed '[t]*o get a material with a dry matter content acceptable for composting without active aeration* […]*, resulting in large total volumes to treat* [e.g. 21% faeces, 19% amendment, 60% food waste (DM)]' (Vinneras et al., 2003, p. 53). Bulking materials with good absorptive capacity (e.g. bark, paper), large pore volume and high stability (e.g. straw) influences the tolerance of the composting process in regard of water content and aeration of the pile (Berger, 2011).

Excess moisture in the vault is a common problem of non-Urine-Diverting systems. If air pockets are filled with urine, aerobic decomposition is decelerated due to limited availability of oxygen, or anaerobic conditions stop the composting process and cause bad odours (Stenström et al., 2011; Austin et al., 2005). Hence, UD is an obvious measure to overcome this problem (Chapter 5.3.1, p. 40 and p. 43) (Rieck et al., 2012; Berger, 2011). In case of UD, it may be necessary to manually water the pile if the water content gets below 40%. Besides, UD has two benefits: the amount of leachate is reduced (lower risk of ground- and surfacewater contamination and recontamination of sanitized material), and the N content is at a lower level (reduces amount of bulking material to balance the C:N ratio) (Berger, 2011).

(iii) Aeration:

Aerobic microorganisms use oxygen as electron acceptor to oxidize carbon during metabolism (Haug, 1993). If aerobic biodegradation under optimal conditions takes place, high temperatures lead to fast and substantial pathogen die-off. Bulking material is important to break up the material, otherwise '*the organic matter in the vault may compact and form impermeable layers, which leads to wet and anaerobic conditions*' (Berger, 2011, p. 6). Some bulking materials (e.g. sawdust) are insufficient to increase the pore space in the pile, hampering aeration that way (Redlinger et al., 2001). Aerobic microbial populations need oxygen concentrations ≥ 5% to survive, otherwise '*anaerobic microorganisms begin to dominate the compost pile, slow the composting process, and produce odors*' (USDA, 2010, p. 11).

Metabolism of organisms can be either aerobic, anaerobic or anoxic. Aerobic metabolism uses O_2 as electron acceptor (Equation 6 gives an example with glucose). Anoxic conditions harness oxidized inorganic compounds of N (mainly nitrate, NO_3^- and nitrite, NO_2^-), or sulfur (especially sulfate, SO_4^{2-}) as electron acceptor (Equation 7 shows an example with glucose and sulfate). Alternatively, CO_2 is oxidized to methane (CH_4). In case of anaerobic fermentation, donor and acceptor is the same organic molecule, always resulting in CH_4 and CO_2 as end-product (Equation 8) (Haug, 1993).

aerobic: $$C_6H_{12}O_{6\,(aq)} + 6\,O_{2\,(g)} \rightarrow 6CO_{2\,(aq)} + 6\,H_2O_{(l)} \qquad \text{(Equation 6)}$$

anoxic: $$C_6H_{12}O_{6\,(aq)} + 3\,SO_{4\,(aq)}^{-} + 6\,H_{(aq)}^{+} \rightarrow 6CO_{2\,(aq)} + 6\,H_2O_{(l)} + 3\,H_2S_{(aq)} \qquad \text{(Equation 7)}$$

anaerobic: $$C_6H_{12}O_{6\,(aq)} \rightarrow 3CH_{4\,(g)} + 3\,CO_{2\,(aq)} \qquad \text{(Equation 8)}$$

Excess heat is released during the oxidation under these conditions. Free enthalpy ($\Delta G°_R$) for these exothermic reactions is - 677kcal/mol, - 107kcal/mol (pH = 7) and - 96kcal/mol for aerobic, anoxic and anaerobic conditions, respectively. These numbers clearly show that the potential to elevate temperatures depends on the oxygen supply (e.g. aerobic metabolism releases 673kcal/mol in form of heat) (Haug, 1993).

Bacteria prefer pH-values between 6 and 7.5 during composting (USDA, 2010). Adding alkalifying materials (e.g. ash, lime) can cause a pH of 9 or above, hampering the composting process, '*while still achieving the goal of pathogen reduction*' (Schönning & Stenström, 2004, p. 22). Hill et al. (2013) further notes that the slow degradation process in the vault under mesophilic conditions may be also hampered by the high ammonia content of the urine.

A problem of small-scale composting systems is the fact that uniform temperatures throughout the whole compost pile are not achieved (Tonner-Klank et al., 2007). It is rather that '*cold zones are formed within the digested or compost material, resulting in local areas with less inactivation and possible regrowth of pathogenic bacteria*' (Schönning & Stenström, 2004, p. 21). Cold zones may account for 20 – 50% of the compost pile (Haug, 1993). Tonner-Klank et al. (2007) detected regrowth of enterococci and total numbers of bacteria at temperatures of 36 and 22°C. Elving et al. (2010) demonstrated the potential for regrowth of *Salmonella* Typhimurium, *Enterococcus* spp. and total coliforms for simulated psychrophilic and mesophilic zones in compost heaps of different feedstocks at temperatures of 14, 24 and 37°C. Vinneras (2007) achieved thermophilic temperatures > 60°C and a 5 log reduction of indicator bacteria in a small-scale composting experiment under laboratory conditions (90L reactor, well-insulated; pile was turned over three times during thermophilic period). Nonetheless, outer parts of the heap reached significant lower temperatures, resulting in a risk for regrowth of bacteria and potential recontamination of the already treated fraction (Vinneras, 2007). The author (2007, p. 3320) further notes that temperatures around 50°C might not be sufficient to sanitize excreta, since '*other factors than the temperature will influence the survival of microorganisms in the compost. This can enable unexpected survival or inactivation of both pathogens and indicator organisms*'.

The problem of imbalanced temperatures throughout the pile is the most commonly cited reason for pathogen regrowth and survival in composting systems (Wichuk & McCartney, 2007). Mixing of the pile is considered to be an important measure to prevent pathogen regrowth. Research with an insulated 216L reactor has shown that thoroughly mixing the pile manually is difficult at this scale, which led to a prolonged time needed for sanitization.

Piles with larger volumes achieve higher temperatures as compared to smaller heaps, because their heat losses are lower. It is therefore critical to insulate small compost heaps (e.g. via styrofoam or plastic cells) to trap and maintain heat for a longer period of time, and achieve temperatures above 50°C. Insulation is even important in tropical regions to reach sufficient temperature levels (Niwagaba, 2009; Niwagaba et al., 2009b).

Jensen et al. (2009) achieved a > 2 log reduction of *Ascaris suum* in faecal material (⅓ of the material was collected from UDDTs, ⅔ from non-UD Composting Toilets) after 4 months of 'composting' (i.e. storage) in small heaps (35 – 53kg). They conclude that Double Vault non-Urine-Diverting Toilets may be able to achieve safe-to-use fertilizer after three to four months as long as the latrine content is stirred periodically (valid for conditions present in Vietnam during summer). Ammonia content was identified as most important factor determining die-off of helminth ova, '[t]*emperature increases in the excreta heaps due to microbiological processes were only seen to a limited extent and only within the first three weeks of storage*' (Jensen et al., 2009, p. 6).

Germer et al. (2010, p. 191) achieved thermophilic temperatures in composting vaults (volume: 1.5 m^3; walls out of concrete bricks; door and removable roof out of wooden boards) with and without insulation (5cm styrofoam) under a tropical, semi-arid climate and concluded that '[a]*dditional insulation of simple compost chambers* [i.e. vaults] *does not increase temperature or improve sanitisation* [under these conditions]'. The uninsulated vaults reached core temperatures > 65°C for over 7 days and > 55°C in outer layers for over 14 days. Nonetheless, the authors detected regrowth of *E. coli*, and Enterococci after the thermophilic phase, but the microbiological parameters were reduced to meet standards after a stabilisation phase of 54 days.

Skilled management is necessary for thermophilic composting (Schönning & Stenström, 2004). Besides small compost volumes, Redlinger et al. (2001) identified insufficient operation (control moisture levels via water or soak materials; improve aeration via regular stirring and mixing) as main reason for failure of the examined Composting Toilets (continuously operated single-vault system with separate areas for collection and composting; faeces are pushed in the composting area after 3 months). They state (p. 4039) that more than half of the toilets had moisture contents < 40% because judging '*was usually beyond the expertise of these first-time users and may be a barrier to adequate maintenance for optimal biodegradation*' (note: Mexico is arid/semi-arid; often excess of moisture is of concern). Schönning & Stenström (2004, p. 23) conclude that '[u]*nless good maintenance can be ensured,* […] *it is questionable if one could rely on domestic-scale "composting" units as an efficient process for pathogen reduction*'.

A number of studies about the performance of Composting Toilets are available, but the variety of different systems (e.g. continuous vs. batch system, urine and faeces mixed or separated) and other influencing factors (e.g. measurements on-site or laboratory, type of bulking/cover material applied, improper maintenance of conditions by users, climatic conditions) together with the inflationary, imprecisely used term *composting* (or even misnomer of systems) and partly insufficient descriptions of the examined system, makes comparisons and statements difficult.

Hill and Baldwin (2012, p. 1813) remark that '[t]*he limited body of literature on MLMC* [mixed latrine microbial Composting Toilets], *especially field versus laboratory studies, generally does not prove them reliable for decomposition or sanitation of fecal matter. Adequate temperatures are seldom, if ever, attained eliminating this reliable mechanism of pathogen destruction. Storage alone is unlikely to be a reliable pathogen destruction mechanism*'. Hill et al. (2013, p. 30) further conclude that '[n]*umerous composting toilet studies indicate a failure to produce sanitized material* […] *due to* […] *poor design, overuse, insufficient maintenance, low temperatures, anaerobic conditions, and excessive urine*' (Hill et al., 2013, p. 30). (Note: Hill & Baldwin (2012) and Hill et al. (2013) do not distinguish between single-vault (continuous) and multiple-vault (batch) systems and if urine is diverted or not.)

Only one study was found about in-situ temperature examinations of alternately used double-vault Composting Toilets without urine diversion, stating that temperatures did not go beyond mesophilic ranges and were similar to ambient temperature (Redlinger et al,. 2002). Fossa Alternas do not achieve thermophilic temperatures as well, whereas the author highlights that pathogen inactivation is based on mesophilic composting (Morgan, 2004). Samples from 'ecosan' toilets (almost entirely Fossa Alternas) in Malawi revealed high numbers of viable helminth ova in the output material (Morgan & Mekonnen, 2013). Continuous operated single-vault Composting Toilets are usually not able to reach thermophilic conditions (Pecora, 2013; Hill et al., 2013; Tonner-Klank et al., 2007; Jenkins, 2005; Redlinger et al., 2001; Moe et al., 2001; Chapman, 1993; Smith et al., 1984). The same applies to Double Vault Urine-diverting Composting Toilets (Pecora, 2013; Mehl, 2008; Hurtado, 2005; Moe et al., 2001).

When thermophilic temperatures are not met, mesophilic conditions do not reliably inactivate pathogens within weeks or months, '[i]*t is therefore not recommended to rely on this temperature range in treatment of faeces, unless the mesophilic process is combined with other process functions, or barriers*' (Schönning & Stenström, 2004, p. 23). The WHO (2006b) guidelines refer to alkaline treatment (e.g. ash, lime) as additional process function to sanitize faecal matter.

The mentioned research and findings indicate that sanitization of excreta via (thermophilic) composting in the field and on household level may be achievable if (i) reactors are insulated properly to trap the heat, (ii) aeration and homogenization of the material is improved by stirring and mixing the material, and (iii) conditions required for composting are managed well (e.g. moisture content, C:N ratio). Thoroughly stirring and mixing the matter in a double-vault toilet seems to be not possible with the underlying design and most likely this will not be possible with another design based on a low-tech, on-site collection and treatment in a double vault system, applicable in developing countries, also. Managing good conditions for thermophilic composting by users is very challenging and it seems that proper conditions are not met in practice.

The end-product of double vault non-Urine-Diverting Toilets is therefore considered to be not properly sanitized and has to undergo a post-treatment before it can be applied as soil conditioner (Berger, 2011). '*Small-scale composting on a household level is less efficient* [as compared to large systems] *and pathogen inactivation is incomplete, as the temperature increases only marginally above ambient*' (WHO 2006b, p. 92). Composting is therefore recommended to be used as secondary (i.e. post) treatment, off-site and at a large scale (i.e. municipal level) only (WHO, 2006b; Schönning & Stenström, 2004). This is the reason why WHO guidelines (2006b, p. 68) only list composting recommendations for treating '*excreta and faecal sludge off-site, at collection and treatment stations from large-scale systems (municipal level)*', operated in batch mode without adding new material. In this case, temperatures above 50°C should be reached in all material for a duration of > 1 week. The duration has to be prolonged if these temperatures cannot be ensured (WHO, 2006b). It has to be highlighted that '[l]*arge systems need a higher level of protection than what is required at the household level*' (WHO, 2006b, p. 68).

Generally, the guidelines stipulate that faeces can be used after on-site treatment if a pathogen reduction of 6 log units is achieved (WHO, 2006b). Hill et al. (2013) commend a subsequent curing period after composting at household level between two and four months. WHO (2006b; 1989) recommends a curing period of 2 – 4 months after maturation as well (based on forced aeration co-composting in large windrow systems). Feachem et al. (1983) suggest a storage time of at least 3 months, which should be prolonged in helminth endemic areas (Stenström et al., 2011). WHO (2006b) recommends storage times of > 1 year for faecal sludge when stored at an ambient temperature of > 20 – 35 °C (1.5 – 2 years for 2 – 20°C) (see Table 10, p. 46).

The observable pathogen reduction of Composting Toilets seem to be primarily based on desiccation, anaerobic degradation and alkalization (Tonner-Klank et al., 2007; Schönning & Stenström, 2004; Redlinger et al., 2001). Hill et al. (2013) advocate therefore to rename Composting Toilets into Dry Toilets to avoid false expectations and capabilities of the underlying process.

Figure 37 shows rather poor examples of ventilation pipes from Composting Toilets in Vanuatu. The ventilation of the inspected Composting Toilets in Vanuatu had various design weaknesses: None of the Composting Toilets had an independent ventilation of each vault. Instead, one or multiple 90° bends were used which increase the friction and hamper the wind and stack effect. Pipes with a diameter of 10cm were used, greater dimensions would be beneficial to better deal with high humidity during the rainy season. None of them had a rain protection at the top, some were equipped with a poor mounted fly-screen.

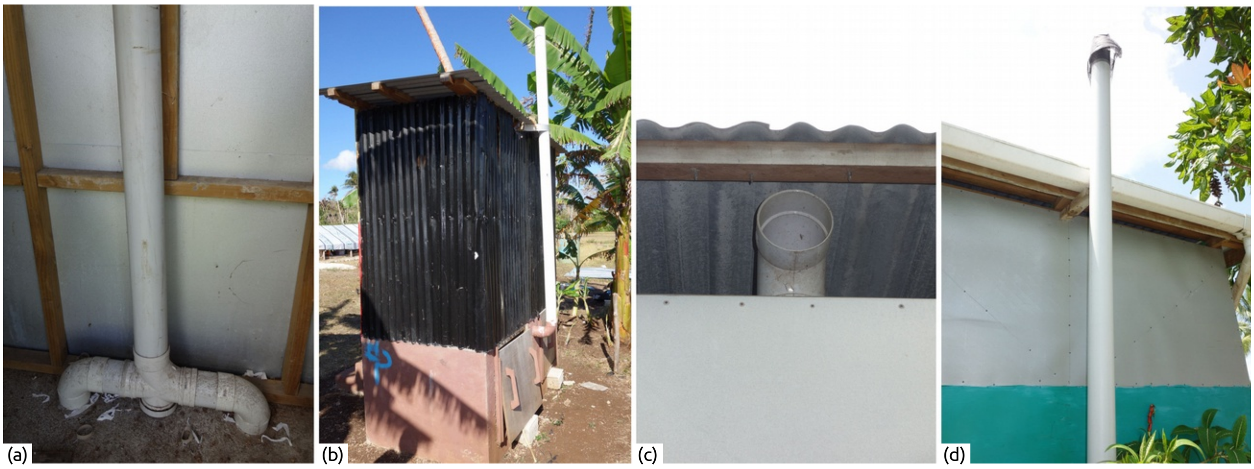


Figure 37: Examples of ventilation systems from Composting Toilets in Vanuatu. All of the inspected toilets had only one pipe for both vaults and included one or more 90° bends, at the junction (a) and (b), or at the top (c). None of them had a rain protection. The ventilation pipe in (c) prevents rain from intruding the vaults, but is not apt for a proper ventilation. (b) and (d) are raised above the roof but the fly screen is poor.

