Michael Grad, BSc

Collection and treatment of fecal disposal in rural areas of developing countries

Case study: Nepal

MASTER THESIS

to achieve the university degree of

Diplom-Ingenieur

Master's degree programme: Civil Engineering, Geotechnical and Hydraulic Engineering

Submitted to

Graz University of Technology

Supervisor:

Univ.-Prof. Dr.-Ing. Dirk Muschalla

Assisting adviser:

Dipl.-Ing. Roman Maier, BSc

Institute of Urban Water Management and Landscape Water Engineering

Graz, 5. December 2016

International Volunteer Day for Economic and Social Development (UN)

Contact:
Michael Grad
m.grad@student.tugraz.at

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To Father and Mother

Acknowledgement

I first want to thank my thesis advisor **Prof. Dirk Muschalla** of the Technical University Graz. He let me come up with my own topic and always steered me in the right direction whenever he thought I needed it. He consistently allowed this thesis to be my own work and always assisted me with constructive criticism. I also want to thank **Roman Maier**, who was involved in the validation survey for this research project. His door was always open and he had an open ear for any sort of request at all time.

A special thanks to my parents, **Klaus and Karin Grad**. They always gave me the backing and safety when there were tough phases during my studies. Thank you for your unfailing support and continuous encouragement throughout my years of study. This accomplishment would not have been possible without them. **Thank you.**

During my studies I made a lot of friends and I have **profound gratitude** for all the support from so many people all along. In this respect I want to thank **Stefan Wagner**, who made me a part of the big social network **TipTop4**. I am honored to have friends I can always count on. Thanks to all those whom assisted me in proofreading this thesis.

Thanks to **Andreas Kramer**, founder of the non-profit organization **Nepal Direct**, who came up with this topic and the objective to implement the findings of this thesis in rural Nepal. I am grateful and indebted for his input and the very valuable feedback on this thesis.

Finally, I want to thank my home country **Austria** to facilitate affordable studies and provide the infrastructure for high-quality education.

Abstract

This thesis analyses the status quo of collection and sanitation technologies for people's elementary needs in developing countries. The focus is put on the rural areas of less developed countries, where people often lack satisfying sanitary conditions. With respect to low resource availability, this thesis examines basic sanitation facilities and furthermore, provides a calculation tool to support the decision-making process for technology selection. Considering the social, infrastructural, educational and financial circumstances on-site, it shall be possible to point out the advantages of one technology over another.

This thesis focuses on two research questions: (i) What are reasonable collection and sanitation technologies in rural areas of developing countries and what are their advantages and disadvantages? (ii) How can the different technologies be compared to each other numerically and what are the significant factors for this purpose? The study is structured accordingly by answering the former question in part one and the latter in part two.

The findings of this research show that different types of technologies, associated with one specific stage of purification, can be compared numerically by all means. The implemented decision-making tool respects the incidental costs over lifespan, the cultural discrepancies arising with this topic, the lack of advanced infrastructure and the environmental impact of the technologies. When considering a particular situation on site, several parameters can be modified by the planning engineer. According to this input, a number of technologies are compared among each other and the most eligible can be determined. The results serve as basic information for further discussion in the decision-making process.

Keywords: collection and primary sanitation technologies; developing countries; rural areas; decision-making process; technology rating tool; technology selection

Kurzfassung

In dieser Diplomarbeit werden Abwassersammel- und Abwasseraufbereitungsanlagen für ländliche Regionen in entwicklungsschwachen Staaten aufgezeigt. Ziel ist es, geeignete Technologien darzulegen und diese, unter Berücksichtigung diverser Rahmenbedingungen, durch ein entsprechendes Bewertungsverfahren vergleichbar zu machen. Neben den technischen Anforderungen sind besonders soziale, infrastrukturelle, finanzielle und ausbildungsspezifische Faktoren bei der Technologiewahl von Bedeutung. Die Ressourcen Strom, Wasser und Bildung stellen oft limitierende Faktoren in entwicklungsschwachen Regionen dar und sind deshalb zentral in den Entscheidungsprozess einzubeziehen.

Dieser Arbeit liegen zwei wesentliche Forschungsfragen zugrunde: (i) Was sind geeignete Sammel- bzw. Reinigungstechnologien in ländlichen Regionen entwicklungsschwacher Länder und was sind deren Vor- bzw. Nachteile? (ii) Wie können diese Technologien numerisch verglichen werden und was sind wesentliche Bewertungsfaktoren dafür? In Teil eins werden anlagenspezifische und technische Grundlagen aufgezeigt, welche in Folge, in Teil zwei, in einem numerischen Berechnungsmodell gewichtet sind.

Durch die individuelle Gewichtung einzelner Bewertungsfaktoren hinsichtlich örtlich veränderlicher Umstände, ist es dem ausführenden Ingenieur möglich, unterschiedliche Technologien einer Reinigungsstufe zu vergleichen. Für jede Anlage wird ein Vergleichswert errechnet. Je höher dieser Wert ist, desto besser eignet sich die jeweilige Technologie für die spezifischen Rahmenbedingungen vor Ort. In dem Rechenmodell sind die Baukosten, Betriebskosten, mangelhafte Infrastruktur und sozial-kulturelle Merkmale berücksichtigt. Diese Faktoren sind wesentliche Säulen für eine breite Akzeptanz in der Bevölkerung und tagen deshalb besonders zur Umsetzbarkeit und Nachhaltigkeit der sanitären Anlagen bei. Die Ergebnisse des Modells sind genau zu analysieren und dienen als unterstützende datenbasierte Grundlage im Entscheidungsprozess.

Stichwörter: Abwassersammel- und Aufbereitungsanlagen; Entwicklungsländer; ländliche Regionen; Entscheidungsprozess; Technologiebewertung; Technologiewahl

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List of Abbreviations

US$	United States Dollar
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids
DC	Developing Countries
WHO	World Health Organization
UN	United Nations
UNDP	United Nations Development Program
HDI	Human Development Index
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
CIA	Central Intelligence Agency
HRT	Hydraulic Retention Time
PE	Person Equivalent
PVC	Polyvinyl Chloride
SPL	Simple Pit Latrines
VIP	Ventilated Improved Pit
Eco-san	Ecological Sanitation
UD	Urine Diversion
UDD	Urine Diversion Dehydration
CT	Composting Toilet
WWTP	Wastewater treatment plant
CST	Conventional Septic Tank
ABR	Anaerobic Baffled Reactor
AF	Anaerobic Filter
UASB	Up-flow Anaerobic Sludge Blanket
CW	Constructed Wetland
WSP	Wastewater stabilization pond
O&M	Operation and maintenance
M&R	Maintenance and repair
GoP	Group of purpose

1 Introduction

In most industrialized countries, water-flush toilets are taken for granted to exist in every household. To achieve such a standard, two main requirements must be satisfied in general. First, a grid-type wastewater disposal network is needed to attach every household to some kind of sewage treatment (either centralized or decentralized). Second, this type of disposal requires water to transport feces and greywater to the treatment plant. For that purpose, clean water is used most of the time. Since all this puts pressure on investments in public infrastructure and assumes high water availability, this type of wastewater disposal is not suitable all over the world. Especially developing countries usually do not have these structures for advanced sanitation. In both rural and urban areas, people often suffer from insufficient sanitary circumstances. Unsatisfying sanitary facilities include flush or pour-flush toilets not connected to a subsequent treatment facility, cesspits or pit latrines without a slab, defecation into a bucket, or total open defecation e. g. in a bush or in a field (www.cia.gov, 2016). These critical issues are one of the main triggers for infectious food or waterborne diseases like bacterial diarrhea, hepatitis A and E or typhoid fever.

The first part (Technologies) of this thesis investigates different basic collection and treatment technologies. The specific technologies are investigated in consideration of ifs estimated dimensions, costs and maintenance requirements. In order to provide a clear review of every technology, its advantages and disadvantages are summarized finally. The aim of this research is to propose the most suitable sanitation facilities for specific on-site conditions. This, among others, has to respect different social and cultural as well as climatic circumstances. Especially social and cultural circumstances are of particular interest in developing countries, as these issues strongly influence people’s behavior. The observed technologies should in every respect fulfill high specifications in terms of reliability, sustainability, ecology, investment costs and recurring costs.

In the second part (Rating system) of this thesis a technology rating system is implemented. For this purpose a calculation tool is developed, which aims to facilitate the technology selection process for diverse sanitary facilities. Since the practical implementations are intended to take place in Nepal, several notes considering the situation on-site can be found throughout the chapters of this thesis. The following investigation and hence, the developed calculation tool is not specific to Nepal in general, but rather to any decision-making process with regard to sanitation and wastewater treatment in developing countries. The research is based on the basic sanitary needs and the feasibility of particular technologies. The findings of this thesis may be applied to any technology selection process in any country in the world.