EXPOSURE PATHWAYS AND RISK MITIGATION

EP_1, EP_2 **EP_3** **EP_5** **EP_{Other}**

(EP_1 & EP_2) Ingestion of composting material, Dermal contact

Similar to EP_1 & EP_2 of Double Dehydration vaults of UDDTs (p. 49).

The vaults should be able to prevent exposure to the containing material (Berger, 2011). The weak point of the inspected Composting Toilets in Vanuatu was obviously the design and implementation of the vault doors (see Figure 23, p. 49). Improper vault doors seem to be a common problem of UDDTs and Composting Toilets. This implies a substantial risk of exposure to excreta and possibly leachate (e.g. playing children, animals spreading pathogens). Broken doors further spoil the wind and stack effect, undermine the principle of fly control by letting in light and compromise acceptance by visibly exposing faeces to users.

There is also a risk of pathogen transmission when the User Interface is moved during alternation of the vaults (Stenström et al., 2011).

Mixing and stirring of the vault material is required to potentially achieve pathogen inactivation through a proper composting process. This manual aeration of the material may expose the executing person to fresh excreta (Vinneras, 2007).

It is further necessary to level the pile formed by faeces in the vault every once in a while. This is either done via the User Interface or the vault door.

Bulking material, amendment, faecal material or a broken false floor can cause the ET pipe to be blocked. This may impound leachate in the vault, including a higher risk of exposure during mixing or levelling of the heap.

In case thermophilic composting is achieved, fungi and actinomycetes form spores which can trigger allergic reactions if inhaled by sensitive persons (Stenström et al., 2011).

Risk mitigation

See risk mitigation EP_1 & EP_2 of UDDTs (p. 50).

The tool used to level the pile and/or stir the contents should be cleaned after usage, stored in a way to be out of reach for children and not be used for other purposes.

The design of the vault door should be as simple as possible with a simple locking mechanism which cannot be opened by children or animals. The doors should be durable, easy to maintain and, if possible, based on locally available materials to ease repair.

A properly built false floor (especially distance to floor, distance in between of the slats; see above), an inclined drainage floor is important to guarantee excessive urine or leachate to be drained away and to avoid anaerobic conditions. In case of blockages, wearing PPE and hand washing is essential to mitigate the risk of pathogen transmission.

If persons show allergic reaction of potentially formed spores, a mask should be worn during levelling the pile or mixing the contents in the vault for aeration.

(EP_3) Contact with flies/mosquitoes

'*All raw materials used for composting attract flies* [e.g. blow fly, phorid fly, housefly, moth fly, soldier fly] *and are good media for fly breeding*' (Feachem et al., 1983, p. 80). Composting Toilets involve therefore a greater risk of fly infestation as compared to UDDTs due to a higher moisture content in the vault on the one hand and fly eggs potentially getting into the vaults via disposed kitchen waste on the other hand (Berger, 2011; Winblad & Simpson-Herbert, 2004).

The ventilation of the inspected Composting Toilets in Vanuatu were often poor (small diameter, one or more 90° bends, no rain protection) causing poor dissipation of moisture, which in turn, leads to a greater risk of fly infestation and bad odours are more likely. Besides, a fly screen on top of the ventilation pipe was often lacking, which is an important measure to control flies in Composting Toilets (see Figure 37 for examples of inspected vent pipes).

Risk mitigation

'*As with single VIP latrines, the superstructure must be kept partially dark at all times to discourage flies*' (Franceys et al., 1992, p. 53). Temperatures above 50°C effectively kill fly larvae, but the larvae may migrate towards cooler zones in the heap. Turning the pile or long curing times of unturned piles may be able to destroy fly eggs (Feachem et al., 1983).

Organic waste from fermented fruits should not be added since these are often infested with fly eggs. Bark, paper and straw used as bulking material have a good absorptive capacity and improve the aeration of the pile. Besides dehydration, the material reduces the risk of fly infestation also by covering the faeces and obstruct access for oviposition (Berger, 2011).

A proper ventilation leads to better aeration and dissipation of moisture. A fly screen is crucial to trap flies in the vaults (see Chapter 5.3.2, p. 47 and Chapter 5.2.2, p. 28 for detailed vent pipe recommendations) (Berger, 2011). A cap or T-joint at the top of the vent pipe prevents rainwater penetration.

Spiders often settle in the ventilation pipe to feed from flies. The webs have to be removed periodically to guarantee good ventilation (Morgan, 2009).

(EP$_5$) Contaminated groundwater/surface water

Collection of urine and faeces together causes larger volumes of leachate. Proper operation of the toilet (especially applying bulking/cover material) and handling of the leachate (collection, treatment, discharge or evaporation) is important to prevent spreading of pathogens (Berger, 2011; Stenström et al., 2011).

Some of the visited Composting Toilets had problems with excessive leachate (see (d) in Figure 23, p. 49). This was due to the lack of a proper drainage system including an infiltration or evapo-transpiration bed for urine or leachate (some had none, some were retrofitted and some had an ET or infiltration bed), improper and/or too little cover/bulking material used, and poor ventilation (see EP$_3$). The distance between the drainage floor and the false floors was just 2 or 3 cm for most of the visited toilets, some toilets did not have a false floor.

High standards of water-tightness are important in flood-prone areas. The vault doors of the Composting Toilets in Vanuatu did not ensure a proper seal against water intrusion.

Risk mitigation

'*The vaults of the latrines should be constructed water-tight to minimize the risk of polluting the surrounding environment including groundwater*' (Stenström et al., 2011, p. 39). It is therefore recommended to coat the vaults inside and outside (Berger, 2011).

Formation of (excessive) leachate should be prevented by maintaining proper conditions in the vault (e.g. C:N ratio, water content, bulking material, good ventilation), UD is beneficial to control the moisture content and to limit leachate being formed. Further, a well built and maintained drainage system is important to prevent urine or leachate percolating into the ground. The ET bed has to be watertight. Infiltration into the ground may cause elevated nitrate levels (see Chapter 5.3.4, p. 70 for more details) and contamination of groundwater.

Additional measures are necessary for flood-prone areas (e.g. raised and inclined vault doors). See Chapter 5.3.2, p. 51 for a more detailed description.

(EP$_{other}$) Other exposure

Besides flies, cockroaches may be attracted by the moist conditions in the vaults and can transmit pathogens into houses or onto food (Feachem, et all., 1983).

Proper treatment of the excreta in the vaults is of highest importance to reduce the risk during further handling, disposal or reuse.

Berger (2011) remarks that leachate can also be collected in a small tank to be diluted with water and applied to non-food plants as high concentrated fertilizer (see Chapter 5.4.4, p. 86).

Risk mitigation

The toilet and the place where food is stored and prepared should be as far apart as possible to avert cockroaches migrating between these food sources (Franceys et al., 1992).

'*The ability of users to consistently monitor and maintain the composting material, i.e. adding organic and bulking material, is critical. The barrier efficacy of the compost chambers depends largely on the ability of users to maintain optimum temperature, moisture, Carbon-Nitrogen ratio, pH etc.*' (Stenström et al., 2011, p. 39).

Since leachate potentially contains high numbers of pathogens, the utilization of former for fertilization involves an elevated risk of disease transmission (see below, p. 86).

5.4.3. Conveyance – Human-Powered Emptying and Transport

'*Emptying composting toilets constitutes a critical handling point*' (WHO, 2006b, p. 83). The risk during Emptying and Transport of Composting Toilets is likely to be higher as compared to UDDTs, since the pathogen inactivation cannot be guaranteed and leachate may be present in the vault. In case of careless operation (especially in humid regions), the material may be very wet and excessive leachate may accumulate in the vault. This increases the risk of pathogen transmission since leachate may contain a large number of pathogens. Apart from that, the risk of aerosol inhalation may be of concern in case of Composting Toilets too, if environmental conditions favour desiccation and the storage time is long enough to dehydrate the excreta into a dry, powder-like material.

The exposure pathways and the measures to mitigate the risks during Emptying and Conveyance are similar to those of dehydrated faeces from UDDTs (Chapter 5.3.3, p. 58).

5.4.4. Use and/or Disposal

Around 40 – 70% of the organic matter and a little less of the nitrogen (N) is lost during the composting process. About 90% of the residual N is present in the organic form which is slowly degraded into a plant available form. The resulting matter is more stable than the starting product and improves the water-holding and buffering capacity of the soil. The greater part of phosphorus (P) is present in an organic form also, whereas the majority of potassium (K) is there in an ionic form already. Compost is generally considered to be a soil improver and complete PK fertilizer. Low temperature composting (i.e. mesophilic, or aerobic degradation at ambient temperatures) can be considered as low temperature variants of thermophilic decomposition. The properties of the end product are quite similar, but there are two major differences: less easily degradable substrate is needed to amend the composting process (reducing the effort during O&M), and the fact that high temperatures are absent cannot ensure the hygienic safety of the faecal compost. Anaerobic decomposition leads to approximately the same amount of degraded organic matter, but nitrogen is retained and about 40 – 70% is present in form of readily available ammonium (NH_4). Sanitization via dehydration preserves more organic matter and N, but the organic matter is less stable as compared to compost (WHO, 2006b; Jönsson et al., 2004). The nutrients in the output material from Composting Toilets have a higher plant availability than dehydrated faeces from UDDTs (Berger, 2011). Especially the availability of P, K and sulphur (S) is good. This fact makes the most available fraction of those nutrients prone to be lost via leachate (Jönsson et al., 2004). Morgan (2003) compared the yield of various plants (spinach, covo, lettuce, green pepper, tomato and onion) in Zimbabwe, grown in 10L buckets on (poor) soil from on-site on the one hand and soil mixed with compost (50:50) obtained from Fossa Alternas on the other, resulting in substantial relative yields of the fertilized plants (Table 19).

Table 19: Small-scale plant trials from Zimbabwe, showing the relative yields of various plants (planted in 10L containers out of cement) which were either cultivated in topsoil only, or in a 50:50 mix of topsoil and compost from Fossa Alternas (Morgan, 2003, s.p.).

Plant	**Growth period**	**Fresh weight**		**Relative yield**
		Topsoil only	**Topsoil / FA[a] mix (50 / 50)**	
Spinach	30 days	72 g	546 g	7.6
Covo	30 days	20 g	161 g	8.1
Covo 2	30 days	81 g	357 g	4.4
Lettuce	30 days	122 g	912 g	7.5
Onion	4 months	141 g	391 g	2.8
Green pepper	4 months	19 g	89 g	4.7
Tomato	4 months	73 g	735 g	10.1

[a] FA = Fossa Alterna

‘Compost’ from Composting Toilet should not be reused without further treatment since pathogen inactivation cannot be guaranteed (see above, p. 76). If no further treatment is undertaken, it is recommended to bury the material (see Chapter 5.3.4, p. 72). If the compost from Composting Toilets not achieving thermophilic sanitization is to be reused nonetheless, it should be applied to ornamental plants, fruit-growing bushes and trees only (Berger, 2011). '*These plants should not be easily accessible in order to minimise the potential risk of infections*' (Berger, 2011, p. 7). Generally, the recommendations from application of dehydrated faeces (Chapter 5.3.4, p. 65) including the most conservative assumptions concerning the safety of the product should be followed (e.g. protective equipment, application technique, crop restriction, withholding time). USDA (2010, p. 4) further remarks that '[i]*mmature or inadequately cured compost may retard plant growth if applied to crops* [...]*, due to the C:N ratio, non-nitrate forms of nitrogen, organic acids, or other chemical constituents that come and go during the composting process*'.

Leachate can be collected and applied as highly concentrated liquid fertilizer, similar to liquid manure used by farmers (Berger, 2011). However, the main goal is to prevent leachate formation in the first place instead of reusing it as fertilizer (Jönsson et al., 2004). '*Leachate* [from Composting Toilets] *has to be handled with care as it contains pathogens*' (Berger, 2011, p. 8). It is therefore not recommended to reuse leachate without further treatment, it is advised to discharge the leachate to an evapo-transpiration bed.

If it is to be applied nonetheless, diluting the leachate with water according to the plant needs of nitrogen is recommended (a dilution ratio water:leachate of 3:1 is common, 10:1 is more conservative). If leachate is applied to sensitive plants, it should always be diluted, application to soil directly requires no dilution. It is recommended to reduce the risk by measures such as subsurface application (Berger, 2011). See Chapter 5.3.4, p. 60 for more detailed instructions about appropriate application and measures to mitigate the risk. The most conservative assumptions in regard of hygienic safety should be used. The risk from reusing leachate is higher as compared to urine obtained via UD (and optional storage) due to its potential high pathogen loads.

6. FIELD RESEARCH IN VANUATU

The field research comprised of interviews with NGOs and the governmental department in charge of sanitation, the examination of existing Composting Toilets and inspection of a potential pilot site including the introduction of the concept of UDDTs.

6.1. Interviews with NGOs and DGMWR

Meetings with NGOs (Oxfam Vanuatu, live&learn Vanuatu, World Vision Vanuatu, Wan Smol Bag) and the governmental department in charge of sanitation (Department of Geology, Mines and Water Resources, DGMWR) took place. The meetings lasted between one and three hours and were based on semi-structured interview guidelines. The aim was to get to know the country specifics in regard of provision of sanitation and water supply. The interviews covered topics like acquisition and transport of materials, substitution of commercial materials with locally available ones, collaboration and interconnection of NGOs and governmental organizations, awareness raising and behavior change, introduction of new types of toilets like Composting Toilets or UDDTs, establishing sanitation marketing or committees. The organisations interviewees shared their experiences freely. The information gained during the interviews was important to establish a good understanding about the difficulty in provisioning sanitation infrastructure in this context.

6.2. Inspection of Composting Toilets

Four Composting Toilets on Efate, Pele and Espirutu Santo were assessed. The two toilets on Efate were used on community level (i.e. shared among households), the toilet on Pele is located in a school yard to be used by pupils, one of the two Composting Toilets on Espiritu Santo was used on household level, and the second one was shared as well.
The assessments were undertaken to examine potential technical flaws (especially because of the similarities in construction of Composting Toilets and UDDTs), and to establish an understanding which problems may arise when a new type of sanitation is introduced.

6.2.1. Tangovauwia school, Pele

A joint venture by the Secretariat of the Pacific Community (SPC), German Agency for International Cooperation (GIZ), Mele-Mele Maat Sanitation Enterprise Group and Live & Learn Vanuatu implemented a Double-Vault Composting Toilet at Tangovauwia Primary School (location: 17°29'58.4"S, 168°24'25.6"E) on Pele Island (approx. 3km north of the main island Efate) in 2011. The toilet was built as part of the ‘Coping with Climate Change in the Pacific Island Region’ (CCCPIR) program and should demonstrate an alternative sanitation system that prevents groundwater pollution and produces a fertilizer to increase the fertility of the sandy soil. The ‘composted’ excreta should be used as a soil conditioner to grow seedlings in a forest nursery to support reforestation on the island. On Pele, drinking water is exclusively obtained from rainwater harvesting, groundwater from hand dug wells is used for washing, bathing and cleaning. A few years ago groundwater was used for drinking purposes too, but deforestation, rising sea levels and especially the increase of water-based Pour-Flush Toilets caused the groundwater to be contaminated (SPC-GIZ, 2012; SPC, 2011). Figure 38 (b) shows the Composting Toilets in red (middle), two of four Pour-Flush Latrines (right) and a temporary classroom (left) including a hand washing facility in front of it (a).