Besides the access to clean drinking water, the availability of basic sanitation facilities is fundamental and thus defined as human rights by the United Nations. Nepal is one of the poorest countries in the world and hence, these elementary needs are not always satisfied. To compare the state of development of different countries, the UNDP generated a value called “Human Development Index” (HDI). This value incorporates the average income in certain countries, the access of people to education and the general conditions of human health. Countries with an HDI below 0.550 are classified as lowly human developed. With an HDI of only 0.548, Nepal is ranked number 145 out of 188 assessed countries. By comparison, Austria, with an HDI of 0.885, is listed at number 23 and belongs to the countries with very high human development. The state of development is not at least also an indicator for the hygienic conditions that can be expected on site. (UNDP, 2015)

1.1 Research questions

This thesis recaps existing collection and treatment technologies with respect to a possible implementation in developing countries. A special focus is put on the rural development and reasonable solutions for realization. By all means, sanitation facilities must grant human dignity, give children and women security, prevent health hazards, sustainably protect the environment and not at least may contribute to preventing emigration from the countryside into cities or foreign countries.

As a result of this thesis, a comparison of important factors concerning the primarily observed technologies shall be appointed. In addition, the rating system shall be developed as a tool in order to simplify the actual technology implementation on site. It has to consider the most important factors related to the primary needs of people in developing countries. In general the limiting factors for the technology selection most likely are scarcity of water and electricity. Due to these boundary conditions the following research questions can be appointed:

- What are reasonable collection and sanitation technologies in rural areas of developing countries and what are their advantages and disadvantages?
- How can the different technologies be compared to each other numerically and what are the significant factors for this purpose?

1.2 Definitions

In this chapter, some basic terms are defined which are essential for the remainder of this thesis. Due to some short descriptions, the terms should get more familiar. Possibly, not every term of this theses is characterized here but the most important ones should, however, be examined.

Biological Oxygen Demand (BOD)

This value defines the amount of oxygen consumed by microorganisms to degrade organic matter over time. It is evaluated by manometric measures in a self-contained system. The microorganisms consume oxygen and though form CO_2. The emerging vacuum can be measured and the BOD value calculated subsequently. The sample is tested for five days and the BOD_5 value is determined, which is distributed in mg/L BOD. Generally, the more organic content is contained within the water, the higher the demand on oxygen for neutralization. Depending to the size of the sample, the available amount of oxygen is defined so that the reaction may expire completely. High BOD values can be caused by a high amount of organic pollution or high contents of nitrate. (Tilley *et al.,* 2014; WTW, 2016)

Chemical Oxygen Demand (COD)

The COD measures the amount of oxygen required for chemical oxidation of organic material in water by a strong chemical oxidant (in mg/L). Since the COD value defines the total oxygen required for complete oxidation, it is always equal to or higher than the BOD_5 value. Therefore, the value is an indirect measure of the amount of organic material present in water. The higher the organic content, the more oxygen is required for chemical oxidation (high COD). A high organic content generally indicates high pollution of the water. To validate the toxicity of the wastewater, the ratio of COD to BOD_5 is significant as it indicates the level of biodegradability. If the COD/BOD_5 value is low (less than 2.0 or 2.5), it indicates a high potential of biodegradability and thus can be treated easily by biological treatment. (Tilley *et al.,* 2014)

Total Suspended Solids (TSS)

The TSS correspond to the total solid matter contained in water. Generally, the solids can be removed by sedimentation, settling or floating. Suspended solids accumulate on the bottom of the tank and form a layer of sludge deposits, which encourage anaerobic treatment conditions. (www.wikipedia.org, 2016)

Total phosphorus (TP)

Total phosphorus (in mg/L) includes the entire amount of phosphorus in dissolved and particle form. It is rich in nutrients and hence, contributes to the growth of organisms. In return, phosphorus is a limiting factor in the primary productivity of surface waters as it contributes to eutrophication of water. (www.sswm.info, 2016)

Total nitrogen (TN)

Total nitrogen (TN in mg/L) is the sum of ammonia and organic nitrogen (TKN), nitrite (NO_2^-) and nitrate (NO_3^-). TN = TKN + NO_2^- + NO_3 (www.sswm.info, 2016)

Biochemical phosphor elimination

The elimination of phosphate is part of the biological wastewater purification. It can be reduced by the particular bacterial strain, which may absorb more phosphor than needed for own cell growth. The bacteria work most efficient when conditions change rapidly between anaerobic to aerobic. (www.sswm.info, 2016)

Nitrification

Nitrification is the aerobic degradation of several bacterial populations that primarily oxidize ammonium and organic nitrogen to nitrite (NO_2^-), and in the second step into nitrate (NO_3^-). The first step is carried out by bacteria called Nitrosomonas, the second by Nitrobacter bacteria. The chemical reaction for the transformation of ammonium to nitrate is shown in the following equation. $NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + H^+$ (www.sswm.info, 2016)

Denitrification

As nitrification is completed, the process of denitrification may be initiated in order to transform nitrate into nitrogen gas, which can be released into the atmosphere. Denitrification proceeds according to the following equation. $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$. (www.sswm.info, 2016)

Eutrophication

Eutrophication occurs due to the enrichment of water by nutrients (especially phosphorus and nitrogen) that accelerate the growth of algae and other plants. These are responsible for the depletion of oxygen, blockage of sunlight and increasing temperatures. Eutrophication can be initiated naturally or as a result of anthropogenic influence (e.g. water pollution) and it harms the ecosystem anyway. (Tilley *et al.,* 2014)

Greywater

Greywater is the total amount of wastewater generated from washing food, clothes, and dishware plus water used for bathing. Water used for toilet flushing or anal cleansing is not collected together with greywater as it may contain pathogenic pollutants. (Tilley *et al.,* 2008)

Brownwater

Brownwater is a mixture of feces and flush-water (urine not included). Brownwater accumulates as residual matter of urine diversion (UD) flush toilets. The quantity mostly depends on the amount of inserted flush-water. It may also include anal cleansing water or dry cleansing material. (Tilley *et al.,* 2014)

Blackwater

Blackwater is a mixture of urine, feces and flush-water together with anal cleansing water or dry cleansing material respectively. Blackwater contains both pathogens of feces and nutrients of urine, whereby the latter is diluted within the flush-water. (Tilley *et al.,* 2008)

Sludge stabilization

Stabilized sludge describes the state of organic material that is completely oxidized and sterilized. When most of the organic contents are degraded, bacteria are forced to starve and subsequently consume their own cytoplasm. The organic matter remaining from the dead bacteria is then degraded by other organisms, which finally results in a fully stabilized product. (Tilley *et al.,* 2008) The stabilization is not time-bound. However, it depends on the estimated stabilization targets. (Tilley *et al.,* 2014)

Anaerobic digestion

Anaerobic digestion is the degradation of organic material hermetically sealed by bacteria and it compounds four stages (see Figure 1-1):

- Hydrolysis: Separation of the chemical compound through the reaction with water. Insoluble molecular compounds break down to sugar, fatty acids and amino acids.
- Fermentation: Products from hydrolysis are converted into organic acids, alcohols, carbon dioxide (CO_2), hydrogen (H) and ammonia (NH_3).
- Acetogenesis: Conversion of organic acids and alcohols into hydrogen (H_2), carbon dioxide (CO_2) and acetic acid (CH_3COOH). Anaerobic conditions are created as residual oxygen is consumed by bacteria.
- Methanogenesis: Methanogenic bacteria convert acetic acid, carbon dioxide and hydrogen into biogas. Therefore, the pH value must stay in a range of 6.5 to 7.5. (Spuhler, 2014)

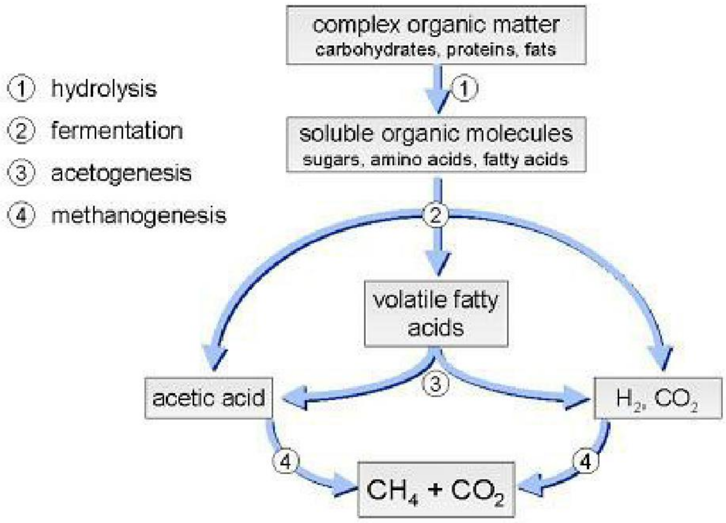

Figure 1-1: Concept of anaerobic digestion (water.me.vccs.edu, 2005)

Wastewater strength

Wastewater can be categorized from weak to strong, referring to the concentration of organic matter. The strength is either judged by its BOD or COD value. Depending on the added quantity of water, the level of dilution and thus the BOD concentration is de- or increased. The more water can be consumed by society, the better the effluent is mixed with clean water and therefore, the lower its BOD value. For example, if water consumption is high (350 – 400 l/person/day), due to dilution the BOD value gets very low (200 – 250 mg/l) and hence wastewater strength is weak. On the other hand, in areas where water is scarce (40 – 100 l/person/day), the BOD value is high (300 - 700 mg/l) and the strength of wastewater is referred to as strong. (Duncan Mara, 2004)