Figure 38: A hand washing facility (a) is placed in front of each of the three temporary classrooms (b, left) which were put up after the main schoolhouse was damaged during TC Pam. Further the Composting Toilet in red (b, middle) and two of the four Pour-Flush Toilets (b, right) are depicted.

The principal of the school, Mr. William Tagawa (2015, pers.comm., 10 November) stated during an interview that the Double-Vault Composting Toilet was built at the school yard in 2011 and withstood TC Pam without being damaged. Mr. Tagawa would have preferred to lock up the Pour-Flush Toilets (> 10 years old; lined with drums) used so far to make the children not having any alternative than using the Composting Toilets. But one toilet was too less for more than 80 pupils, hence the school had to keep using the Pour-Flush Toilets. He stated that 4 Double-Vault Composting Toilets would be needed to refrain from the pit latrines.

Maintenance was undertaken by GIZ in the first phase of the project, but not long ago the responsibility was handed over to the school. Dried grass clippings from the school lawn are used as bulking material. The vaults are designed to last for approximately 9 months, but the filling rate seems to be lower in practice. The principal assumed that this may be because the kids prefer to use the pit latrines and use the Composting Toilets only on rare occasion when all Pour-Flush Toilets are occupied. He further believed that the children do not use the toilet as they were told, although they are reminded twice a week how to properly use them. The toilet had to be decommissioned due to bad smell and fly infestation when one vault was half-full the first time. To solve these problems, GIZ retrofitted the toilet with an infiltration trench to discharge the excessive leachate.

The principal further reported that hygiene lessons are taught at school and every kid has to wash hands after using the toilet and before having lunch. Deworming of the pupils is undertaken by staff of the Health Center once a year. The school collects rainwater in two 6000L tanks (included screens), one for drinking water, the second tank for hand washing and flushing the toilets. After TC Pam, donors assessed the quality of the stored water and recommended to boil it before drinking. Nonetheless the water is not treated because a facility to boil the water is not available in the school. The principal further mentioned that the stored water becomes already scarce since the last rainfall in may 2015 was almost half a year ago.

Mr. Tagawa confirmed that people used the groundwater for drinking and cooking a few years ago. He states that an awareness raising conducted by GIZ established a general understanding in the community about groundwater contamination from water-based latrines, but still '*people don't think very hard about the toilets they are using*'. It was planned to build a shared Composting Toilet in Piliura, the next village west of the school. He refers that there have been debates about the siting of the shared toilet. The implementers suggested to build it in the center of the village, but the residents wanted it to be outside of the village due to privacy, but people had also concerns about smell and flies that may repel tourists. Nonetheless, the principal said that he really likes the Composting Toilet and prefers it over any other toilet. When the concept of Urine-Diverting Dry Toilets has been introduced to the principal, he was interested and remarked that he would not have any reluctance in using urine or faeces to fertilize crops (William Tagawa 2015, pers.comm., 10 November).

Figure 39 shows the Composting Toilet from the front (a). A hand washing facility next to the toilet was missing, but hand washing stands were placed in front of each classroom instead (Figure 38, (a)). Cover material was not present in the Composting Toilet, which may be reasoned due to the toilet being out of order during the inspection. Instructions how to use the toilet (i.e. poster) were not displayed, neither inside nor outside the cubicle. The vault doors were not fixed properly, and a locking mechanism to avoid them from being opened by children was lacking (Figure 39, (b)). The vent pipe protruded about 50cm above the roof, but neither a flyscreen nor a rain protection was present. Only one ventilation pipe was installed to aerate both vaults and included two 90° bends (c). (d) shows the inactive vault with the false floor.

Figure 39: Composting Toilet from the front (a), sideways including vault doors and vent pipe (b), two 90° bends of the vent pipe (c) and the false floor in the unused vault (d).

6.2.2. Tagabe Catchment, Blacksands, Efate

With more than 1500 households, the Blacksands area (including Manples) is the biggest agglomeration of informal settlements in the north-west of the capital Port Vila (NHC, 2012). Blacksands is numbered among those sites in Vanuatu which are considered to be '*major sources of ground and surface water and coastal pollution*' (SOPAC, 2007, p. 20). It was therefore identified as one of three hotspots in Vanuatu with very high priority (DGMWR Vanuatu, 2007). Trundle & McEvoy (2015) interviewed five community leaders during a transect walk in the area which refered to problems arising from floods, groundwater contamination, river water quality and decreased crop yields. The area lies on an alluvial floodplain in the lower reaches of the Tagabe River catchment with high groundwater levels between 1 and 3m. The sanitation comprises mostly of pit toilets, drinking water is obtained from hand dug wells (Crennan & Booth, 2007). '*Monthly monitoring of the Tagabe River* […] *shows high levels of bacteria from human waste, and high COD and nitrogens from industry and human waste*' (SOPAC, 2007, p. 19).
Access to piped water would be an effective mean to decrease the health risk emanating from the consumption of groundwater, but connecting communities to the piped water network provided by UNELCO has been difficult because of disputes about tenure of the squatter settlements. While the health risk could be reduced that way, the ongoing eutrophication of the river from toilet plumes would be still of concern. Hence Composting Toilets have been piloted as a potential option to avoid the problems arising from pit-based sanitation (Crennan & Booth, 2007). Two Composting toilets in Salvabay and Paama community have been assessed.

Salvabay community

Brian Roberts (2015, pers.comm., 25 November), the WASH officer from Wan Smolbag (WSB), explained during an interview that three Composting Toilets have been implemented in the Blacksands area and another one was planned to be built in January 2016. The inspected toilet in Salvabay (Figure 40; location: 17°42'26.3"S, 168°18'19.3"E) was built to be exclusively used by women. This is because many families and households that settled in Salvabay come from Tanna, where it is 'Kastom' (i.e. traditional culture) in some communities that men and women do not use the same defecation places. The roof of the toilet cubicle has been blown off during TC Pam, which further led to the User Interface being stolen. The roof has been already repaired by WSB at the time of inspection, but the toilet was still out of operation because the new interface, which will be out of fiber-glass, was still missing. Hence the users built a 'bush toilet' next to the Composting Toilet to serve as a substitute (Figure 40 (a) and (e)). The Composting Toilet is operated by the community and is maintained by staff from WSB, who conduct inspections once per month. Sawdust is used as bulking material, residual organic waste is not added to supplement the composting because it is used to feed pigs. The 'composted' excreta is used to fertilize vegetables. A problem mentioned by Mr. Roberts is the fact that people throw all kinds of waste into the vaults. Especially children tend to not using the toilet as intended, despite instructions that were displayed in the cubicle but have been stolen later. He further states that people like the toilet and asked for further Composting Toilets, but at the moment there is no money for funding (2015, pers.comm., 25 November).

Figure 40 (a) shows the toilet cubicle. A wash basin (incl. soap) for hand washing was not present. The toilet was out of operation due to the User Interface being absent, cover material was therefore not available in the cubicle. Only one ventilation pipe was used to aerate both vaults and included three 90° bends as apparent in (b) and (c). The design of the ventilation system omitted the need of a rain protection, but a fly screen at the end was lacking. The contents of the left vault were easily accessible (e.g. for children or animals) because the vault door was broken (d), the right one was sealed with a sheet metal (not shown).

Figure 40: Side view of the Composting Toilet in Salvabay (a). The vent pipe ended below the roof with a 90° bend (b). One vent pipe was used to aerate both vaults and included three 90° bends (b, c). The left vault door was broken (d). A bush-toilet was built next to the Composting Toilet as an temporary replacement (e).

Paama community

Another Composting Toilet (Figure 41; location: 17°42'28.4"S, 168°17'38.1"E) located in the Paama community has been examined in the Blacksands area. Simion Tavoa from Live & Learn Vanuatu provided background information and acted as translator during an interview with a member of the Disaster Response committee of Blacksands (2015, pers.comm., 26 November): The groundwater table is influenced by the tide and varies between 2 and 4 meters. Despite people know that the groundwater is contaminated, they use it for drinking because water is expensive to acquire. People have been instructed to boil the water before used for drinking, but some do not adhere to the recommendation what has been noted to come along with increased incidence rates of diarrhea in children.

The Composting Toilet was built in 2014 and is located next to a church to be used by church attenders. The toilet was opened for the community and used by about 15 households after TC Pam damaged or destroyed many toilets in the community, and materials to repair or rebuild them were not available. A flood in October 2014 came close to the toilet but the vaults stayed dry since they are built above ground. It was stated that there are no problems with smell as long as enough sawdust is used after defecation. The 'composted' excreta has not been used so far since the first operation cycle was not completed until then. Wan Smol Bag supplies cover material for the toilet and checks the facility fortnightly. Female community members clean the toilets. People are satisfied with and like the toilet, especially the fact that no water is needed was highlighted. The interviewee further noted that the community would like to have 2 or 3 additional toilets of this type (Member of the Disaster Response committee of Blacksands, 2015, pers.comm., 26 November).

Some of the community members already use cow dung to fertilize their crops. When the concept of UDDTs has been explained, the committee member stated that he would not have any problems in using urine to fertilize crops. He especially liked the fact that it can be used on household level without the need for further treatment and that it is available continuously all year long. He was very interested in UDDTs and would like to get more information to get a better idea of the concept (Member of the Disaster Response committee of Blacksands, 2015, pers.comm., 26 November).

Live & Learn was so friendly to provide information from an interview conducted with a member of the Paama community from 5th of October 2015. According to the interviewee, the toilet is cleaned every Saturday by another family in turn. The respondent further stated that he is satisfied with the toilet, and the fact that the toilet does not rely on water was again highlighted as a big advantage. Nonetheless, when the interviewee was asked which toilet he would choose if he could build a new toilet, he stated to go for a '*flush toilet because it is easy and clean*'.

The toilet was built before TC Pam swept over the country and withstood the cyclone without being damaged. Figure 41 (a) shows the toilet including the ventilation system, which was identical with the one in Salvabay (Figure 40 (b) and (c)). One pipe with three 90° bends was used to aerate both vaults, the pipe ended below the roof and lacked a fly screen. The hand washing stand on the left side of the cubicle is enlarged in Figure 41 (c), neither water nor soap was available during the inspection. A prefabricated seat riser out of fiber-glass was installed on the left vault (d). The vault door of the active (i.e. left) vault was broken as vaguely apparent in (b). Intrusive smell was not detected. Sawdust was available in the toilet (further replenishment was stored in a house nearby) but a vessel or similar was missing (e). The drop hole cover of the inactive vault could be lifted and moved by hand without the need of any tools (e).

Figure 41: Front view of the Composting Toilet in the Paama community including the ventilation system (a). The door of the active vault was broken (b). A hand washing facility was present next to the toilet (neither water nor soap were available) (c). A prefabricated user interface out of fiber-glass was used (d). Saw dust was present in the toilet, but a vessel was missing. The drop hole cover of the inactive vault was not properly mounted (e).

6.2.3. Sarakata catchment, Espiritu Santo

The Sarakata catchment on Espirutu Santo was identified as one of three hotspots in Vanuatu with very high priority as well (DGMWR Vanuatu, 2007). The Sarakata flood plain is inhabited by more than 3000 people, '[t]*his large population puts a high demand on the natural resources and contributes to the high levels of groundwater contamination through the use of unsuitable sanitation systems*' (Kalmet, 2013, p. 1). Hence, Composting Toilets were piloted in Solway, Pepsi and Butmas communities as a potential mean to reduce the stress on water resources from pit latrines in areas with shallow groundwater (GEF, 2013).

According to Gina Buletare from the Municipal Council in Luganville, the idea was that Composting Toilets spread themselves with the help of a sanitation marketing approach by training a committee how to construct and manage the toilets. Three demonstration toilets were built with assistance from the committee. The costs were covered through the project and funds by Live & Learn, subsidies for future toilets built by the committee were not considered. The project ceased after 2 years, which was too short in the interviewee's opinion. The target households for the demonstration toilets were chosen by the committee and included one Double Vault Composting Toilet on household level for a disabled man in Pepsi and two Double Vault toilets for church attenders in Solway (Gina Buletare, 2015, pers.comm., 7 December).

Pepsi

The owner of the toilet in Pepsi (Figure 42; location: 15°30'29.2"S, 167°09'49.8"E), a disabled man, was interviewed with the help of one of his grandchildren translating into Bislama. The man used a 'bush toilet' before the Composting Toilet was built. Depending on availability, either dry leafs, dry grass or sawdust is used as bulking material. It usually takes around 9 months until one vault is full, the 'composted' excreta is used to fertilize cabbage. The owner remarked that he noticed a significant difference in yields when he started to use the output material as fertilizer. But the biggest advantage from the man's point of view is the fact that the toilet stays dry and can still be used during floods. When asked for potential improvements, he mentioned that the vault doors do not close properly, causing the vault contents to trickle out with increasing fill levels (Composting Toilet owner in Pepsi, 2015, pers.comm., 6 December).

Figure 42, (a) gives a front view of the Composting Toilet in Pepsi. The access to the toilet via the stairs with large gaps in between the steps was obviously an impediment for the man with his walking stick. A hand washing facility was not present. The vent pipe included two 90° bends and had a fly screen on top, but a rain cover was missing. The back doors themselves seemed to be robust, but the fixing mechanism was a constructional flaw (b). Bulking material was not available in the toilet cubicle, because the owner was '*waiting for someone to mow the grass*'. The lack of bulking material may be the reason why the vault contents were very wet, causing urine and leachate to percolate through the insufficient vault doors and pooling on the ground in the back of the toilet (c). Hence a bad smell was going out from the toilet.

Figure 42: Front of the Composting Toilet in Pepsi (a), the 'infiltration bed' on the backside including the two vault doors (b), and an enlarged view of the vault door from the active vault with liquids pooling in the bed (c).

Solway

Two Double-Vault Composting Toilets have been built for church attenders in Solway (Figure 43; location: 15°29'54.3"S, 167°10'14.5"E). Johnny, a member of the church who works with young people in a nearby youth center, was interviewed (2015, pers.comm., 7 December):

Usually people build 'bush toilets' when they move to a new plot of land. An upgrade from a 'bush toilet' to a VIP is rare, he only knows about 4 to 5 VIP toilets in the wider area. If people want to improve their sanitation, they rather go for a water-based sanitation system. But in his opinion, people would be very interested in and may want to go for Composting Toilets or UDDTs once they get to know the advantages of these toilets.

The Composting Toilet of the church consists of two Double Vault toilets, one for male and the other one for female users. The toilet is operated and maintained by the members of the church. Each vault has a dedicated toilet cubicle with a separate door as apparent in Figure 43 (a). When a vault is filled to capacity, the respective toilet door is locked and the adjoining cubicle is used from then on. Female church members cleaned the toilets in the past. Now all church members are divided into groups, each week another group is responsible for tasks like mowing the grass (to be used as bulking material when dry) or cleaning the toilets. The members of the church have been informed how to use the toilet by the implementing committee, there are no problems with people throwing garbage or alien things into the vaults. When he was asked if there are any dislikes or suggestions for improvements, he mentioned that the heightened structure in combination with the siting next to the road makes some people uncomfortable to use the facility. Sometimes adolescents make fun of people who enter the toilet (Johnny, church member, 2015, pers.comm., 7 December). An interview of a Composting Toilet user from Mele village (conducted by Live & Learn, 2015, 3 October) revealed similar problems, as the toilet was built next to a road and was rarely used because '*we do not like going to the toilet in open areas*'. The reduced privacy due to the need of climbing the steps of the heightened structure was criticized as well. The interviewee suggested to '*plant trees or locate it* [i.e. the toilet] *somewhere else*' to improve the situation. Another interviewee criticized the lack of privacy and improper siting too, and recommended that the '*next time, let the whole community participate in the decision making*'.

Figure 43 (a) shows the Composting Toilet in Solway, located next to the road. Each vault had its own toilet cabin which is locked when the vault is inactive. The facility included rainwater harvesting which was stored in a tank on the left side of the construction for drinking and hand washing (no soap present). The vaults were equipped with a drainage pipe to drain the leachate into a planted infiltration trench (b). Two vent pipes aerated four vaults, included two 90° bends and were fitted with a fly screen on top (c). The pipes protruded about 50cm above the roof, but lacked a rain cover. The toilet cubicles were clean with parts of the floor tiled, and bulking material (i.e. dried grass) was available. The vault doors were all in good order (e).

Figure 43: Composting Toilet at a church in Solway with separated toilets for men and women, and a tank for rainwater storage (a). A planted infiltration bed was implemented in the back (b). One vent pipe aerated both vaults. It protruded about 50cm above the roof. A fly screen was fitted at the end, but a rain cover was missing (c). The toilet cubicles were clean and partly tiled, bulking material was available (d). All four vault doors were in good order (e).

6.3. Inspection of potential pilot sites, Emae

Potential pilot sites featuring the underlying conditions were identified to trial UDDTs. The coastal villages *Finonge*, *Tongamea*, *Makatea* and *Reisu* at Emae have been chosen as a result of discussions with Jake Ward from Oxfam Vanuatu. Emae belongs to the Shepherd Islands and is located approximately 50km north of the main island (location: 17°03'48.7"S, 168°22'42.0"E). The island was considerably affected by TC Pam in march 2015, especially the coastal villages were affected by floods and in some areas coastal erosion occurred (Figure 44) (Shefa Provincial Government Council, 2015).

The chiefs of Finonge, Tongamea and Reisu and one WASH committee member of Makatea were interviewed, followed by a walk through the villages to assess the prevalent conditions. The concept of UDDTs has been presented to the interviewees, and further to a group of approximately 20 interested parties from different villages from the island to evaluate the acceptance towards this technology, especially in regard of urine and/or faeces reuse.

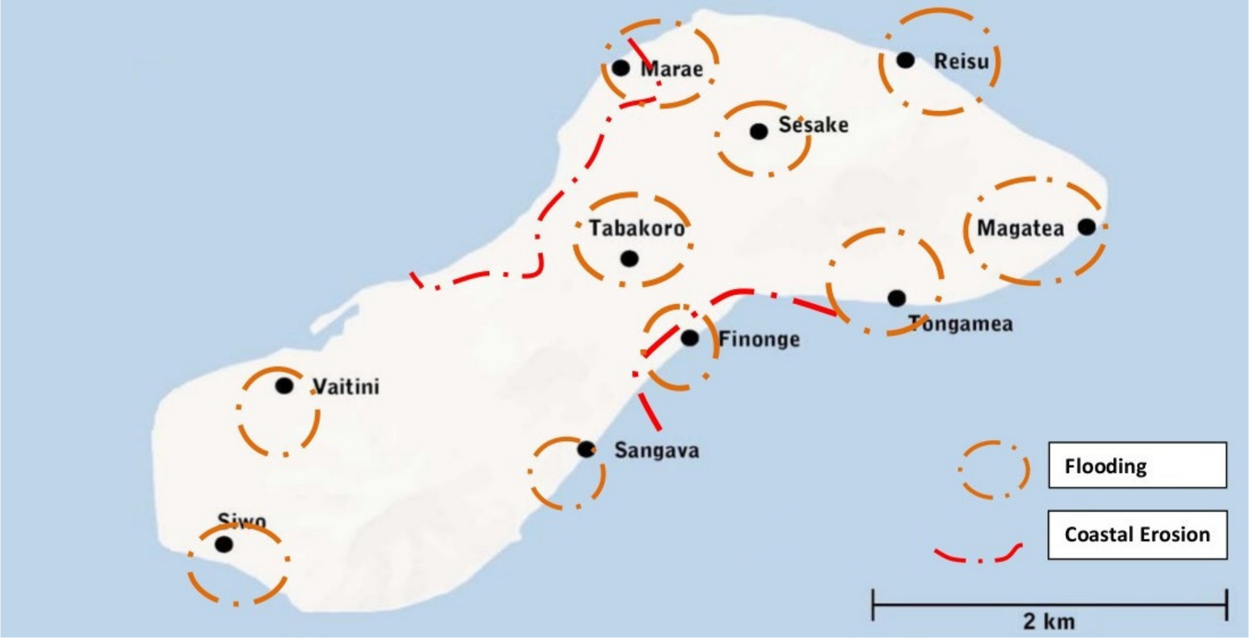


Figure 44: Map of Emae with its villages, showing the areas affected by floods (brown) and coastal erosion (red) caused by Tropical Cyclone Pam in March 2015 (Shefa Provincial Government Council, 2015, p. 3).

The chief of Finonge village, James Willie (2015, pers.comm., 2 December), reported that the village consists of 27 households and accomodates a health center as well as Worarana & Nofo Primary and Junior Secondary School with approximately 270 students. Drinking water is obtained from rainwater harvesting only and is usually not treated before consumption. The groundwater is contaminated according to an assessment by Oxfam and should be boiled if used for drinking purposes. Hence groundwater from hand dug wells and hand pumps is used for washing and cooking only. Although no considerable rainfall occurred since TC Pam, the groundwater level of three hand dug wells were between 1 and 2m, and was influenced by the tide. An indirect gravity feed system fed by a solar water pump will be installed by Oxfam to distribute the groundwater to 10 taps in the village and schools.

The village has 24 toilets in total, 8 Pour-Flush and 16 ‘bush toilets’. The flood that came along with TC Pam caused many toilets to overflow (Figure 45, (a)). This also occurred in 2010, when heavy rainfall over four days in a row induced a flood that lasted for one week with water levels of more than 1m (Figure 45, (b)). Both events destroyed many family gardens in the area and resulted in crop failure. Families usually farm more than one garden, depending on how much land they own or they are able to rent. Crops from home gardens are also sold at road markets on the island (James Willie, 2015, pers.comm., 2 December).

Figure 45: Floods in Finonge during TC Pam in 2015 (a) and due to heavy, long-lasting rainfall in 2010 (b) (Marie Willie, 2015; Marie Willie, 2010).

The concept of Urine-Diverting Dry Toilets was introduced to a group of approximately 20 interesting parties including the chief of Finonge and some chiefs of the south-western part of the island. The attendees were very interested in UDDTs and asked many questions. Oxfam conducted workshops about sanitation in the community recently, and the inhabitants already decided if they want to upgrade their sanitation facilities or build a new toilet. Some of them stated that now they know UDDTs and their advantages, they would like to reconsider their decision. The people did not seem to have any reserve of using urine and faeces to fertilize edible crops.

David Maripu, the chief of Tongamea (34 households), stated that approximately 80% of the sanitation facilities in his village are Pour-Flush and the remaining 20% ‘bush toilets’. The pits of Pour-Flush Toilets are usually 2.5 to 3m deep. The pit is simply covered with soil when its capacity is reached, the toilet facility is then moved to a new pit. The groundwater table is around 3 to 4m, and is contaminated according to an assessment by Oxfam Vanuatu. Hence groundwater is not used for drinking purposes but for cooking and washing. Drinking water is obtained from rainwater stored in concrete and fiber-glass tanks and may becomes short in the dry season. A solar powered pump will be installed by Oxfam to distribute groundwater to taps. The chief was very interested in UDDTs and he thought that people would like this type of toilet. He was especially keen on the idea that UDDTs may be built as an extension to a house. In his opinion it would be definitely worth to pilot this new type of toilet and collect practical experience with the reuse of urine and faeces (David Maripu, 2015, pers.comm., 1 December). Figure 46 shows a concrete rainwater storage tank (a) and a Pour-Flush Toilet (b) from Tongamea.

Figure 46: Concrete tank to store rainwater (a) and a Pour-Flush Toilet (b) in Tongamea.

Christopher Daniel, a member of the WASH committee in Makatea (2015, pers.comm., 1 December) reported that one household uses a VIP Toilet in Makatea, the remaining 9 rely on ‘bush toilets’ (~ 1.5m deep). Drinking water is obtained from a direct gravity feed system distributing spring water to four taps and was rehabilitated/built by Oxfam in July/August 2015. He further stated that the drinking water was limited during the last drought, so the taps were opened only twice a week to fill one jerry can (i.e. 25L) per household. He also liked the concept of Urine-Diverting Dry Toilets and asked if there are other ways to make use of the nutrients from the urine. He further showed the most common plants families grow in their home gardens, such as taro, yam, manioc, sweet potatoes, cucumber, tomatoes, cabbage, carrot, corn, lettuce, beans, peanut, capsicums, banana, pineapple, papaya, pumpkin, sugar cane, kava, and tabacco. Groundwater is used to water plants and has to be carried several hundred meters from the hand dug well uphill (Christopher Daniel, 2015, pers.comm., 1 December).
Figure 47 shows the view from Makatea (a), which is not situated in a low-lying coastal setting like the other three villages. This picture further shows a concrete rainwater storage tank in the front left and another tank out of fiber-glass to the right. Behind the concrete tank one can see a ‘bush toilet’. (b) shows one of the four taps which can be locked with a padlock, and (c) depicts a Dry Toilet.

Reisu was the smallest of the four visited villages with only 4 households which share one ‘bush toilet’. The chief of the village, Jeffery Pakoa, liked the concept of UDDTs too (2015, pers. comm., 1 December). From his point of view it would be a big benefit for the community if they would not have to dig new pits anymore, which has to be done usually every second year in their case.

Figure 47: The view from Makatea including a Dry Toilet behind the concrete storage tank on the left, and another tank out of fiber-glass on the right hand side is shown in (a). One of the four lockable taps with multiple jerry cans used to obtain drinking water is depicted in (b), and (c) shows a Dry Toilet from the village.

7. CONCLUSION

The aim of this thesis was to assess the applicability of three sanitation systems in rural coastal areas prone to floods and featuring high groundwater tables. This was achieved by dividing the sanitation systems into its functional groups in order to identify potential exposure pathways and recommend measures to reduce the risk on basis of these entities. A focus was on the reliability of pathogen inactivation during the treatment of the two reused-oriented systems in order to assess if and how the subsequent risk can be limited to acceptable levels during application of excreta, urine or faeces as soil conditioner or fertilizer, and during consumption of products.

Applicability under the underlying conditions

The prevalent SINGLE-PIT SYSTEM (i.e. ‘bush toilets’, Dry Toilets, VIP Toilets and Pour-Flush Toilets) is not well suited for the underlying conditions.

Both Dry and Wet Toilets include a significant risk of groundwater contamination. Attenuation of pathogens is much higher in the unsaturated zone (i.e. distance between bottom of pit and groundwater table) than in the saturated zone (i.e. groundwater). Furthermore, the flow rate in the saturated zone is usually distinctly higher than in the unsaturated zone, allowing pathogens to travel much farther comparatively once they reach the groundwater. A sufficient retention time of effluents from pits in the unsaturated zone is therefore crucial. The retention time depends on the actual hydraulic load of the pit, grain size distribution of sediments and thickness of the unsaturated zone. Acceptable retention times of pathogens cannot be achieved in unconsolidated sediments with high permeability (medium sand, coarse sand, gravel) and sandstones, limestones or fractured rock. Moreover, the common practice in the South Pacific to dig pit latrines until the water table is reached enables the direct contamination of the groundwater. Pour-Flush Toilets include the greatest risk because the flushwater acts as a transport medium for pathogens to the groundwater and hydraulic loadings are high compared to Dry Toilets. Nonetheless, Dry latrines are also of concern in case seasonal groundwater fluctuations raise the table to be higher than the bottom of the pit, causing saturated conditions in some or all layers of the pit.

Besides, floods may cause pit latrines to overflow, leading to the spread of pathogens in the surrounding environment. The toilets are then usually temporarily inaccessible, or maybe even permanently inoperable in case of collapsing pits or pits filled up with sediments.

Both alternative systems URINE-DIVERSION-DRY TOILETS (UDDTs) and COMPOSTING TOILETS are suitable for areas prone to floods and characterized by shallow groundwater. This holds true as long as the vaults and especially their doors are watertight, and the effluents (i.e. leachate from Composting Toilets or urine from UDDTs) are not infiltrated into the ground. The latter includes the risk of microbiological contamination of the groundwater (especially leachate), but chemical contamination via nitrate is of major concern from a long-term perspective (leachate and urine).

Reliability of treatment

The concept of COMPOSTING TOILETS (i.e. Double-Vault non-Urine-Diverting Toilets) is based on a thermophilic composting process taking place in the vaults. Inactivation of pathogens should be achieved via sustained temperatures > 50°C.

Research suggests that sanitisation of excreta via thermophilic composting on household level may be achieved in case (i) reactors are insulated to trap the heat, (ii) aeration and homogenization of the material is improved by stirring and mixing the material, and (iii) the C:N ratio and moisture content of the pile are managed well. Practical experience has shown that the latter two factors, (ii) and (iii), are neither practicable nor obtainable in the field, respectively. Diverting the urine via a Urine-Diverting Dry Toilet User Interface is recommended to simplify the management by reducing the amount of carbonaceous bulking material needed to adjust the C:N ratio and the moisture content in the vault.

Research has shown that Composting Toilets without urine diversion do not achieve a thermophilic composting process in practice since the temperature in piles increases only slightly above ambient, disqualifying this otherwise reliable treatment method. Observable reductions of pathogens are assumed to be caused primarily by storage time, desiccation, anaerobic degradation and alkalization. A post-treatment of the output is therefore necessary before it is potentially used as soil conditioner. The risk of handling the product is considered to be high.

Composting Toilets are therefore not recommended because this type of system did not prove to ensure a reliable treatment of the excreta under field conditions.

DOUBLE VAULT URINE-DIVERSION-DRY TOILETS collect urine and faeces separately with the help of its User Interface. This allows an independent treatment of the two fractions.
Urine may be either collected and utilized as fertilizer, or alternatively discharged into an evapotranspiration bed (including an underground overflow device to prevent ponding during the rainy season). Simply infiltrating the urine into the ground via a soak pit is not recommended since it may elevate nitrate levels in the groundwater.
Urine has to be treated before being reused, except when urine collection and application as well as consumption of fertilized products occurs on household level only. Storing the urine for a minimum of one month in closed tanks or containers is the simplest treatment method.
The treatment of faeces is based on dehydration as the pathogen die-off increases with decreasing moisture contents. Cover material is applied after defecation to increase the desiccation of faecal matter. It is highly recommended to use plant ash as cover material over any alternative, since it has shown the best results in pathogen inactivation by increasing the pH-value.

Research suggests that the treatment of faecal matter in UDDTs is more reliable and includes a lower risk during handling of the output products as compared to Composting Toilets. However, a post-treatment of feacal matter is recommended before reuse.

Technical design and implementation

The technical design of all functional groups should preclude avoidable exposure pathways while being affordable, simple and robust. This is especially important when considering the medium- to long-term goal of improved sanitation technologies being adopted by and disseminate in the population without assistance from NGOs or the government. The design of on-site sanitation evolved over time by incorporating the experiences gained in the field. A local mason may not be familiar with certain aspects, for example why pit heads should be lined, why proper slabs are important, or why minimum diameters for ventilation systems are required. He or she may just copy an observed technical design, potentially overlooking a small but crucial detail. Even when a particular design element is known, its implementation may be perceived to be more expensive, awkward or unnecessary, as long as its function or reason is unknown.
It is therefore important to develop country specific guidelines adapted to the prevalent conditions and make this information available for the population in a readily understandable form and free of charge. Further, key persons (e.g. craftspeople, WASH committee members) should possess profound knowledge which goes beyond know-how and includes the *know-why* in order to avoid recurring mistakes to be made during the implementation.

Simple, cost-effective measures (e.g. finishing the floor and User Interface with water repellant paint; solar-powered lights) may increase the appreciation in value, which in turn may reduce health risks by increasing the motivation to clean, operate and maintain the toilet properly.