Part one: Technologies

2 Sanitation in developing countries

> *"Over 90% of sewage in developing countries is discharged without any treatment into receiving bodies of water [..]"* (Kabir Das Rajbhandari, 2011)

The governments of developing countries and public institutions in charge must develop an understanding of environmental and social consequences when discharging untreated effluent into the nearest surroundings. Loose exposure to polluted wastewater may cause dramatic diseases among a country's population. Very often epidemic plagues are the consequence of irresponsible fecal handling. Countries and people need to be educated that wastewater absolutely needs to be treated before discharge or being reused for agricultural irrigation. Before defining standards about the targeted treatment quality, it is essential that the government determines where, when and how much to invest in treatment technologies. (Manuel Mariño & John Boland, 1999)

The collection, treatment, and disposal of accumulated wastewater, constitutes a significant challenge for developing countries. In remote areas, it is especially important to make well-considered decisions concerning the intended technological application. For instance, it would be uneconomic and impractical to provide energy- and maintenance-intensive treatment systems to communities living in remote regions with very poor access to public infrastructure. The same discussion has to take place for water-flush technologies. Water-flush technologies may only be considered when water availability is non-restrictive, a proper grid-type network is pre-existing or the required installations are feasible at low cost. Most likely those treatment facilities can be neglected for the rural areas of DCs (developing countries). Hence, more appropriate solutions need to be found. A number of technologies are outlined in the following chapters of this thesis. Ideally, all the treatment systems do not require external energy supply, may run with very little efforts of repair and maintenance work, and anyway should be prone to serious disturbances. Not all possible technologies will be discussed in this thesis since they cannot be conducted economically. (M. Karpuzcu *et al.,* 2008; Udert & Wachter, 2012)

Nepal

Almost 50% of the rural Nepal population is forced to deal with non-improved sanitation facilities (see chapter 2.2). In the rural areas of Nepal the usage of pit latrines is a widespread method for collection of human excreta. According to experience, these need to be emptied every five to ten years. Very often the excavated contaminated matter is then directly extracted into neighboring fields. In small rural settlements, a public water distribution network is hardly ever available. Therefore, private households usually do not have direct access to potable water. If people want to obtain drinking water, they need to go to a public standpipe, which is mainly designed for up to 50 houses. At this place, people collect drinking water, do their laundry and dishes and even take showers. Consequently, the effluent is quite polluted and in general there is no public awareness for purifying the water before it flows back into the environment.

2.1 Social and cultural issues

Cultural beliefs and public perceptions of excreta and greywater management vary widely all over the world. Because of that reason, successfully implemented technology on one site must not automatically fit another site, even if the geological circumstances would be appropriate or technical implementations would be simple. It is essential that cultural beliefs and public perceptions are respected in the process of technology selection. (WHO, 2006)

> *"Social acceptance is not just a simple yes or no, but a flexible parameter that changes with time."* (Kabir Das Rajbhandari, 2011)

There are many differences between children, women and men in terms of behavior, preferences, special needs, access to resources and money, time spent at home or available information and education. The biological differences are obvious though gender roles can vary with social, economic and technological change. Gender roles are always socially constructed and their breakthrough generally takes decades. Sanitation with the same rights to everyone means that both men and women need to take part in the decision-making process. Due to a widespread gender imbalance, this requires deliberate and skilled facilitation to elicit information about female needs and wishes. (Dr. Dinesh Chandra Devkota)

Nepal

Due to cultural evolution, people in Nepal are not used to dry anal cleansing after defecation. It is most common to wash the buttocks with water, whereas cleansing with paper or other dry material is generally unaccepted. This mainly influences the technology selection for collection and primary treatment facilities since dry toilets most likely won't be accepted by local people. In addition, squatting pans are very commonly used, whereas constructions to sit on are not traditional.

The Nepalese caste system is very strict. About 13% of the population count to the lowermost cast, of which people are called Dalit. These people generally do not have any land to live on. All over Nepal about 29% of the population is landless, meaning they do not have any physical space to construct their own houses or toilets. Mostly people live as squatters in public places and slums where toilet constructions are not legally considered. (Dr. Dinesh Chandra Devkota)

Different religious and cultural circumstances are key issues to a successful implementation of new sanitary technology. Dealing with this topic generally is a private and intimate issue. Hence, it is closely associated with aspects of human dignity. Due to social taboos, the knowledge about treatment and reuse of excreta strongly varies between different cultures and regions. Generally, education about the health benefits, security aspects or enhanced privacy may be reasons to persuade municipality from sanitary development. Another approach to satisfy skeptic users may be showing examples of successfully implemented sanitary systems from neighboring villages and its benefits to the local communities. If a technology is socially and culturally unaccepted, it can never be run sustainably. (Dr. Dinesh Chandra Devkota)

2.2 Health and hygiene

The treatment performance of the technology, as well as convenience and comfort, constitute important issues for the acceptance and hence the success or failure of a sanitation system. In addition, the simplicity of toilet surface cleaning, odorless operation, avoidance of mosquito-plagues and the general safety of usage are absolutely important to prevent hazardous infections. If a sanitary technology is supposed to be successfully implemented, another party of interest, people who are finally instructed to do dirty maintenance or cleaning work, have to be respected and involved in the decision-making process. They generally have critical knowledge about the peculiarities and challenges, which are affiliated with the system. Their opinion particularly has to be respected in terms of hygiene and safety issues. (Hu *et al.,* 2016)

Nepal

Hygienic circumstances in Nepal are in a critical state. Due to insufficient access to safe drinking water and proper sanitation facilities, skin diseases, acute respiratory infections (ARI) and diarrheal diseases are widespread. These are the main reasons for a high child mortality, which affects 14% among children under the age of five years. They are prone to get infected with diarrhea, which can be traced back to poor sanitary conditions. (Ministry of Health and Population *et al.,* 2012)

There are big discrepancies between urban and rural regions in Nepal regarding the quality of sanitation facilities. Table 2-1 shows the different development of sanitary facilities between urban and rural areas of Nepal. As can be seen, more than 50% of rural population is faced with insufficiently improved sanitation facilities. This is an alarming value and shows a great potential for improving the current situation. (Ministry of Health and Population *et al.,* 2012)

Table 2-1: Household sanitation facilities (Ministry of Health and Population *et al.,* 2012)

Percent distribution of households and de jure population by type of toilet/latrine facilities, according to residence, Nepal 2011

	Households			Population		
Type of toilet/latrine facility	Urban	Rural	Total	Urban	Rural	Total
Improved, not shared facility	52.5	35.8	38.2	58.1	36.7	39.5
Flush/pour flush to piped sewer system	15.9	1.4	3.5	18.0	1.3	3.5
Flush/pour flush to septic tank	32.0	23.7	24.9	35.0	23.9	25.4
Flush/pour flush to pit latrine	2.1	3.3	3.1	2.3	3.4	3.3
Ventilated improved pit (VIP) latrine	0.4	0.6	0.6	0.4	0.6	0.6
Pit latrine with slab	2.1	6.6	6.0	2.4	7.3	6.7
Composting toilet	0.0	0.2	0.2	0.0	0.2	0.2
Shared facility[1]	36.7	15.9	18.9	29.5	12.6	14.9
Flush/pour flush to piped sewer system	11.4	1.7	3.1	8.4	1.2	2.2
Flush/pour flush to septic tank	22.6	10.0	11.8	18.7	7.7	9.2
Flush/pour flush to pit latrine	1.2	1.3	1.3	1.0	1.1	1.1
Ventilated improved pit (VIP) latrine	0.3	0.3	0.3	0.3	0.3	0.3
Pit latrine with slab	1.2	2.6	2.4	1.1	2.3	2.1
Non-improved facility	10.8	48.3	42.9	12.4	50.6	45.6
Flush/pour flush not to sewer/septic tank/pit latrine	0.4	0.3	0.3	0.4	0.2	0.3
Pit latrine without slab/open pit	1.6	8.0	7.1	1.7	7.7	6.9
No facility/bush/field	8.7	39.9	35.5	10.3	42.7	38.4
Total	100.0	100.0	100.0	100.0	100.0	100.0
Number	1,546	9,280	10,826	6,338	41,785	48,123

Note: Total includes three households using bucket under non-improved facility not shown separately.
[1] Facilities that would be considered improved if they were not shared by two or more households

2.3 Climate and topography

Temperature is a very important factor in terms of destruction processes. The higher the temperature, the more effective is the breakdown of degradable matter. Figure 2-1 outlines the upper boundaries required for the destruction of different types of pathogens.

For example, if the temperature of manure could constantly be held above 50 °C for at least one day, all pathogens would be eliminated. Generally, the temperatures can hardly be reached or even held without any external power supply, which certainly is not a very realistic option in developing countries. Hence, by increasing the contact time to more than one year at ambient temperatures of approximately 20 – 30 °C, pathogenic matter can be decomposed equally. That impact of temperature needs to be considered when selecting and dimensioning a sanitation facility.

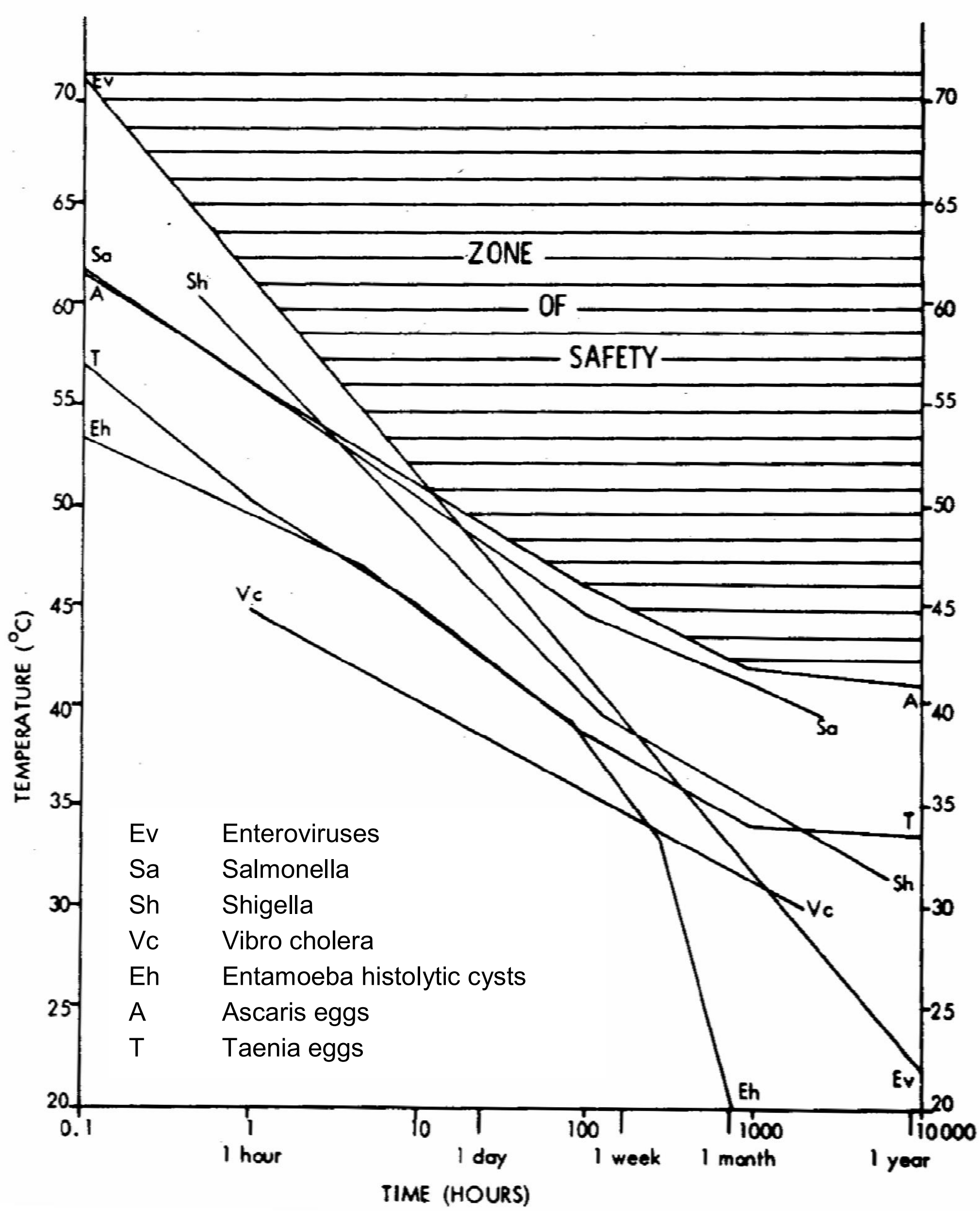

Figure 2-1: The influence of time and temperature on pathogen destruction process (Sandy Cairncross & Richard G. Feachem, 1999)

Topography and constitution of roads are another important factor if a motorized emptying and transportation device is required for standard operation. If sludge cannot be treated on-site, transportation of wastewater within pipelines by gravity flow might be an alternative. This is only suitable if the transportation distances are short and the volumetric flow rate is constantly high. In any other case, a solution with sewers is uneconomical and thus generally not adaptable. However, piping is always a user-friendly way to instantly remove domestic wastes and thus is likely used for waste collection and conveyance inside residential areas. (Hu *et al.,* 2016)

Nepal

Nepal's topography is very different when comparing the north to the south. The southern area is located at about 100 meter above sea level (m a.s.l.), whereas farming is still done at 5000 m a.s.l. at the southern face of the Himalaya. For that reason, temperatures vary significantly in different parts of Nepal. Except for the main road from Kathmandu to Pokhara, the general road conditions are very poor, which influences the accessibility of remote villages. Due to underdeveloped infrastructure, vacuum trucks are not able to reach every village, which needs to be considered for the further technology selection. Besides bad road conditions, electricity availability is another serious problem off from Kathmandu. Even if the infrastructure is intact, it does not guarantee that the net is energized. In many villages, the daily electricity supply is restricted to one or two hours. For this thesis, this is important since the observed wastewater treatment technologies are supposed to run without or alternatively with just little amounts of energy supply. Otherwise, the installation of an additional power unit may get necessary.

3 Technologies

For an effective implementation of sanitary infrastructure in developing countries it is most important to research the defining factors of the different technologies available. In this thesis applicable technologies for remote rural areas are investigated. There are numbers of collection and primary sanitation technologies as well as storage and treatment facilities. Due to scarcity of skilled labor for both, construction and maintenance work, small scale and low-tech solutions are investigated in this chapter. These should ideally work without external electricity input, need to be simple in maintenance, should require a low financial investment for construction and operation, and generate additional value for the customers.

The technology research is split into four main subcategories that respect the different stages of fecal collection and treatment. The first part describes "Collection and primary sanitation", the second "On-site storage and treatment", the third "Semi-centralized wastewater treatment" and the last "Greywater disposal". The research does not include technologies for further sludge disposal since these are mostly unconvertible in rural areas of developing countries. This investigation of treatment facilities goes as far as vacuum trucks evacuating the residual matter.

3.1 Collection and primary sanitation

In developing countries it is a popular practice to dispose of human excreta in water streams and so just shift the burden to downstream communities. This causes serious hygienic problems and negative effects on the environment and natural resources. To prevent health risks and ecological damages, there are two possibilities of how to treat human waste. One is urine-diversion, where liquid and solid excreta never get mixed. The second possibility is to collect a mix of solid and liquid excreta, which then are processed together or separated. Both sanitation methods generally allow some water usage for flushing or anal cleansing. This water may be collected separately. The better solid components can be separated from liquids, the easier the further destruction process will be. Initially, it is important to know that most of the pathogens are contained in feces, while urine is quite sterile with few exceptions. Discharged effluent should finally be free of pathogens as well as low on nitrite, nitrate and phosphorus so that ground- and surface waters do not get affected negatively. (Kabir Das Rajbhandari, 2011)

In general, there are two possibilities to select an appropriate collection and sanitation technology. If only elemental hygiene performances need to be fulfilled and low-cost constructions are most significant, traditional toilets like simple pit latrines (SPLs) or cesspits are preferred. Alternatively, basic hygiene as well as convenience and comfort can be raised to a higher standard by using more elaborate technologies. Besides, additional value may be generated and ecological sustainability can be achieved. (Hu *et al.,* 2016)

3.1.1 Pit latrines

Pit latrines can generally be classified into two types, a SPL and a ventilated improved pit (VIP) latrine. A double vault pit latrine is a subcategory of VIP latrines. In this chapter, some basic information about the construction, functioning and maintenance of pit latrines is given and the differences of these three types will be explained.

Dimensioning

A pit latrine should be designed at least for one year of usage. For the calculation of the pit excavation necessary, a pit volume of 0.07 m^3 per user per year can be estimated. (WHO, 2003)

A pit should be considered to be full as soon as the heap reaches 0.5 m below the floor plate. The free space remaining is then filled with cover material (see p. 26). This secures avoidance of acrid odors while the pit is unused. Accordingly, the upper 0.5 m of the pit may not be respected for the calculation of the particular storage volume.