The technical design and implementation of UDDTs is more complex in comparison to the other examined sanitation systems. An improper implementation of the two main weak points – the urine piping and the vault doors – may compromise the treatment's reliability (leaking or broken pipes wetting dehydrated faeces), or may expose children to fresh faecal matter, allow unobstructed access for animals and disqualifies its applicability for flood-prone areas (broken or unsealed vault door). It is therefore important to provide a sound technical design including explanations to minimise the involved risks of technical failure.

Operation and maintenance

Lack of operation and maintenance (O&M) is a common reason why systems partly or completely fail, which in turn may cause dislike or even lead to toilets being abandoned. O&M of Single-Pit Systems is comparatively low, especially due to the fact that neither Dry nor Wet Systems are emptied but simply abandoned. The main task of Dry Toilets is to keep it clean, as it is with VIPs which further require regular cleaning of the ventilation system. O&M of Pour-Flush Toilets include regular cleaning too and require the continuous provision of flushwater. Nonetheless, when comparing the amount of work involved in the O&M of these systems, the effort for digging new pits, moving the slab and resettling or constructing a new toilet cubicle should not be overlooked when Dry Toilets, VIP Latrines or Pour-Flush Toilets are filled up due to normal use or sediments from floods.

However, UDDTs include a considerable number of tasks for O&M: besides keeping the toilet clean, users have to make sure that no water or urine enters the vault, cover material is provided, the ventilation system is cleaned regularly, the mound formed below the interface is pushed to the sides, potential objects clogging the urine drainage funnel are removed and the urine piping is maintained occasionally. In case urine is reused, jerry cans or tanks have to be cleaned regularly and depending whether the urine is to be treated or not, the user has to manage multiple jerry cans (e.g. 5+1 alternately used jerry cans of 25L for an assumed production of 125L urine by a 5 person household and storage of one month) or at least two tanks with a sufficient volume. Further, the User Interface has to be switched when a storage cycle is completed which goes along with the emptying of the dehydrated faeces (including the opening/disassembly and closing/assembly and potentially maintenance of the vault doors). Beyond that, the post-treatment of the feacal matter may be necessary. These tasks include many exposure pathways that have to be considered and require an awareness of the users and executing person(s) about the involved risks. To limit the risk of infection, it is of high importance that the executing person applies Personal Protection Equipment (PPE) during O&M procedures and sticks to good hygiene behavior (e.g. no smoking or eating during, and obligatory hand washing afterwards).

Key persons (e.g. members of the WASH committee) that possess the know-how and *why* could be used to conduct inspections of toilets and offer advise what and how to fix, and may help to procure spare parts.

Reuse of urine and/or faeces

While the application of urine and/or faeces to fertilize crops and plants has obvious benefits, it includes also potential risks during handling of urine and/or faeces and ultimately when products are consumed. It is therefore important to comply with reuse practices (i.e. application techniques, crop restrictions, withholding periods) in order to reduce the risk during consumption. The risk of pathogen transmission during application should be limited through a proper preceding treatment of urine and/or faeces, as well as sticking to the use of PPE, good hygiene behaviour and application techniques.

It is important to adapt official recommendations and guidelines to local conditions, taking into account the local site conditions, plant requirements, and characteristics of urine and faeces. It is of utmost importance that the users, executing person(s) and consumers understand the included risk and the need of applying measures in order to ensure a long-term adoption of risk reduction measures. Therefore, awareness raising is of considerable importance.

The amount of urine produced per person per year is sufficient to fertilize 300 – 400m². This may require a combined collection and evapo-transpiration of urine in case there is no need for such amounts.

The feedback from people in Vanuatu that have been introduced to the concept of UDDTs was very positive. Nonetheless, it is very important to openly discuss pros and cons of Urine-Diversion-Dry Toilets and to make the expectable workload clear from the outset. Urine-Diversion-Dry Toilets are obviously more complex in construction and involve more O&M tasks than Single-Pit Systems. The application of urine and/or faeces as fertilizer requires further a good understanding about reuse practices. Further benefits of UDDTs are their usability during floods, applicability in areas with high water tables, and provision of fertilizer to increase crop yields as well as the resilience to natural disasters. Well managed vaults are free from odour making UDDTs suitable to be extended to one's house which improves privacy and comfort considerably.

8. REFERENCES

Australian Bureau of Meteorology, and CSIRO (2011a). Current and future climate of Vanuatu. Australian Bureau of Meteorology, Commonwealth Scientific and Industrial Research Organisation.

Australian Bureau of Meteorology, and CSIRO (2011b). Climate change in the Pacific: scientific assessment and new research. Volume 2, Australian Bureau of Meteorology, Commonwealth Scientific and Industrial Research Organisation.

Albonico, M., Crompton, D.W., and Savioli, L. (1999). Control strategies for human intestinal nematode infections. Adv Parasitol, vol. 42, pp. 277–341.

ARGOSS (2002). Assessing Risk to Groundwater from On-site Sanitation: Scientific Review and Case Studies. British Geological Survey Commissioned Report, UK.

ARGOSS (2001). Guidelines for Assessing the Risk to Groundwater from On-Site Sanitation. British Geological Survey Commissioned Report, UK.

AusAID (2006a). Water Safety Plan, Water Supply Description Assessment, Vanuatu, Australian Agency for International Development. Canberra, Australia.

AusAID (2006b). Pacific Country Report Sea Level & Climate: Their Present State, Vanuatu, Australian Agency for International Development. Canberra, Australia.

Austin, L.M. (2007). Design and operation criteria for urine-diversion ecological sanitation systems with particular reference to public health. University of Pretoria, South Africa.

Austin, L.M., Duncker, L.C., Matsebe, G.N., Phasha, M.C., and Cloete, T.E. (2005). Ecological Sanitation, Literature Review. WRC Report No. 246/05. University of Pretoria, South Africa.

Banerjee, G. (2011). Underground pollution travel from leach pits of on-site sanitation facilities. Clean Techn Environ Policy, vol. 13, pp. 489–497. doi:10.1007/s10098-010-0331-3

Bani, E. (2010). Vanuatu's National Assessment Report for the implementation of the Barbados Programme of Action (BPoA) and the Mauritius Strategy for Implementation (MSI).

Barker, J., and Jones, M.V. (2005). The potential spread of infection caused by aerosol contamination of surfaces after flushing a domestic toilet. Journal of Applied Microbiology 99(2), pp. 339–347. doi:10.1111/j.1365-2672.2005.02610.x

Barrett, M. (2002). Groundwater and Sanitation: Nutrient Recycling and Waterborne Disease Cycles. In: Proceedings of the 1st international conference on ecological sanitation. Nanning, China.

Berendes, D., Levy, K., Knee, J., Handzel, T., and Hill, V.R. (2015). Ascaris and Escherichia coli Inactivation in an Ecological Sanitation System in Port-au-Prince, Haiti. PLOS One 10(5). doi:10.1371/journal.pone.0125336

Berger, W. (2011). Technology review of composting toilets – Basic overview of composting toilets (with or without urine diversion). Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Eschborn, Germany.

Bird, C., Ame, S., Albonico, M., and Bickle, Q. (2014). Do shoes reduce hookworm infection in school-aged children on Pemba Island, Zanzibar? A pragmatic trial. Trans R Soc Trop Med Hyg. 108(5), pp. 297-304. doi:10.1093/trstmh/tru037

Bischel, H.N., Duygan, B.D.Ö., Strande, L., McArdell, C.S, Udert, K.M., and Kohn, T. (2015). Pathogens and pharmaceuticals in source-separated urine in eThekwini, South Africa. Water Res vol. 85, pp. 57-65. doi:10.1016/j.watres.2015.08.022

Brikke, F., and Bredero, M. (2003). Linking Technology Choice with Operation and Maintenance in the context of community water supply and sanitation – A reference Document for Planners and Project Staff. World Health Organization and IRC Water and Sanitation Centre. Geneva, Switzerland.

Brikke, F. (2000). Operation and maintenance of rural water supply and sanitation systems – A training package for managers and planners. World Health Organization and IRC Water and Sanitation Centre. Geneva, Switzerland.

Buckley, C.A., Foxon, K.M., Brouckaert, C.J., Rodda, N. Nwaneri, C., Balboni, E., Couderc, A., and Magagna, D. (2008a). Scientific Support for the Design and Operation of Ventilated Improved Pit Latrines (VIPs) and the Efficacy of Pit Latrine Additives. WRC Report No. 357/08. Pollution Research Group University of KwaZulu-Natal, South Africa.

Buckley, C.A., Foxon, K.M., Hawksworth, D.J., Archer, C., Pillay, S., Appleton, C., Smith, M., and Rodda, N. (2008b). Research into UD/VIDP (Urine Diversion Ventilated Improved Double Pit) Toilets: Prevalence and die-off of Ascaris ova in urine diversion waste. WRC Report No. 356/08. Pollution Research Group University of KwaZulu-Natal, South Africa.

Calizaya, J.C., Garcia, S., Miglio, R., Vargas, C., Inga, D., Lopez, C., Oliva, D., Vega, R., and Palomino, J. (2009). A guide for an Integrated system of ecological sanitation in suburban and rural areas – ECODESS. Fondo de las Americas Peru, Water for People, AVINA, CENCA, Peru.

Carlander, A., and Westrell, T. (1999). A microbiological and sociological evaluation of urine-diverting, double-vault latrines in Cam Duc, Vietnam. Report no. 91, Swedish University of Agricultural Sciences, Sweden.

Castalia (2005). Infrastructure Regulatory Review For Government of Vanuatu. Castalia Strategic advisors.

CAWST (2011). Introduction to Low Cost Sanitation – LatrineConstruction. A CAWST Construction Manual. Centre for Affordable Water and Sanitation Technologies (CAWST), Canada.

Chapman, P.D. (1993). Compost toilets: an option for human waste disposal at remote sites. MSc thesis, Lincoln University, Lincoln, New Zealand.

Chien, B., Phi, D., Chung, B., Nga, N., Stenstrom, T., Carlander, A., Westrell, T., and Winblad, U. (2001). Biological study on retention time of microorganisms in faecal material in urine-diverting eco-san latrines in Vietnam. In: Proceedings of the 1st international conference on ecological sanitation. Nanning, China.

Corrales, L.F., Izurieta, R., and Moe, C.L. (2006). Association between intestinal parasitic infections and type of sanitation system in rural El Salvador. Tropical Medicine & International Health 11(12), pp. 1821-1831. doi:10.1111/j.1365-3156.2006.01737.x

Crennan, L. (2007). Sustainable sanitation manual and construction guidelines for a waterless composting toilet. IWP – Pacific Technical Report (International Waters Project) no. 52.

Crennan, L., and Berry, G. (2002). Issues for Community-based Sustainable Resource Management and Conservation: Considerations for the Strategic Action Programme for the International Waters of the Pacific Small Island Developing States, Volume 3: A Synopsis of Information Relating to Waste Management, Pollution Prevention and Improved Sanitation with a Focus on Communities in the Pacific Islands Region. South Pacific Regional Environment Programme.

Crennan, L., and Booth, S. (2007). Vanuatu, project report on composting toilets: eco-sanitation workshop, Tagabe river management committee, 09th – 13th August 2004. EU EDF 8 – SOPAC Project Report 63.

Curtis, V., Cairncross, S., and Yonli, R. (2000). Domestic hygiene and diarrhoea – pinpointing the problem. Trop Med Int Health. 5(1), pp. 22-32. doi:10.1046/j.1365-3156.2000.00512.x

Curtis, C.F., Malecela-Lazaro, M., Reuben, R., and Maxwell, C.A. (2002). Use of floating layers of polystyrene beads to control populations of the filaria vector Culex quinquefasciatus. Ann Trop Med Parasitol. 96(2), pp. 97-104. doi:10.1179/000349802125002446

Deegener, S., Samwel, M., and Gabizon, S. (2006). Urine Diverting Toilets – Principles, Operation and Construction. Women in Europe for a Common Future (WECF), Netherlands.

Deegener, S., Samwel, M., and Wendland, C. (2015). Urine Diverting Dry Toilets – Principles, Operation and Construction, 2nd revised edition. Women in Europe for a Common Future (WECF), Netherlands.

Delepiere, A. (2011). Household UDDTs after cyclone disaster – Padma and Rohitra villages, Barishal Division, Bangladesh. Sustainable Sanitation Alliance (SuSanA). Eschborn, Germany.

DGMWR Vanuatu (2007). Integrated Water Resource Management – Hotspot Analysis Report Republic of Vanuatu. Department of Geology, Mines and Water Resources, Government of Vanuatu. Port Vila, Vanuatu.

Dillon, P. (1997). Groundwater pollution by sanitation on tropical islands, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Division of Water Resources. Adelaide, Australia.

Drangert, J.O. (2010). Sustainable Sanitation for the 21st Century. A sourcebook and set of powerpoints, Chapter 2.7 – Construction and monitoring. Linköping University, Sweden, available at: goo.gl/xTExVC (03.03.2017).

Drechsel, P., Scott, C.A., Raschid-Sally, L., Redwood, M., and Bahri, A. (2010). Wastewater irrigation and health – assessing and mitigating risk in low-income countries. Earthscan, IWMI, IDRC.

EcoSanRes (2005). Guidelines for the Safe Use of Urine and Faeces in Ecological Sanitation Systems. EcoSanRes Fact Sheet 5, Sweden.

EcoSanRes (n.d.a). Risks and Safe Handling of feaces from Urine Diversion Dry Toilets (UDDT). EcoSanRes Uganda knowledge node Factsheet, Uganda.

EcoSanRes (n.d.b). Risks and Safe Handling of urine from Urine Diversion Dry Toilets (UDDT). EcoSanRes Uganda knowledge node Factsheet, Uganda.

Elving, J., Ottoson, J.R., Vinneras, B., and Albihn, A. (2010). Growth potential of faecal bacteria in simulated psychrophilic/mesophilic zones during composting of organic waste. J Appl Microbiol 108(6), pp. 1974-1981. doi:10.1111/j.1365-2672.2009.04593.x

Endale Y.T., Yirsaw, B.D., and Asfaw, S.L. (2012). Pathogen reduction efficiency of on-site treatment processes in eco-sanitation system. Waste Manag Res 30(7), pp. 750-754. doi:10.1177/0734242X11432190

Eriksen, L., Andreasen, P., and Ilsoe, B. (1996). Inactivation of Ascaris suum eggs during storage in lime treated sewage sludge. Water Research 30(4), pp. 1026-1029. doi:10.1016/0043-1354(95)00258-8

ESF (2009). Urine Diversion Dehydration Toilet (UDDT) – Construction Manual. Ecosan Services Foundation (ESF), India.

ESF & seecon (2007). Training Material on “Urine-Diversion Dehydration Toilets” and Urine Management. Ecosan Services Foundation (ESF), India, seecon GmbH, Switzerland.

Esler, S. (2015). Vanuatu Post-Disaster Needs Assessment, Tropical Cyclone Pam, March 2015. Government of Vanuatu, Port Vila, Vanuatu.

Esrey, S., Gough, J., Rapaport, D., Sawyer, R., Simpson-Hébert, M., Vargas, J., and Winblad, U. (1998). Ecological Sanitation. Swedish International Development Cooperation Agency (SIDA). Stockholm, Sweden.

Exley, J.L.R., Liseka, B., Cumming, O., and Ensink J.H.J. (2015). The Sanitation Ladder, What Constitutes an Improved Form of Sanitation?. Environ. Sci. Technol. 49(2), pp. 1086–1094. doi:10.1021/es503945x

Falkland, T. (2002). From Vision To Action Towards Sustainable Water Management In The Pacific, Theme 1: Overview Report Water Resources Management. Canberra, Australia.

FAO (2014). Country: Vanuatu, indicators: total food protein, vegetal total food protein, year: 2011. FAOSTAT database collections, Food and Agriculture Organization of the United Nations, available at: goo.gl/KYchNy (01.04.2016).