Construction

A pit latrine requires a subterranean and an above ground construction. The subterranean construction is realized by a square, rectangular or circular pit into the ground, which must not reach deeper than 2 meters above the groundwater level. If the groundwater level is high, nitrogen, phosphorus and pathogens may contaminate the groundwater and thus cause serious problems for drinking water quality. For stability reasons, circular pits generally are preferred. A pit should be covered with a wooden or concrete cover slab. It is supplied with a hole in the middle where excreta can fall through. Whatever type of soil is present in the ground, when using a concrete cover slab, at least the upper 0.5 m of the excavation need to be lined. Appropriate material therefore can either be concrete bricks or rubble stones. If lining is necessary also depends on the soil stability conditions and it should end at least 0.1 m above ground level. For the above ground construction, the latrine is covered with a shelter. The shape of the shelter and the inserted material for it may vary depending on the available construction materials that also are a cost factor. (WHO, 2005)

The location of a pit latrine has to be considered very closely. Figure 3-1 summarizes the decision criteria for an appropriate site selection. In order to prevent living areas from unpleasant odors, latrines should be constructed about 6 meters away from nearby houses. Therefore the regular airstream should also be observed and be taken into account for adequate site selection. In addition, the construction must be placed well away from any water source and absolutely downstream of any standpipes. The soil below the bottom of the excavation should be permeable, so that liquids can seep through. If all these terms are fulfilled, water pollution can mostly be prevented. Nevertheless, groundwater contamination cannot be precluded entirely, especially not in densely populated areas. (WHO, 2005)

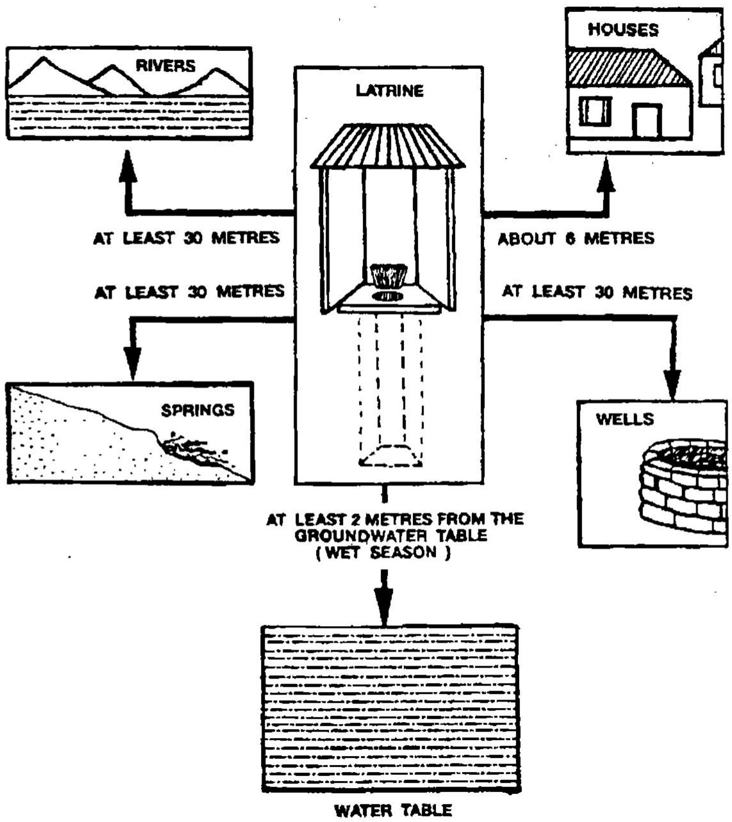

Figure 3-1: Where to mount a SPL (WHO, 2005)

The following construction material is typically applied to subsurface structure and shelter respectively. (WHO, 2005; Nikiema *et al.,* 2011)

- Concrete bricks, cut tree limbs with soil cement or rubble stones for pit lining
- Reinforced concrete or wooden beams for cover slab
- Concrete bricks, rubble stones, wooden slats or natural fibers fixed on wooden beams for superstructure
- Rush mats, tiles or corrugated sheets for roof construction
- The costs for the superstructure are highly dependent on the availability of material.

Cost consideration

Generally, the initial costs are low for simple pit constructions. Depending on the required amount of pits for the construction, the investment costs increase. The most critical costs are those for desludging. If the pit excavation is carried out in permeable soil and the pit lining is either spread out or not executed watertight, liquids can seep into the adjoining soil. As a consequence, the time intervals for pit emptying would be extended and costs saved.

3.1.1.1 Simple pit latrines

SPLs in general are the most basic form of sanitation available. They can be conducted with urine, feces, dry bulking and cover material and some anal cleansing water. Figure 3-2 shows a typical SPL. In contrast to VIP latrines, the latrine ventilation in Figure 3-2 does not affect the digestion process and only provides a static air flow within the cabin. Though SPLs are simple in terms of processing, there are still two things that need to be considered. Firstly, the less water enters the pit, the more effective is the destruction process to be expected. Urine and water seep through the pit content and percolate into the soil at the bottom or through the side walls. Microbial activity thereby degrades a part of the organic fraction. Secondly, a tight-fitting lid should always cover the hole of the floor slab while the toilet is unused since flies and mosquitos should be prevented from entering and breeding within the pit. As the pit is likewise fed with urine and anal cleansing water, the heap should be covered with the appropriate material after defecation for better composting, to reduce acrid smell and prevent fly breeding. This can either be conventional cover material like dry soil, ash or lime, or even animal excrement like dried horse or cow dung (see cover material, p. 26). However, all the materials have to be able to absorb liquid residues and consequently reduce acrid odors. Furthermore, sawdust and leaves, as well as household wastes like vegetable and fruit peel, can function as additives, but together will decrease the lifespan of the pit as it is filled up more rapidly. Due to the constant addition of cover material, the excreta's consistency within a simple latrine is supposed to be dry, which is important for further treatment. The treatment performance of SPLs, however, is limited. (WHO, 2005)

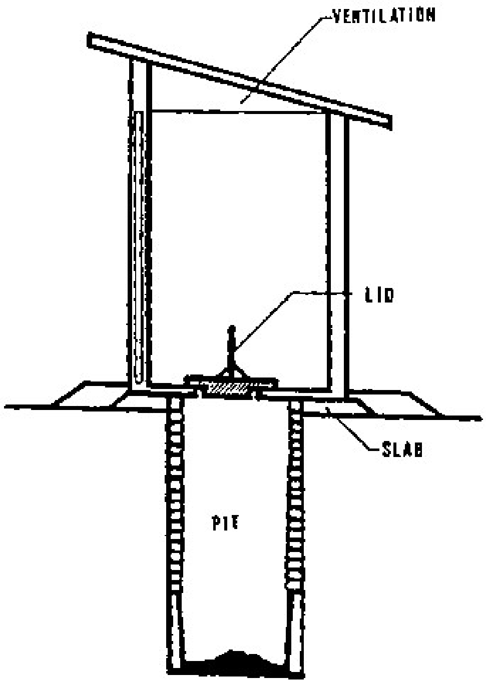

Figure 3-2: Cross section of a SPL (WHO, 1996)

Dimensioning

The volumetric capacity of a pit should not be less than one cubic meter in order to ensure a minimum lifespan of 10 years if used by only a single person. Per person and year 40 to 60 L of accumulated solids can be expected. If cleansing material, such as paper or leaves are disposed into the pit the accumulated matter of solids may rise up to 90 L per person and year. The pit excavation should at least be 3 m deep with a diameter of approximately 1 m. If the diameter exceeds 1.5 m, the risk of collapse increases. However, the longer a pit lasts until it is filled up, the lower will be the average annual economic costs respectively the higher are the social benefits. (WHO, 1992)

Construction

The underground- as well as the above ground construction of SPLs are simple. Figure 3-2 shows the required pit excavation with some lining in the upper section. In order to avoid surface water entry into the pit, the latrine may be slightly raised from ground level. The slab is required to cover the pit and to provide a base plate for the latrine construction. Since no ventilation pipe is installed for pit aeration, a lid has to cover the defecation hole. This prevents acrid odors being permanently present in the upper compartment. A ventilation slot between the roof and the sidewalls of the superstructure also provides a static circulation of fresh air.

In case the groundwater level is high or when excavating rocky soil, the latrine shelter may be raised so as to gain additional volume or to provide groundwater from contamination. The pit is thus prone to flooding. The defecation hole can either be executed by a simple squatting plate or with a classic toilet seat. The pit lining is individually depending on the surrounding soil conditions. (WHO, 2005; O'Riordan, 2009)

Maintenance

Other than keeping the slab and the shelter clean, there is no requirement for daily maintenance. When a pit is fully filled up, there are mainly two options on how to proceed. The pit can either be pumped out by a vacuum truck or alternatively the superstructure and squatting plate are moved to a new pit. The prior technique assumes that the sludge is transported to a composting field where the matter gets decomposed and can hence be utilized as agricultural fertilizer. The second technique presumes ditching a new hole and the relocation of the superstructure and the squatting plate. In addition, the previous pit has to be covered and decommissioned. If the pit was not lined for stability reasons, a tree may be grown on top of the old pit. The roots of the tree absorb the nutrients derived from the compost formed from excreta. An additional ecological value may thereby be generated. (Eawag/Sandec, 2008; Tilley et al., 2008)

Review

SPLs are low-cost technologies and require very few resources. The main advantages and disadvantages are listed in Table 3-1.

Table 3-1: Advantages (+) and disadvantages (-) of SPLs (Tilley *et al.,* 2008)

+ Construction and repair work can be done with locally available material and laborers	– Flies and acrid odors are constantly present
+ No constant source of water required	– Low BOD and pathogen reduction capacity and contamination of groundwater is possible
+ Low construction costs depending on the lining material and the depth of the lining	– Costs for pit emptying may be significant compared to investment costs
+ Little land area requirements	– Sludge needs secondary treatment and/or appropriate discharge
	– Neither feces nor urine is convenient for further utilization
	– The pit may be prone to flooding
	– Stagnant water in the pit favors insect breeding.