Feachem, R.G., Bradley, D.J., Garelick, H., and Mara, D.D. (1983). Sanitation and disease: Health aspects of excreta and wastewater management. Report no. 11616. World Bank studies in water supply and sanitation. John Wiley & Sons, United States of America.

Franceys, R., Pickford, J., and Reed, R. (1992). A Guide to the Development of on-Site Sanitation. World Health Organization. Geneva, Switzerland.

Gaba, E. (2009). Bathymetric and topographic map of New Caledonia and Vanuatu, Oceania. Wikimedia Commons, available at: goo.gl/GRtSZK (03.03.2017).

GEF (2013). Sustainable Management of the Sarakata Watershed – Progress Snapshot. Available at: goo.gl/U6NpHs (03.03.2017).

Gensch, R., Miso, A., and Itchon, G. (2011). Urine as liquid fertiliser in agricultural production in the Philippines – A practical field guide. Xavier University Press, Philippines.

Germer, J., Addai, S., and Sarpong, D. (2009a). Nutshell Guideline 1 – Small scale composting of human faeces. Re-use of Ecological Sanitation Products in Tropical Agriculture (RESPTA), University of Hohenheim. Stuttgart, Germany.

Germer, J., Addai, S., and Sarpong, D. (2009b). Nutshell Guideline 2 – Fertilization with human urine. Re-use of Ecological Sanitation Products in Tropical Agriculture (RESPTA), University of Hohenheim. Stuttgart, Germany.

Germer, J., Boh, M.Y., Schoeffler, M., and Amoah, P. (2010). Temperature and deactivation of microbial faecal indicators during small scale co-composting of faecal matter. Waste Manag. 30(2), pp. 185-191. doi:10.1016/j.wasman.2009.09.030

Government of Vanuatu (2010). Millennium Development Goals 2010 Report for Vanuatu, Government of Vanuatu. Port Vila, Vanuatu.

Graham, J. P., and Polizzotto, M. L. (2013). Pit Latrines and Their Impacts on Groundwater Quality: A Systematic Review. Environ Health Perspect, 121(5), pp. 521-530. doi:10.1289/ehp.1206028

Guness, M., Pillay, S., Rodda, N., Smith, M., and Buckley, C.A. (2006). Quality of leachate from buried urine diversion toilet waste.

Gutterer, B., Sasse, L., Panzerbieter, T., and Reckerzügel, T. (2009). Decentralised wastewater treatment systems (DEWATS) and sanitation in developing countries – A practical guide. Water, Engineering and Development Centre (WEDC), Loughborough University, UK, in association with Bremen Overseas Research (BORDA), Germany.

Harvey, P.A. (2007). Excreta Disposal in Emergencies – A Field Manual. Water, Engineering and Development Centre (WEDC). Loughborough University, UK.

Haug, R.T. (1993). The Practical Handbook of Compost Engineering. Lewis Publishers, Washington DC, USA.

Hill, G.B., Baldwin, S.A., and Vinneras, B. (2013). Composting toilets a misnomer: Excessive ammonia from urine inhibits microbial activity yet is insufficient in sanitizing the end-product. J Environ Manag vol. 119, pp. 29-35. doi:10.1016/j.jenvman.2012.12.046

Hill, G.B., and Baldwin, S.A. (2012). Vermicomposting toilets, an alternative to latrine style microbial composting toilets, prove far superior in mass reduction, pathogen destruction, compost quality, and operational cost. Waste Manag 32(10), pp. 1811-1820. doi:10.1016/j.wasman.2012.04.023

Höglund, C. (2001). Evaluation of Microbial Health Risks Associated with the Re-use of Source-separated Human Urine. PhD Thesis. Department of Biotechnology and Applied Microbiology, Royal Institute of Technology (KTH) and the Department of Water and Environmental Microbiology, Swedish Institute for Infectious Disease Control (SMI), Stockholm, Sweden.

Hoffmann, H. (2014). SuSanA Forum, thread: Use of lime for faeal sludge treatment?. SuSanA, available at: goo.gl/undftM (03.03.2017).

Hoffmann, H. (2012). Construction of bench style double vault urine diversion toilet and alternatives. Rotaria del Peru SAC, Peru.

Howard, G., Reed, B., McChesney, D., and Taylor, R. (2006). Human excreta and sanitation: Control and protection. In: Protecting Groundwater for Health – Managing the Quality of Drinking-water Sources, Schmoll, O., Howard, G., Chilton, J., and Chorus, I. (Eds). World Health Organization, Geneva, Switzerland, pp. 587-612.

Hua, M. (2000). A study of the ecological sanitation project in Dalu village, Guangxi province, China. Paper presented at the WSSCC Expert Consultation in Bellagio, Italy.

Huuhtanen, S., Laukkanen, A., and Pulkkinen, I. (2009). A guide to sanitation and hygiene in developing countries. Global Dry Toilet Association of Finland, Tampere University of Applied Sciences. Tampere, Finland.

Hurtado, D. (2005). Compost latrines in rural Panama: Design, construction and evaluation of pathogen removal. MSc thesis, Michigan Technological University, USA.

IARC (2012). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Biological Agents, Volume 100(B). International Agency for Research on Cancer, World Health Organization. Geneva, Switzerland.

ISF-UTS (2011). Vanuatu Water, Sanitation and Hygiene Sector Brief, Institute for Sustainable Futures, University of Technology Sydney. Sydney, Australia.

Jenkins, J. (2005). The Humanure Handbook. A Guide to Composting Human Manure. 3rd Ed. Jenkins Publishing, Grove City, PA, US.

Jenkins, M.W., Cumming, O., Scott, B., and Cairncross, S. (2014). Beyond ‘improved’ towards ‘safe and sustainable’ urban sanitation: assessing the design, management and functionality of sanitation in poor communities of Dar es Salaam, Tanzania. J Water Sani Hyg Dev 4(1), pp. 131-141. doi:10.2166/washdev.2013.180

Jensen, P.K.M., Phuc, P.D., Konradsen, F., Klank, L.T., and Dalsgaard, A. (2009). Survival of Ascaris eggs and hygienic quality of human excreta in Vietnamese composting latrines. Environ. Health 8(57). doi:10.1186/1476-069X-8-57

Jiayi, L., and Junqi, W. (2001). The practice, problem, and strategy of ecological sanitary toilets with urine diversion in China. In: Proceedings of the 1st international conference on ecological sanitation. Nanning, China.

Jimenez-Cisneros, B., and Maya-Rendon, C. (2007). Helminths and sanitation. Communicating current research and educational topics and trends in applied microbiology. Formatex Research Centre, pp. 60–71. Badajoz, Spain.

Jimenez, B., Navarro, I., and Maya, C. (2010). Pathogens in dry sanitation systems and risk of using sludge produced in agriculture. Conference Paper from the 3rd International Dry Toilet Conference. Tampere, Finland.

Johnson, D.L., Mead, K.R., Lynch, R.A., and Hirst, D.V. (2013). Lifting the lid on toilet plume aerosol: a literature review with suggestions for future research. Am J Infect Control. 41(3), pp. 254-258. doi:10.1016/j.ajic.2012.04.330

Jönsson, H., Richert-Stintzing, A., Vinneras, B., and Salomon, E. (2004). Guidelines on the use of urine and faeces in crop production, EcoSanRes Publications Series, Report 2004-2. Stockholm, Sweden.

Jönsson, H., and Vinneras, B. (2007). Experiences and suggestions for collection systems for source-separated urine and faeces. Water Sci Technol 56(5), pp. 71-76. doi:10.2166/wst.2007.558

Kalbermatten, J.M., Julius, D.S., Gunnerson C.G., and Mara, D.D. (1982). Appropriate Sanitation Alternatives: A Planning and Design Manual. World Bank Studies in Water Supply and Sanitation No. 2. The Johns Hopkins University Press Baltimore, Maryland, USA.

Kalmet, R. (2013). IWRM in Vanuatu: an achievement story. Available at: goo.gl/hCE95o (03.03.2017).

Kassis, E. (2010). Port Vila Urban Development Project, Phase 1: Situation Analysis and Master Plan Formulation, Volume 3: Sanitation, Egis-Bceom International, France, Qualao Consulting Ltd., Vanuatu.

Kingston, P. A. (2004). Surveillance of Drinking Water Quality in the Pacific Islands: Situation Analysis And Needs Assessment Country Reports. World Health Organization, Geneva, Switzerland.

Krauss, S., and Griebler, C. (2011). Pathogenic Microorganisms and Viruses in Groundwater. acatech Materialien Nr. 6, Munich, Germany.

Krishnan, S. (2011). On-site Sanitation and Groundwater Contamination: A Policy and Technical Review. INREM Foundation, Anand, India.

Kvarnström, E., Emilsson, K., Richert-Stintzing, A., Johansson, M., Jönsson, H., Petersens, E., Schönning, C., Christensen, J., Hellström, D., Qvarnström, L., Ridderstolpe, P., and Drangert, J.O. (2006). Urine Diversion – One Step Towards Sustainable Sanitation. Report 2006-1, EcoSanRes Programme, Stockholm Environment Institute. Stockholm, Sweden.

Lan, Y., Xueming, L., Qinhua, W., Hongbo, X., Caiyun, N., and Lianghong, N. (2001). Observation of the inactivation effect on eggs of Ascaris suum in urine diverting toilets. In: Proceedings of the 1st international conference on ecological sanitation. Nanning, China.

Lewis, W.J., Foster, S.S.D., and Drasar, B.S. (1982). The Risk of Groundwater Pollution by On-Site Sanitation in Developing Countries – A Literature Review. IRCWD/SANDEC Report No. 01/82.

Lorentz, S., Wickham, B., and Still, D. (2015). Investigation into Pollution from On-Site Dry Sanitation Systems. WRC Report No. 2115/1/15. University of KwaZulu-Natal, Partners in Development, South Africa.

Makaya, J.M., Somda, M.K., Savadogo, A., Dianou, D., Barro, N., and Traore, A.S. (2014). Survival of enteric bacteria in source-separated human urine used as fertiliser: Effects of temperature and ammonia. Afr J Environ Sci Technol 8(9), pp. 511-520. doi:10.5897/AJEST2014.1748

Mamani, G., Rontetap, M., and Maessen, S. (2014). Sanitation Solutions for Flood Prone and High Table Water Areas. Final Report Sante Brac Project Country, Bangladesh.

Mara, D.D. (2003). Domestic Wastewater Treatment in Developing Countries. Earthscan, London, UK.

Mara, D.D. (1985). The Design of Pour-Flush Latrines. UNDP Interregional Project INT/81/047, The World Bank and UNDP, Washington, DC, USA.

Mara, D.D. (1984). The Design of Ventilated Improved Pit Latrines. UNDP Interregional Project INT/81/047, The World Bank and UNDP, Washington DC, USA.

Maxwell, C.A., Curtis, C.F., Haji, H., Kisumku, S., Thalib, A.I., and Yahya, S.A. (1990). Control of Bancroftian filariasis by integrating therapy with vector control using polystyrene beads in wet pit latrines. Trans R Soc Trop Med Hyg. 84(5), pp. 709-714.

Mbuligwe, S.E., and Kaseva, M. (2005). Pollution and Self-Cleansing of an Urban River in a Developing Country: A Case Study in Dar es Salaam, Tanzania. Environmental Management 36(2), pp. 328-342. doi:10.1007/s00267-003-0068-4

McKinley, J.W., Parzen, R.E., and Guzmán, A.M. (2012). Ammonia Inactivation of Ascaris Ova in Ecological Compost by Using Urine and Ash. Applied and Environmental Microbiology 78(15), pp. 5133-5137. doi:10.1128/AEM.00631-12

Mehl, J.A. (2008). Pathogen Destruction and Aerobic Decomposition in Composting Latrines: A Study from Rural Panama. MSc thesis, Michigan Technological University, Michigan, USA.

Moe, C.L., Izurieta, R., Sobsey, M.D., Cohen, L.F., and Esrey, S.A. (2001). Microbiological studies of ecological sanitation in El Salvador. In: Proceedings of the 1st international conference on ecological sanitation. Nanning, China.

Moilwa, N., and Wilkinson, M. (2006). Effect of hygiene communication on emptying of urine diversion toilets. Sustainable development of water resources, water supply and environmental sanitation: 32nd WEDC conference, Colombia, Sri Lanka, 13-17 November 2006, 9p.

Morgan, P., and Mekonnen, A.T. (2013). Paving the way to scaling-up – Factors contributing to the adoption of eco-san toilets and safety of humanure in Malawi. Sanitation and Hygiene Applied Research for Equity (share) and Aquamor, available at: goo.gl/ZsIhpe (03.03.2017).

Morgan, P. (2009). Ecological Toilets. EcoSanRes Programme, Stockholm Environment Institute. Stockholm, Sweden.

Morgan, P. (2004). An ecological approach to sanitation in Africa – A compilation of experiences. Aquamor, Zimbabwe.

Morgan, P. (2003). Experiments using urine and humus derived from ecological toilets as a source of nutrients for growing crops. Aquamor, available at: goo.gl/C0xb9Z (03.03.2017).

Morgan, P., Mara, D.D., and Mundial B. (1982). Ventilated improved pit-latrines: recent development in Zimbabwe (Technical Note No. 2) vol. 3. World Bank. Washington DC, USA.

Morgan, P., and Shangwa, A. (2010). Teaching Ecological Sanitation in Schools – A compilation of manuals and fact sheets. Aquamor, Zimbabwe.

Morshed, G., and Sobhan, A. (2010). The search for appropriate latrine solutions for flood-prone areas of Bangladesh. Waterlines 29(3), pp. 236-245. doi:10.3362/1756-3488.2010.024

Muchiri, E., and Mutua, B. (2010). UDDTs at a residential plot Nakuru, Kenya. Case study of SuSanA. Sustainable Sanitation Alliance (SuSanA). Eschborn, Germany.

Mucke, P. (2016). WorldRiskReport 2016. Alliance Development Works, and United Nations University – Institute for Environment and Human Security (UNU-EHS), Berlin, Germany.

Münch, E., and Dahm, P. (2009). Waterless Urinals – A proposal to save water and recover urine nutrients in africa. 34th WEDC International Conference. Addis Ababa, Ethiopia.

Münch, E., and Winker, M. (2011). Technology review of urine diversion components – Overview of urine diversion components such as waterless urinals, urine diversion toilets, urine storage and reuse systems. Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Eschborn, Germany.

NHC (2012). Port Vila Informal Settlements Upgrading Projection – Basic Data on Port Vila Informal Settlements. National Housing Corporation, Government of Vanuatu. Port Vila, Vanuatu.

Nick, A., Foppen, J. W., Kulabako, R., Lo, D., Samwel, M., Wagner, F., and Wolf, L. (2012). Sustainable sanitation and groundwater protection – Factsheet of Working Group 11. Sustainable Sanitation Alliance (SuSanA). Eschborn, Germany.

Niwagaba, C. B. (2009). Treatment technologies for human faeces and urine. PhD thesis, Swedish University of Agricultural Sciences. Uppsala, Sweden.

Niwagaba, C., Kulabako, R.N., Mugala, P., and Jönsson, H. (2009a). Comparing microbial die-off in separately collected faeces with ash and sawdust additives. Waste Manag 29(7), pp. 2214-2219. doi:10.1016/j.wasman.2009.02.010

Niwagaba, C., Nalubega, M., Vinneras, B., Sundberg, C., and Jönsson, H. (2009b). Substrate composition and moisture in composting source-separated human faeces and food waste. Environ Technol 30(5), pp. 487-497. doi:10.1080/09593330902788236

Nordin, A. (2010). Ammonia sanitisation of human excreta – Treatment technology for production of fertiliser. PhD thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Nordin, A., Niwagaba, C., Jonsson, H., and Vinneras, B. (2013). Pathogen and indicator inactivation in source-separated human urine heated by the sun. J Water Sanit Hyg Dev 3(2), 181-188. doi:10.2166/washdev.2013.174

Ntabadde, M.K. (2004). Design of a dry toilet ventilation system to accelerate drying. BSc thesis, Makerere University. Makerere, Uganda.