3.1.1.2 Pour-flush pit latrine

Pour-flush toilets require water poured in manually after defecation. It can be upgraded to a cistern flush toilet by implementing a continuous water supply. However, pour-flush pit latrines utilize greywater for flushing and do have a water trap to hold odors, mosquitos and flies from entering the superstructure. The amount of flush water varies from 2 to 3 L per usage. Figure 3-3 shows a pour-flush toilet with the installed water trap. (O'Riordan, 2009)

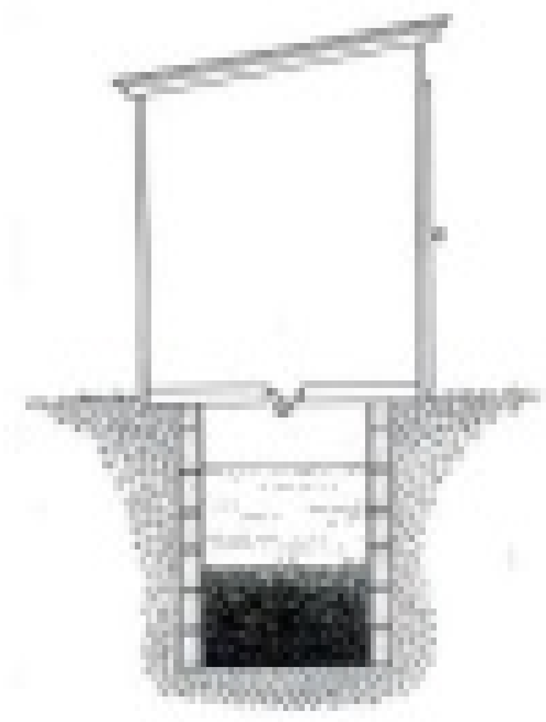

Figure 3-3: Pour flush pit latrine (O'Riordan, 2009)

Construction

As can be seen in Figure 3-3 solids and sludge settle down to the bottom while liquids accumulate above. The water trap as a constructive element integrated into the floor slab (see Figure 3-4, up left) can be made out of cement or fiberglass and prevents the acrid smell from entering the upper compartment. The S-shaped water trap (see Figure 3-4, down left) determines the amount of water needed for flushing. Ideally, the water trap head is approximately 2 cm so water can be saved. The diameter of the water trap should be approximately 7 cm so that feces may still pass through. Figure 3-4 shows the design and function of a water trap. (Tilley *et al.,* 2008; O'Riordan, 2009)

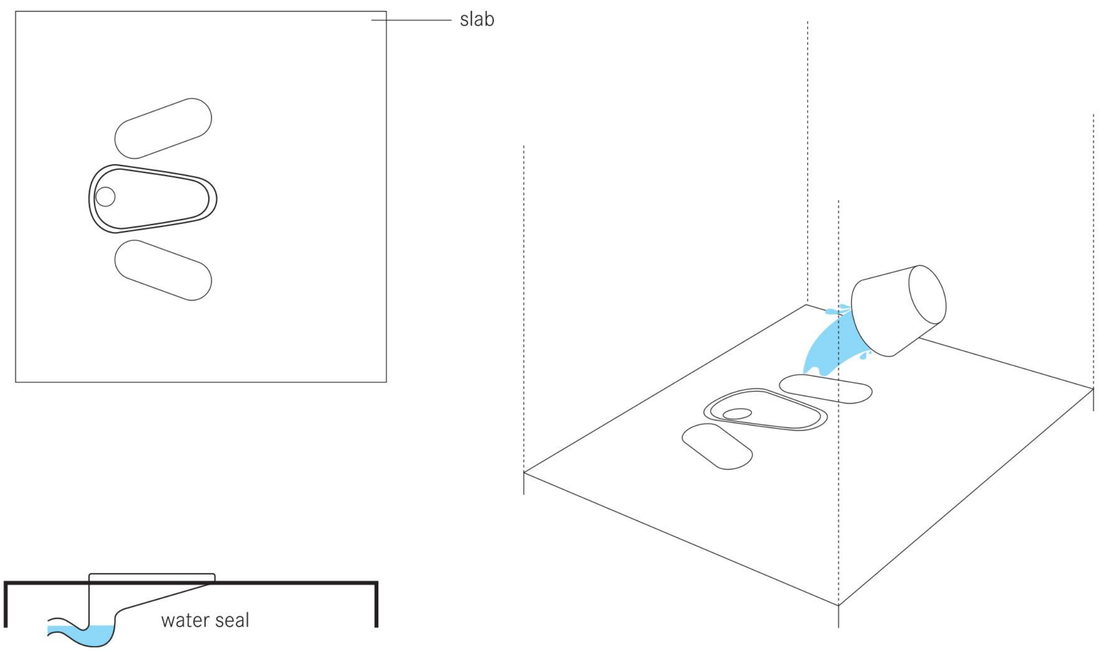

Figure 3-4: Squatting pan with water trap (Tilley *et al.,* 2008)

Maintenance

In general, pour-flush pit latrines are not prone to inappropriate usage. For emptying a pit, filled with a lot of liquids and sludge, service by trucks with mobile bulk tanks will be inevitable. These trucks empty the pit by suction but they require eligible infrastructure for accessibility. Depending on the size of the pit, the quantity of users and the amount of flush water inserted, a frequent evacuation by pumping is necessary. To reduce water consumption and the risk of clogging the water trap, dry cleansing materials and products used for menstrual hygiene should be collected separately and not flushed through the toilet.

Review

Pour-flush pit latrines are low-cost technologies and require very few resources but always some source of flush water. The main advantages and disadvantages are listed in Table 3-2.

Table 3-2: Advantages (+) and disadvantages (-) of pour-flush toilets (Tilley *et al.,* 2008)

+ Due to the water trap, acrid odors and problems with mosquitos can be avoided	– Always require some source of water (reuse of greywater or collected rainwater is possible)
+ Low investment costs and operational costs depend on the price of water	– Material may not be available everywhere – Coarse dry material may clog the water trap

3.1.1.3 Ventilated improved pit latrines

A VIP latrine functions pretty much the same as a SPL. Additionally, they are equipped with a ventilation pipe from the digestion sump to the roof. Thus causing the lid covering the defecation hole becoming unnecessary and a constant circulation of air through the digestion chamber can be attained. This again encourages the decomposition process of the heap and occurring odors can be reduced and deflected. (O'Riordan, 2009)

Construction

Generally, the construction is very similar to a SPL. In addition, there's only a ventilation pipe that needs to be installed. The minimum diameter of the pipe is 100 mm and the preferred material is PVC. The ventilation pipe must reach a sufficient height above rooftop (minimum 0.5 m) and the installation of a fly screen on top has to be ensured. The latrine is favored to be located in windy regions but if the vent pipe is colored in black and oriented at the sunny side of the latrine, the air flow (hot air rises) gets fostered too. A possible arrangement of the vent pipe considering the specific air flow is shown in Figure 3-5. (WHO, 2005)

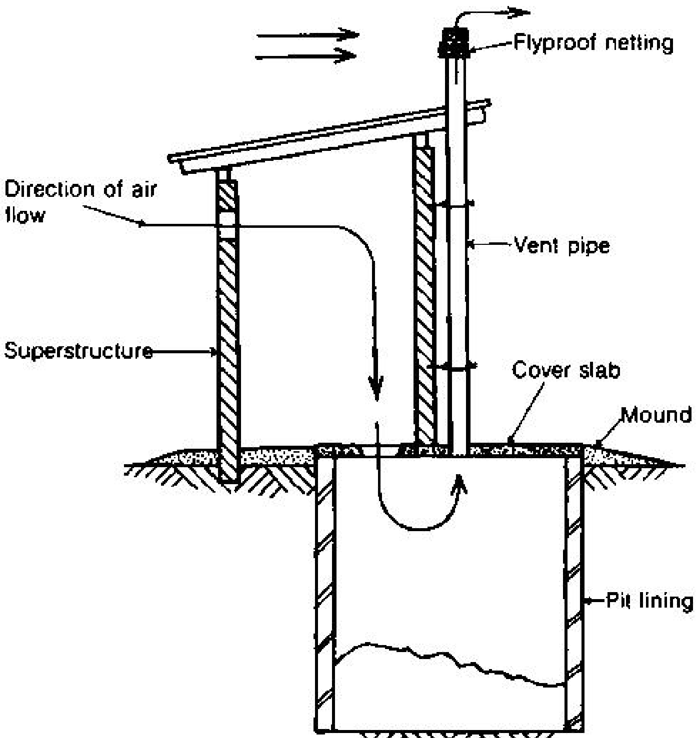

Figure 3-5: VIP latrine (WHO, 1992)

Maintenance

Like SPLs, VIP latrines generally do not require very frequent maintenance. The regulation of the moisture content is significant in terms of preventing fly and mosquito breeding and can be achieved by the amount of added covering material. If the pit fills up to about 0.5m below the surface, the pile should be covered with sufficient soil material and the hole sealed to ensure undisturbed degradation. Further, another cavity has to be ready for use in order to assure continuous availability. This can either be a separate pit some meters away or a second chamber underneath the floor slab, still using the same superstructure (see double-fault pit latrines, chapter 3.1.1.4). After at least one year, preferably two years or even longer, the pit can be emptied and destructed matter lodged at a landfill site in order not to contaminate soil or endanger the community. (Nikiema *et al.,* 2011)

Review

VIP latrines are low cost technologies, require very few resources and little land area. The main advantages and disadvantages are listed in Table 3-3.