Nunn, P., Kumar, L., Eliot, I., and McLean, R. (2016). Classifying Pacific islands. Geosci Lett 3(7), 19pp. doi:10.1186/s40562-016-0041-8

Odong, J. (2007). eThekwini Urine Diversion Toilets: A Threat to Groundwater. Nat Sci 5(3), pp. 9-11.

O'Lorcain, P., and Holland, C.V. (2000). The public health importance of Ascaris lumbricoides. Parasitology 121, pp. 51-71.

Overmars, M., and Gottlieb, S. (2009). Adapting to climate change in water resources and water services in Caribbean and Pacific small island countries. Applied Geoscience And Technology Division of the Secretariat Of The Pacific Community (SPC/SOPAC), Global Environment Facility (GEF). Suva, Fiji.

Peasey, A. 2000. Health aspects of dry sanitation with waste reuse. WELL studies in water and environmental health, task no. 324; Loughborough University, Leicestershire, UK.

Pecora, G. (2013). Case Study: International Composting Toilet Systems. Available at: goo.gl/gsVvOI (03.03.2017).

Pickford, J., and Shaw, R. (1997). Technical Brief No. 54: Emptying Pit Latrines. WEDC, Loughborough University. Leicestershire, UK.

Polprasert, C. (2007). Organic Waste Recycling: Technology and Management. 3rd Edition. IWA Publishing. London, UK.

PSIDS (2009). Views on the Possible Security Implications of Climate Change to be included in the report of the Secretary-General to the 64th Session of the United Nations General Assembly. Pacific Small Island Developing States, United Nations Member States.

Spickett, J., Katscherian, D., and McIver, L. (2013). Health Impacts of Climate Change in Vanuatu: An Assessment and Adaptation Action Plan. Glob J Health Sci. 5(3), pp. 42–53. doi:10.5539/gjhs.v5n3p42

Still, D., and Foxon, K. (2012). Do pit additives work?. Water Research Commission (WRC), University of Kwazulu-Natal, Partners in Development (PiD), South Africa.

Sullivan, C.A., and Guglielmi, F. (2007). Pacific Island Water Resources: An Overview of East Timor, Kiribati, Solomon Islands, Tuvalu and Vanuatu, Oxford University. Oxford, UK.

Reed, B., and Shaw, R. (2012a). Latrine slabs: an engineer's guide. Water, Engineering and Development Centre (WEDC), Loughborough University. Leicestershire, UK.

Reed, B., and Shaw, R. (2012b). Pour-flush latrines. Water, Engineering and Development Centre (WEDC), Loughborough University. Leicestershire, UK.

Reed, B., and Shaw, R. (2012c). Simple pit latrines. Water, Engineering and Development Centre (WEDC), Loughborough University. Leicestershire, UK.

Reed, B., and Shaw, R. (2012d). Latrine pit design. Water, Engineering and Development Centre (WEDC), Loughborough University. Leicestershire, UK.

Reed, B., and Shaw, R. (2012e). Latrine pit excavation and linings. Water, Engineering and Development Centre (WEDC), Loughborough University. Leicestershire, UK.

Redlinger, T., Graham, J., Corella-Barud, V., and Avitia, R. (2002). Ecological toilets in hot arid climates. In: Proceedings of the 1st international conference on ecological sanitation. Nanning, China.

Redlinger, T., Graham, J., Corella-Barud, V., and Avitia, R. (2001). Survival of Fecal Coliforms in Dry-Composting Toilets. Appl Environ Microbiol 67(9), pp. 4036-4040. doi:10.1128/AEM.67.9.4036-4040.2001

Richert, A., Gensch, R., Jönsson, H., Stenström, T., and Dagerskog, L. (2010). Practical guidance on the use of urine in crop production. EcoSanRes and Stockholm Environment Institute. Stockholm, Sweden.

Rieck, C., Münch, E., and Hoffmann, H. (2012). Technology Review of Urine-Diverting Dry Toilets (UDDTs). Overview of Design, Operation, Management and Costs. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Eschborn, Germany.

Roma, E., Philp, K., Buckley, C., Xulu, S., and Scott, D. (2013). User perceptions of urine diversion dehydration toilets: Experiences from a cross-sectional study in eThekwini Municipality. Water SA vol. 39(2), pp. 305-311. doi:10.4314/wsa.v39i2.15

Rose, C., Parker, A., Jefferson, B., and Cartmell E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. Crit Rev Environ Sci Technol 45(17), pp. 1827-1879, doi:10.1080/10643389.2014.1000761

Rybczynski, W., Polprasert, C., and McGarry, M. (1978): Low-Cost Technology Options for Sanitation: A State-Of-The-Art Review and Annotated Bibliography. World Bank, Transportation and Water Department. Washington DC, US.

Schönning, C., and Stenström, T.A. (2004). Guidelines for the safe use of urine and faeces in ecological sanitation systems. EcoSanRes Publications Series, Report 2004-1, Stockholm Environment Institute. Stockholm, Sweden.

Schönning, C. (n.d.). Urine diversion – hygienic risks and microbial guidelines for reuse. Swedish Institute for Infectious Disease Control. Solna, Sweden.

Shefa Provincial Government Council (2015). Emae island assessment report. Port Vila, Vanuatu.

Sherpa, A.M., Koottatep, T., Zurbrügg C., and Cissé, G. (2014). Vunerability and adaptability of sanitation systems to climate change. J Water Clim Change 5(4), pp. 487-495, doi:10.2166/wcc.2014.003

Smith, E.D., Poon, C.P., Struss, S.R., Bandy, J.T., and Scholze, R.J. (1984). Appropriate technology for treating wastewater at remote sites on army installations: Preliminary findings. Construction Engineering Research Laboratory (Technical report: N-160).

SOIL (2011). The SOIL guide to ecological sanitation. Sustainable Organic Integrated Livelihoods (SOIL). Sherburne, USA.

SOPAC (2007). National Integrated Water Ressource Management Diagnostic Report Vanuatu. South Pacific Islands Applied Geoscience Commission (SOPAC) Miscellaneous Report 648. Suva, Fiji.

SPC (2011). Pele school opens composting toilet to combat climate change. Available at: goo.gl/LbY0eS (03.03.2017).

SPC-GIZ (2012). Adaption to Climate Change through Composting Pele Island, Vanuatu. Coping with Climate Change in the Pacific Island Region (CCCPIR). Suva, Fiji.

Stenström, T. A., Seidu, R., Ekane, N., and Zurbrügg, C. (2011). Microbial exposure and health assessment in sanitation technologies and systems. Stockholm Environment Institute. Stockholm, Sweden.

Sugden, S. (2006). WELL FACTSHEET: The Microbiological Contamination of Water Supplies. WEDC, Loughborough University, available at: goo.gl/tOVkC0 (03.03.2016).

Tilley, E., Ulrich, L., Lüthi, C., Reymond, Ph., and Zurbrügg, C. (2014). Compendium of Sanitation Systems and Technologies – (2nd Revised Edition). Swiss Federal Institute of Aquatic Science and Technology (Eawag). Dübendorf, Switzerland.

Tonner-Klank, L., Moller, J., Forslund, A., and Dalsgaard, A. (2007). Microbiological assessments of compost toilets: In situ measurements and laboratory studies on the survival of fecal microbial indicators using sentinel chambers. Waste Manag 27(9), pp. 1144-1154. doi:10.1016/j.wasman.2006.04.021

Trundle, A., and McEvoy, D. (2015). Climate change vulnerability assessment: Greater Port Vila. UN-HABITAT Cities and Climate Change Initiative and RMIT University Climate Change Adaptation Program. Melbourne, Australia.

Uddin, M.S. (2011). Assessment of UDDTs as a flood resilient and affordable sanitation technology, and their potential to contribute to the fertilizer demand. MSc Thesis, UNESCO-IHE Institute for Water Education. Delft, Netherlands.

Uddin, S.M., Ronteltap, M., and van Lier, J.B. (2013). Assessment of urine diverting dehydrating toilets as a flood resilient and affordable sanitation technology in context of Bangladesh. J Water Sanit Hyg Dev 3(2), pp. 87-95. doi:10.2166/washdev.2013.113

Udert, K., Larsen, T., Biebow, M., and Gujer, W. (2003). Urea hydrolysis and precipitation dynamics in a urine-collecting system. Water Res 37(11), p. 2571-2582. doi: 10.1016/S0043-1354(03)00065-4

UN-DESA (2017). Small Island Developing States (SIDS). United Nations Division for Sustainable Development (UN-DESA), New York, USA, available at: goo.gl/zsTvNs (03.03.2017).

UNESCO (2012), Catalogue of Rivers for Pacific Islands, United Nations Educational, Scientific and Cultural Organization. Apia, Samoa.

UNFCCC (2005). Climate Change, Small Island Developing States. Climate Change Secretariat (UNFCCC). Bonn, Germany.

UNHCR (2014). Technical Brief: WASH Guidance on Camp Closure. United Nations High Commissioner for Refugees. Geneva, Switzerland.

USDA (2010). Part 637 National Environmental Engineering National Engineering Handbook. Chapter 2, Composting. U.S. Department of Agriculture (USDA).

USDA, and USEPA (2012). Microbial Risk Assessment Guideline: Pathogenic Organisms with Focus on Food and Water. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS) and U.S. Environmental Protection Agency (EPA).

Vinneras, B. (2007). Comparison of composting, storage and urea treatment for sanitising of faecal matter and manure. Bioresour Technol 98(17), pp. 3317–3321. doi:10.1016/j.biortech.2006.07.011

Vinneras, B. (2002). Possibilities for Sustainable Nutrient Recycling by Faecal Separation Combined with Urine Diversion. PhD thesis, Swedish University of Agricultural Sciences. Uppsala, Sweden.

Vinneras, B., Björklund, A., and Jönsson, H. (2003). Thermal composting of faecal matter as treatment and possible disinfection method – laboratory-scale and pilot-scale studies. Bioresour Technol 88(1), pp. 47-54. doi:10.1016/S0960-8524(02)00268-7

Vinneras, B., Nordin, A., Niwagaba, C., and Nyberg, K. (2008). Inactivation of bacteria and viruses in human urine depending on temperature and dilution rate. Water Res 42(15), pp. 4067-4074. doi: 10.1016/j.watres.2008.06.014

VMOH (2012). Health Service Delivery Profile Vanuatu. Vanuatu Ministry of Health, Government of Vanuatu. Port Vila, Vanuatu.

VMOH (2010). Health Sector Strategy 2010 – 2016. Vanuatu Ministry of Health, Government of Vanuatu. Port Vila, Vanuatu.

VMOH (2008). Vanuatu Multiple Indicator Cluster Survey 2007, Final Report. Vanuatu Ministry of Health, Government of Vanuatu. Port Vila, Vanuatu.

VNSO (2014). 2013 Vanuatu Demographic and Health Survey, Final Report. Vanuatu National Statistics Office, Government of Vanuatu. Port Vila, Vanuatu.

VNSO (2013). Vanuatu Hardship & Poverty Report, Analysis of the 2010 Household Income and Expenditure Survey. Vanuatu National Statistics Office, Government of Vanuatu. Port Vila, Vanuatu.

VNSO (2012). 2010 Vanuatu Household Income and Expenditure Survey. Vanuatu National Statistics Office, Government of Vanuatu. Port Vila, Vanuatu.

VNSO (2011a). 2009 National Population Housing Census, Analytical Report Volume 2. Vanuatu National Statistics Office, Government of Vanuatu. Port Vila, Vanuatu.

VNSO (2011b). 2009 National Population Housing Census, Analytical Report Volume 1. Vanuatu National Statistics Office, Government of Vanuatu. Port Vila, Vanuatu.

VNSO (2002). Statistical Pocket Book for 2002. Vanuatu National Statistics Office, Government of Vanuatu. Port Vila, Vanuatu.

Vögeli Y., Lohri C.R., Gallardo A., Diener S., and Zurbrügg C. (2014). Anaerobic Digestion of Biowaste in Developing Countries: Practical Information and Case Studies. Swiss Federal Institute of Aquatic Science and Technology (Eawag). Dübendorf, Switzerland.

Wagner, E.G., and Lanoix, J.N. (1958). Excreta disposal in rural areas and small communities. World Health Organization. Geneva, Switzerland.

Wang, J.Q., Sun, F. Y., Wang, Y.B., Xiao J., Xue J.R., Zhang, Y.H., and Pan S.C. (1999). Reduction of microorganisms in dry sanitation due to different adsorbents under low temperature conditions. In: Urban stability through integrated water-related management, The 9th Stockholm Water Symposium. Stockholm, Sweden.

WaterAid (2011) Technical handbook – Construction of ecological sanitation latrine. Water Aid Nepal, Nepal.

Werner, C., Fall, P.A., Schlick, J., and Mang, H.P. (2004). Reasons for and Principles of Ecological sanitation. In: Werner et al. (Eds.), Proceedings of the 2nd International Symposium on Ecological Sanitation. Eschborn, Germany.

Westrell, T. (2004). Microbial risk assessment and its implications for risk management in urban water systems. PhD thesis, Linköping University, Department of Water and Environmental Studies. Linköping, Sweden.

WHO (n.d.). Fact sheets on environmental sanitation. WHO, Geneva, Switzerland, available at: goo.gl/QJDNWe (03.03.2017).

WHO (2016a). Soil-transmitted helminth infections, Fact sheet No. 366. World Health Organization. Geneva, Switzerland, available at: *goo.gl/4WOYGL* (03.03.2017).

WHO (2016b). Schistosomiasis, Fact sheet No. 115. World Health Organization. Geneva, Switzerland, available at: goo.gl/BY3Kyf (03.03.2017).

WHO (2015). Sanitation safety planning: manual for safe use and disposal of wastewater, greywater and excreta. World Health Organization. Geneva, Switzerland.

WHO (2014). The top 10 causes of death, Fact sheet No. 310. World Health Organization. Geneva, Switzerland, available at: *goo.gl/wWtyd2* (03.03.2017).

WHO (2013). Diarrhoeal disease, Fact sheet No. 330. World Health Organization. Geneva, Switzerland, available at: *goo.gl/GtUfLd* (03.03.2017).

WHO (2009). Global health risks, Mortality and burden of disease attributable to selected major risks. World Health Organization. Geneva, Switzerland.

WHO (2006a). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Volume 1: Policy and regulatory aspects. World Health Organization. Geneva, Switzerland.

WHO (2006b). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Volume 4: Excreta and greywater use in agriculture. World Health Organization. Geneva, Switzerland.

WHO (2006c). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Volume 2: Wastewater use in agriculture. World Health Organization. Geneva, Switzerland.

WHO (2003). State of the Art Report – Health Risks in Aquifer Recharge Using Reclaimed Water. World Health Organization. Geneva, Switzerland.

WHO (1997). Vector Control: Methods for Use by Individuals and Communities. World Health Organization. Geneva, Switzerland.

WHO (1989). Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture – Measures for public health protection. World Health Organization. Geneva, Switzerland.

WHO, and UNICEF (2014a). Estimates on the use of water sources and sanitation facilities – Vanuatu, World Health Organization. Geneva, Switzerland, and United Nations Children's Fund, New York, USA.

WHO, and UNICEF (2014b). Progress on drinking water and sanitation: 2014 update. World Health Organization. Geneva, Switzerland/UNICEF, New York, USA.

Wichuk, K., and McCartney, D. (2007). A review of the effectiveness of current time-temperature regulations on pathogen inactivation during composting. J Environ Engin Sci 6(5), pp. 573-586. doi:10.1139/S07-011

Winblad, U., and Kilama, W. (1985). Sanitation without Water. Revised and Enlarged Edition. MacMillan Publishers Ltd., London, UK.

Winblad, U., and Simpson-Hébert, M. (2004). Ecological Sanitation – revised and enlarged edition. Stockholm Environment Institute. Stockholm, Sweden.