Table 3-3: Advantages (+) and disadvantages (-) of VIP latrines

+ Construction and repair work can be done with locally available material and laborers	– Low BOD and pathogen reduction capacity and possible contamination of groundwater
+ No constant source of water required	– Costs for pit emptying may be significant compared to investment costs
+ Low investment costs depending on the lining material and the depth of the lining	– Sludge needs secondary treatment and/or appropriate discharge
+ Compared to the SPL, there is no need for a lid to close the defecation hole	– Neither feces nor urine is convenient for further utilization
+ Acrid odors and problems with flies or mosquitos can be reduced (compared to non-ventilated pits)	– The pit may be prone to flooding
+ Little construction and operational costs depending on the price of water	– Stagnant water in the pit favors insect breeding.
+ Little land area requirements	

3.1.1.4 Double-fault pit latrines

A double-fault pit latrine functionally equals a simple pit or even VIP latrines, with the difference of having two subsurface compartments. This type of latrine is useful when adequate space is limited for digging new pits. Once one compartment is filled the second gets activated for defecation. The progress of decomposition and hence the destruction process of pathogens increase with time and therefore depend on the time that it takes to fill the first pit. A sufficient retention time is 6 months at least, but better 2 years. Double-vault pit latrines can be upgraded by being equipped with vent pipes to convey odors (see Figure 3-6). (WHO, 2003)

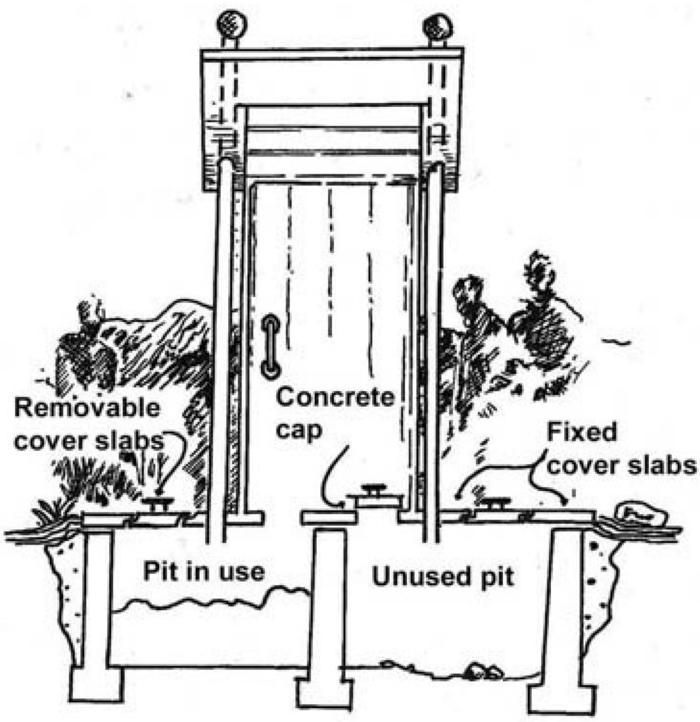

Figure 3-6: Ventilated improved double-vault pit latrine (WHO, 2003)

Construction

The subsurface part of the construction is divided into two compartments. The dividing wall between the compartments may be built out of concrete or brickwork. To ensure that the cover slab can be mounted safely, sufficient stability of the earth facing walls is important. These have to resist tilting into the excavated pit. Because of that reason an appropriate footing of the concrete walls and some fair deep assembling has to be considered. Depending on the cover slab, especially its thickness and reinforcement, the superstructure can either be designed from concrete, bricks or even timber work. Both subsurface compartments need to have a ventilation pipe installed. The ventilation can either be ensured by two separate pipes or as well by one shared pipe with a connection in both compartments. (WHO, 2003)

Review

Double-fault pit latrines are low cost constructions and in general require very few resources. The main advantages and disadvantages are listed in Table 3-4.

Table 3-4: Advantages (+) and disadvantages (-) of ventilated improved double-vault pit latrines

+ Longer life span than single pit latrines	– No specific reuse of feces and urine
+ Excavation of humus is easier than fecal sludge	– The pit may be prone to flooding; stagnant water in the pit may facilitate insect breeding
+ Effective pathogen reduction	– Manual removal of humus required
+ Fecal material may be used as soil conditioner	– Risk of groundwater contamination
+ Acrid odors and problems with flies or mosquitos can be reduced (compared to non-ventilated pits)	– Higher construction costs than single VIP latrines but in return, fewer operational costs if self-emptied
+ Constant source of water not required	

3.1.2 Ecological sanitation systems

First of all, it needs to be clarified that in general an ecological sanitation (eco-san) system is nothing else than a composting system with the main objective of reusing valuable nutrients contained in excreta for fertilization. Eco-san systems are reasonable where a suitable water supply, sewer system or any further sewage treatment plant is unavailable. There are at least two possible methods for primary destruction of pathogens. One is pathogen destruction by dehydration, which is common at ‘urine-diversion dehydration (UDD)’ toilets. The other is destruction by decomposition, which is applied at ‘composting toilet (CT) systems. A third opportunity is ‘wet UD’, where feces get flushed away to be treated in a further secondary treatment phase whereas urine may be utilized right after collection. (Kabir Das Rajbhandari, 2011)

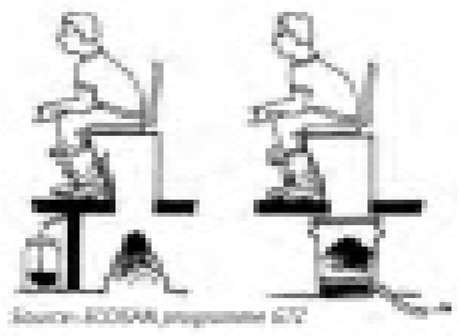

Figure 3-7: Dealing with liquids (Kabir Das Rajbhandari, 2011)

The left example of Figure 3-7 shows a UD system where urine gets separated from excreta right at the origin. As long as anal cleansing water plus flush water is not mixed with the fecal heap, the technology can be operated as a UDD system. In contrast, the example to the right shows a typical non-urine-diversion CT system. Excreta fall down onto a grid and after the liquid seeps through the solid content, it gets separated and discharged at the bottom of the chamber. Since liquids get contaminated by contacting feces, they have to be conveyed to a secondary treatment facility or evaporated in another evapotranspiration bed. Both systems can be designed as CT systems. For that purpose, the amount of liquids entering the digestion chamber is significant. It must not exceed small amounts of anal cleansing water and urine in any case. (Kabir Das Rajbhandari, 2011)

However, independent of the destruction method that gets implemented, the selected sanitation method needs to operate sufficiently with little or, even better, without any water supply. Besides, residuals and end-products must not influence ground- and surface waters negatively. (Kabir Das Rajbhandari, 2011)

UD toilets do separate the urine from feces at the point of collection (see Figure 3-7) but still do not say much about any further treatment of liquid and fecal matter. In the following, the main differences of the particular eco-san systems are listed:

- **UDD** toilets do not allow any water to enter the processing vault.
- **UD-CTs** do allow anal cleansing water to enter the processing vault.
- **Wet (water-flush) UD** toilets do allow the usage of anal cleansing water as well as flush-water to transport the fecal matter to a secondary treatment system.