Winker, M. (2009). Pharmaceutical residues in urine and potential risks related to usage as fertiliser in agriculture. PhD thesis, Technical University of Hamburg-Harburg. Hamburg, Germany.

Winker, M., Vinneras, B., Muskolus A., Arnold, U., and Clemens, J. (2009). Fertiliser products from new sanitation systems: Their potential values and risks. Bioresour Technol 100(18), pp. 4090–4096. doi:10.1016/j.biortech.2009.03.024

9. APPENDIX

Table A.1: Suggested minimal horizontal distances between sanitation and water supply facilities. See source for References (Lorentz et al., 2015, p. 17, adapted).

Horizontal distance	Conditions	Considered contaminants	Reference
6 m	For sandy soils	Chemical, microbial	Dyer & Bhaskaran , 1945
10 m	For sandy or clay soils, except fissured rock environments	Microbial	Banerjee, 2011
15 m	Water abstraction rates do not cause the water gradient to change significantly	Chemical, microbial	Franceys et al., 1992
15 m	Water abstraction point in area higher than latrine, at least 2 m distance between bottom of the pit and water table	Chemical, microbial	Kimani-Murage & Ngindu, 2007
15 m	–	Chemical, microbial	Amadi et al., 2013
20 m	For fine sandy soil where water table varies between 5 – 20 m below ground level	Chemical, microbial	Still & Nash, 2002
30 m	–	Chemical, microbial	Dzwario et al., 2006
30 m	–	Chemical, microbial	Adejuwon & Adeniyi, 2011
30 m	Bottom of the leach pit should be at least 1.5 m above water table	Chemical, microbial	Sphere project, 2006
30 m	For VIP toilets only, sited downslope of a drinking water source on slightly raised ground, on firm soil	Chemical, microbial	Bester & Austin , 2000
30 m	Downslope, not in coarse or fissured ground	Chemical, microbial	Harvey et al., 2002
50 m	For fine to coarse sand, water table between 0 – 11 m below ground level	Chemical, microbial	Tandia et al., 1999
50 m	–	Chemical, microbial	WaterAid, 2011
10 – 90 m	30 m distance is not recommended for highly permeable soils, with a shallow and fluctuating water table	Viruses	Dillon, 1997
15 – 50 m	Dependent on depth of water table, soil composition and aquifer characteristics	Chemical, microbial	Xu & Braune, 1995
15 – 50 m	–	Chemical, microbial	Lewis et al., 1982
8 m	Pit latrine in a low permeable soil and downslope of a drinking water point	Chemical, microbial	McCarthy et al., 1994
30 m	For pit latrines on ground level, above the highest point of water table, high permeable soil, toilet system upslope of drinking water point	Chemical, microbial	McCarthy et al., 1994
7.5 m	If highest water table level > 5 m below the bottom of pit or soak-away	Chemical, microbial	CSIR, 2005; Devilliers , 1987
15 m	If highest water table level is between 1 – 5 m below ground	Chemical, microbial	CSIR, 2005; Devilliers , 1987
30 m	If highest water table level < 1 m	Chemical, microbial	CSIR, 2005; Devilliers , 1987
No safe distance	Area comprises of coarse soil, fissured rock or limestone	Chemical, microbial	CSIR, 2005

Table A.2: Summarized results from studies where faeces have been treated with a pH-elevating additives (Schönning & Stenström, 2004, p. 25).

Area of Investigation	Type of toilet	Additive	pH, temp, moisture	Most important findings- Inactivation of pathogens and indicators	Reference
Vietnam (during hot and dry season)	12 latrines, 2 of each type. All urine-diverting, most double-vault or multi-bucket	Kitchen ash and leaves. 200 – 700 ml per visit	pH: 8.5 – 10.3 temp: 31.1 – 37.2 °C moisture: 24 – 55% (mean values for each latrine)	**Controlled die-off experiments in challenge tests:** T_{90} for *Salmonella typhimurium* phage 28B varied from 2.4 to 21 days. pH most important factor for die-off Ascaris viability 0 – 5% after 9 weeks (except in 2 latrines). pH in combination with temperature affect die-off	Carlander & Westrell, 1999
South Africa (hot to cold climate)	Various urine-diverting toilets	Wood chips	pH: 8.6 – 9.4 moisture: 4 – 40%	**Organisms present in material:** After 10 months: All indicators present in high numbers (10^2 – 10^6/g). *Salmonella* present After 12 more months: Faecal streptococci ~10^4/g, clostridia & coliphages present, *Salmonella* absent	Austin, 2001
South Africa	2 urine-diverting toilets	Wood chips and turning	pH: 8.4 – 8.6 moisture: 4 – 9%	**Organisms present in material:** After 2 months: Indicators except coliphages present (~10^2/g). *Salmonella* absent	Austin, 2001
El Salvador	118 double-vault urine-diverting latrines, 38 single-vault solar latrines (composting latrine)	Lime, ash or lime-mixed soil	pH: 6.2 – 13.0	**Organisms present in material:** Faecal coliforms inactivated after 500 days. pH most important factor Ascaris inactivated after 450 days (pH > 11), after 700 days (pH 9 – 11). Temperature strongest predictor for inactivation	Moe & Izurieta, 2003
China	2 latrines	Plant ash mixed with faeces in ratio 1:3	pH: 9 – 10 temp: -10 – 10°C	**Controlled challenge test and organisms present in material:** After 3 months: > 7 log 10 reduction of *Salmonella typhimnurium* phage 28B and faecal coliforms. 1% viability of *Ascaris*	Wang et al., 1999
China		No detailed information given	pH > 8	**Controlled challenge test:** Inactivation of *Ascaris* within 120 days	Lan et al., 2001

Figure A.3: Plant trials from the Philippines to examine the effect of urine used as fertilizer for sweet corn, eggplant and petchay. A randomized complete block design was undertaken on three different sites to compare urine application (equivalent to 75% (T1), 100% (T2) and 125% (T3) of the calculated optimum nitrogen requirement of the plants) with no fertilizer application (C1) and a synthetic fertilizer (C2) (Gensch et al., 2011, p. 9ff, adapted).

Table A.4: Recommendations for urine application as fertilizer for various crops from a local guideline in Niger (Richert et al., 2010, p. 50f, adapted).

Plant	**Application period**		
	Two weeks after sowing or planting	**Start of the flowering** **(3 weeks after the first application)**	**During fructification**
Tomato	0.5 L / plant	0.5 L / plant	0.3 L / plant (3 weeks after 2nd application)
Aubergine	0.5 L / plant	0.7 L / plant	0.3 L / plant (3 weeks after 2nd application)
Pepper	0.6 L / plant	0.7 L / plant	0.5 L / plant (3 weeks after 2nd application)
Potatoes	2.5 L / m^2	2.5 L / m^2 at start of tuberization (4 weeks after the 1st application)	
Lettuce	Sandy soil: 1 L / m^2 Clayey soil: 0.7 L / m^2	Sandy soil: 1 L / m^2 Clayey soil: 0.7 L / m^2 (2 weeks after the 1st application)	
Onion, garlic	1 L / m^2	1.5 L when bulb starts to form (4 weeks after the 1st application)	0.3 L / plant (3 weeks after 2nd application)
Melon, marrow	0.5 L / plant	1 .0 L / plant	0.5 L / plant (3 weeks after 2nd application)
Cucumber	0.5 L / plant	0.7 L / plant	0.3 L / plant (3 weeks after 2nd application)
Cabbage	2 L / m^2	2.0 L / m^2	
Carrot	1 L / m^2	1.25 L / m^2	
Sorghum	0.7 L / plant (start of tillering)	0.7 L / plant	
Mango	0 – 4 years: 4 × 2 L / a per tree (at the start & in the middle of rainy as well as cold season)	> 4 years: 4 × 6 L / a per tree (at the start & in the middle of rainy as well as cold season)	
Orange	0 – 4 years: 4 × 1.5 L / a per tree (at the start & in the middle of rainy as well as cold season)	> 4 years: 4 × 5 L / a per tree (at the start & in the middle of rainy as well as cold season)	
Papaya	3 L / tree (1 month after sowing)	4 L / tree (6 weeks after the 1st application) NB: make same application for the next production cycle	4 L / tree (6 weeks after 2nd application)
Banana	3 L / tree (1 month after planting)	4 L / tree (6 weeks after the 1st application) NB: make same application for the next production cycle	3 L / tree (6 weeks after 2nd application)

Table A.5: Effect of selected disinfection methods on faecal coliform levels on lettuce in West Africa (Drechsel et al., 2009, p. 252).

Method	Log unit reductions[a]	Comments
Dipping in a bowl of water	1.0 – 1.4	• Increased contact time from a few seconds to 2 minutes improves the efficacy from 1–1.4 logs. • Not very efficient compared to washing with other sanitizers. • Not very effective for helminth eggs if washing has to be done in the same bowl of water. • Warming the water did not result in different counts.
Running tap water	0.3 – 2.2	• Effective compared with washing in a bowl, also for helminth egg removal. • Increased efficacy only with increased contact time from a few seconds to 2 minutes. • Limited application potential due to absence of tap water in poor households.
Dipping in a bowl with a salt solution	0.5 – 2.1	• Salt solution is a better sanitizer compared to dipping in water if the contact time is long enough (1–2 mins). • Efficacy improves with increasing temperature and increasing concentration, but high concentrations have a deteriorating effect on the appearance of some crops like lettuce.
Dipping in a bowl with a vinegar solution	0.2 – 4.7	• Very effective at high concentration (> 20ml/L) but this could have possible negative effects on taste and palatability of the washed vegetables. • To achieve best efficacy and keep the sensory quality of product the contact time should be increased to 5–10 mins. • Efficacy is improved even at low concentration if carried out with a temperature over 30°C.
Dipping in a bowl with potassium permanganate solution	0.6 – 3.0	• Most effective at higher concentrations (200ppm), a temperature of 30°C or higher and a contact time of 5–10 mins. • Higher concentration colours washed vegetables purple which requires more water for rinsing or may raise questions of a negative health impact.
Dipping in a bowl with a solution containing a washing detergent (OMO™)	1.6 – 2.6	• Significant reductions could be achieved with 5–10 mins' contact time. • Residual perfumes and soap taste might affect consumer's sensory perception. • As OMO contains surfactants which could affect health, thorough rinsing is required
Dipping in a bowl of water with added household bleach	2.2 – 3.0	• Tested dosages (commercial bleach) resulted in 165–248µS/cm salinity (= concentration indicator). • Effective with 5–10 mins' contact time, and widely used in Francophone West Africa. • May pose a health risk if dosage is not well explained.
Dipping in a bowl of water containing chlorine tablets	2.3 – 2.7	• Effective at 100ppm but tablets not commonly available in some West African countries. • Effect of higher concentrations on efficacy not tested.

[a] ranges are due to different concentrations or contact times of disinfectant (see comments column)
From Amoah et al. (2007b), modified

Table A.6: Tolerance level of common plants to salinity (Brady & Weil, 1999 as cited in Richert et al., 2010, p. 6).

Tolerant	Moderately tolerant	Moderately sensitive	Sensitive
Barley (grain)	Ash (white)	Alfalfa	Almond
Bermuda grass	Aspen	Broad bean	Apple
Black cherry	Barley (forage)	Cauliflower	Apricot
Cotton	Beet (garden)	Cabbage	Bean
Date	Broccoli	Celery	Blackberry
Olive	Cow pea	Clover	Boysenberry
Rosemary	Fescue (tall)	Corn	Carrot
	Fig	Cucumber	Celery
	Harding grass	Grape	Grapefruit
	Kale	Lettuce	Lemon
	Orchard grass	Pea	Onion
	Oats	Peanut	Orange
	Pomegranate	Radish	Peach
	Rye (hay)	Rice (paddy)	Pear
	Ryegrass (perennial)	Squash	Pineapple
	Safflower	Sugar cane	Potato
	Sorghum	Sweet clover	Raspberry
	Soybean	Sweet potato	Strawberry
	Squash (zucchini)	Turnip	Tomato
	Wheat		

Table A.7: Survival times of selected excreted pathogens in soil and on crop surfaces at 20 – 30 °C (WHO, 1989, p. 63).

Pathogen	**Survival time**	
	In soil	**On crops**
Viruses		
Enteroviruses[a]	< 100 but usually < 20 days	< 60 but usually < 15 days
Bacteria		
Faecal coliform	< 70 but usually < 20 days	< 30 but usually < 15 days
Salmonella spp.	< 70 but usually < 20 days	< 30 but usually < 15 days
Vibrio cholera	< 20 but usually < 10 days	< 5 but usually < 2 days
Protozoa		
Entamoeba histolytica cysts	< 20 but usually < 10 days	< 10 but usually < 2 days
Helminths		
Ascaris lumbricoides eggs	Many months	< 60 but usually < 30 days
Hookworm larvae	< 90 but usually < 30 days	< 30 but usually < 10 days
Taenia saginata eggs	Many months	< 60 but usually < 30 days
Trichuris trichiura eggs	Many months	< 60 but usually < 30 days

[a] Includes polio-, echo-, and coxsackieviruses

From Feachem et al. (1983), reproduced by permission of World Bank.

Table A.8: Carbon / Nitrogen ratios of different materials (Jenkins, 2005, p. 34).

Material	**% N**	**C:N Ratio**	**Material**	**% N**	**C:N Ratio**
Activated Sludge	5 – 6	6	Onion	2.65	15
Amaranth	3.6	11	Paper	–	100 – 800
Apple Pomace	1.1	13	Pepper	2.6	15
Blood	10 – 14	3	Pig Manure	3.1	14
Bread	2.1	–	Potato Tops	1.5	25
Cabbage	3.6	12	Poultry Carcasses	2.4	5
Cardboard	0.1	400 – 563	Purslane	4.5	8
Coffee Grnds.	–	20	Raw Sawdust	0.11	511
Cow Manure	2.4	19	Red Clover	1.8	27
Corn Cobs	0.6	56 – 123	Rice Hulls	0.3	121
Corn Stalks	0.6 – 0.8	60 – 73	Rotted Sawdust	0.25	200 – 500
Cottonseed Ml.	7.7	7	Seaweed	1.9	19
Cranberry Plant	0.9	61	Sewage Sludge	2 – 6.9	5 – 16
Farm Manure	2.25	14	Sheep Manure	2.7	16
Fern	1.15	43	Shrimp Residues	9.5	3.4
Fish Scrap	10.6	3.6	Slaughter Waste	7 – 10	2 – 4
Fruit	1.4	40	Softwood Bark	0.14	496
Garbage (Raw)	2.15	15 – 25	Softwoods (Avg.)	0.09	641
Grass Clippings	2.4	12 – 19	Soybean Meal	7.2 – 7.6	4 – 6
Hardwood Bark	0.241	223	Straw (General)	0.7	80
Hardwoods (Avg.)	0.09	560	Straw (Oat)	0.9	60
Hay (General)	2.1	–	Straw (Wheat)	0.4	80 – 127
Hay (legume)	2.5	16	Telephone Books	0.7	772
Hen Manure	8	6 – 15	Timothy Hay	0.85	58
Horse Manure	1.6	25 – 30	Tomato	3.3	12
Humanure	5 – 7	5 – 10	Turkey Litter	2.6	16
Leaves	0.9	54	Turnip Tops	2.3	19
Lettuce	3.7	–	Urine	15 – 18	0.8
Meat Scraps	5.1	–	Vegetable Prod.	2.7	19
Mussel Resid.	3.6	2.2	Water Hyacinth	–	20 – 30
Mustard	1.5	26	Wheat Straw	0.3	128 – 150
Newsprint	0.06 – 0.14	398 – 852	Whole Carrot	1.6	27
Oat Straw	1.05	48	Whole Turnip	1	44
Olive Husks	1.2 – 1.5	30 – 35			

10. CURRICULUM VITAE

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11. AFFIRMATION

I certify, that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.
Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Vienna, 03.03.2017 Dominik, RAAB