UDD systems as well as UD-CTs can be implemented as single or double vault systems. Single vault systems do only have one toilet seat or squatting pan, whereas double vault systems work with two identical constructions. There is no functional difference between these types, only a constructive and when considering the investment costs. Wet UD toilets are always designed as a single structure but one must not forget that they require a connection to a sewer and a further secondary treatment system. If a UD eco-san toilet is supposed to be constructed, it is primarily important that the project is culturally acceptable, economically affordable and sustainable. If these points are not satisfied the implementation of the technology will definitely fail. (Kabir Das Rajbhandari, 2011)

Cover and bulking material

To cover human feces, sawdust, ash, coconut coir, lime or dry soil, are adequate additives. These materials support the desiccation process and thus decomposition, prevent fly breeding and avoid acrid odors. As this leads to an increase of the pH value, the covering contributes to a stabilization of the manure and pathogens can effectively be killed (see sludge stabilization, p. 5). The required time to execute the destruction process until neutralization of hazardous pathogens mostly depends on the deployed cover material and the moisture content of the heap. It takes at least 3 months in case of using plant ashes and 10 months when sawdust, dry soil or sand is added. Thereafter, the converted humus can safely be deployed as fertilizer on farmland. (WHO, 2003; Hu *et al.,* 2016)

In some cases, bulking material is added to the pile. This can be wood chips, dried leaves, coconut husks etc. It mainly functions as decomposable place holders and additionally provides air pockets to enable the circulation of air through the solid matter. (Schölzel & Bower, 1999; WHO, 2003; Kabir Das Rajbhandari, 2011; Hu *et al.,* 2016)

Urine as fertilizer

An adult person produces about 0.8 to 2.0 liters of urine per day, children about half as much. Human urine consists to 95% of water. The different ingredients included are more or less valuable for further usage. In general, urine is rich on nitrogen, phosphorus and potassium, whereas feces contain only a small amount of nutrients that can be reused for fertilization. The pH value of urine varies from 5 to 7.5. In Figure 3-8 the apportionment of valuable substances contained in urine and feces is illustrated. (Bastian Etter & Kai M. Udert, 2015)

Figure 3-8: Apportionment of contained nutrients in human urine and feces (Bastian Etter & Kai M. Udert, 2015)

Most pathogenic matter is contained in feces, whereas the content of valuable nutrients is pretty low. In contrast, the nutrient content of urine is high and hazardous infection potential is way lower than when dealing with feces. In case feces and urine are not separated primarily, it is harder to detox excreta, but still not impossible. If liquid residues are contaminated by feces, they must be evaporated, sterilized or otherwise treated before a safe re-utilization as fertilizer is possible. Subsequently, the degradation process, with its purpose to eliminate all harmful pathogens, takes more time, needs higher temperatures and sometimes requires the addition of chemicals like chlorine. If urine and feces get primarily separated, environmental benefits such as a mitigation of eutrophication of river streams may occur. (Lienert & Larsen, 2010; Kabir Das Rajbhandari, 2011; Hu *et al.,* 2016)

The destruction of pathogens is based on a combination of increased pH-value, ammonia concentration, temperature and time. During storage, the pH-value of urine rises from about 6 up to 9. This increase of pH is caused by the decomposition process of urea into ammonia/ammonium (NH_4^+/NH_3) and hydrocarbonate. At high pH-values, bacteria, viruses and intestinal helminths die off over time. The higher the processing temperature, the more effective is the natural destruction process. Table 3-5 shows the difference between fresh and stored urine considering a number of parameters. (GTZ, 2009)

Table 3-5: Composition of nitrogen, ammonium, nitrate, nitrite and phosphorus in fresh and stored urine (GTZ, 2009)

	Fresh urine	**Stored urine**
pH-value	6.2	9.1
Total nitrogen, TN (mg/L)	8830	9200
Ammonium/Ammonia-N, NH_4^+/NH_3 (mgN/L)	460	8100
Nitrate and nitrite, NO_3^- and NO_2^- (mgN/L)	0.06	0
Total phosphorus, TP (mg/L)	800 – 2000	540

Nitrate can be absorbed by the crops directly whereas ammonia first needs to be converted. This transformation is done by natural bacteria contained in the soil and progress is primarily dependent on temperature. If soil temperature is low (e.g. less than 5 °C), transformation is decelerated and may take up to 6 weeks in order to reduce 50% of ammonia. At the same time nitrogen is converted to nitrate. If temperature is high (e.g. 20 °C), the same process would be accelerated and then may only take one week. (www.wasser-wissen.de, 2009)

Before urine can be re-utilized as fertilizer, it has to be stored for at least one month at temperatures greater than 4 °C. After that, the urine mixture may still contain viruses and protozoa but it can be used for irrigation. Protozoa elimination can be achieved either by increasing the processing temperature above 20 °C with the same storage time or by increasing the storage time up to 6 months at temperatures greater than 4 °C. However, if a family's urine shall be reused for fertilization of their own crops, direct reuse without storage is possible. (Schönning & Stenström, 2004)

A good example for the intensity of using urine as fertilizer is a dosage of approximately 3 liters per 100 m² infertile soil. If improved soil conditions are available, only half as much needs to be applied on the fields. When fertilizing the fields, it should be observed that valuable nitrate won't get lost by evaporation. In the following there are a few basic guidelines about how to dispose of the fertilizer ideally. Furthermore, Figure 3-9 visualizes some examples for urine disposal. (AGES, 2009; Kabir Das Rajbhandari, 2011)

- The fertilizer may be brought into a small ditch next to the crops and be covered with soil so that nitrogen evaporation can be avoided.
- Fertilization should be avoided when the soil is very dry or temperatures are high. In return drizzling or slight rain provides perfect conditions so that the fertilizer can percolate together with rainwater.

- The soil should have a good adsorptive capacity and its pH-value should be low.

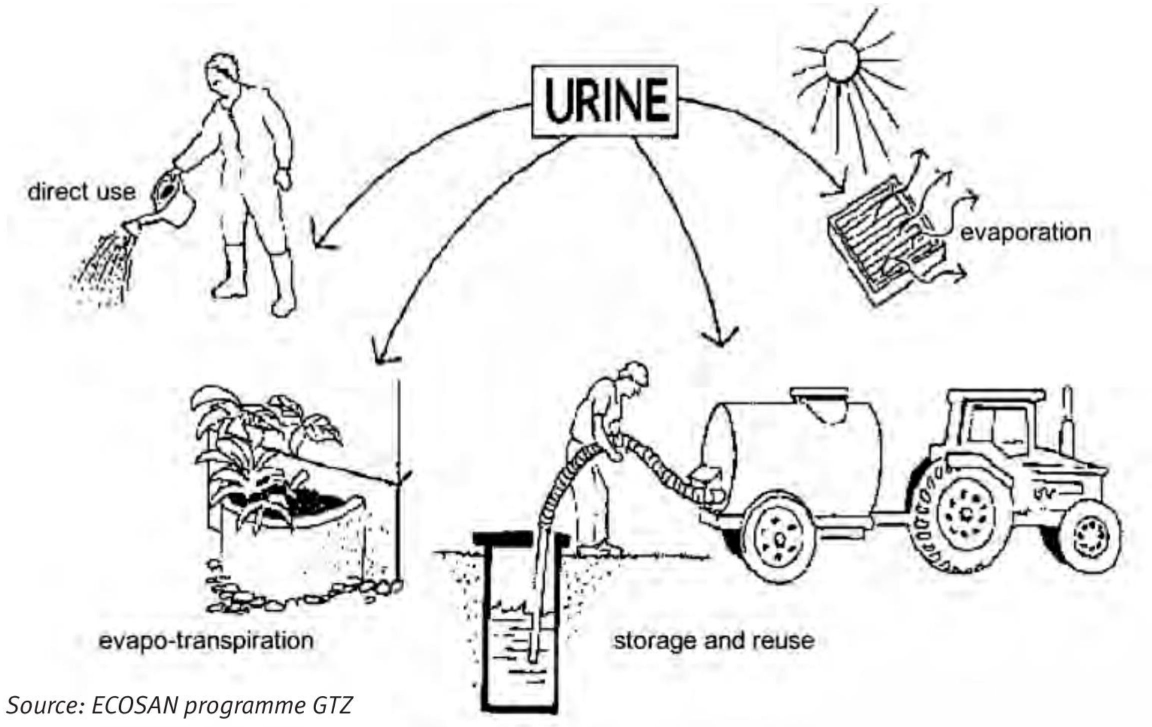

Figure 3-9: Alternative approaches of handling urine diverted from feces (Kabir Das Rajbhandari, 2011)

Dimensioning

The fecal storage time is counted from the date of the last fecal matter contributes to the processing chamber. In order to ensure full bacterial destruction of pathogens and a reduction of viruses, protozoans and parasites simultaneously, the calculated storage time should not be less than one year. However, in warm climates (20 – 35 °C) the commissioning time might be less. (Kabir Das Rajbhandari, 2011) In order to kill harmful pathogens effectively, a sufficient retention time and processing temperature are essential. The connection between the hydraulic retention time (HRT) and the processing temperature is described in chapter 2.3.

For the dimensioning of all fecal sanitation systems, an estimated constructive guide value of 0.07 m^3 per user and year can be expected (WHO, 2003). In the following, an example for a toilet dimensioning is given. A single vault construction shall be established for a family of four. For fecal collection round barrels with a diameter of 0.6 m and a usable height of 1 m are applied. As every family member produces 70 L of fecal matter and the barrels have a capacity of 280 L, the facility can be used for exactly one year. Covering the fecal heap with appropriate cover material (see p. 26) is important in order to avoid acrid odors while the bin is in dehydration or composting mode. Thus the barrel should at least provide another 30 cm atop so that there's enough space for inserted cover material. Alternatively, the barrel can be closed by a tight fitting lid instead of adding cover material on top of the heap.

Construction

The constructive design slightly varies between the particular subcategories. How these differ is precisely described in the following chapters. However, UD toilets require a facility to separate urine from feces in any case.

Figure 3-10 shows different types of appropriate user interfaces. All of them are suitable for UDD toilets, inasmuch as option 1 and 2 are not conducted with anal cleansing water. In return option 3 permits the use of anal cleansing water as long as this water does not enter the fecal gap. UD-CTs may typically be appointed with user interfaces like shown in option 1 or 2. Little amounts of anal cleansing water are permitted to enter the fecal gap.

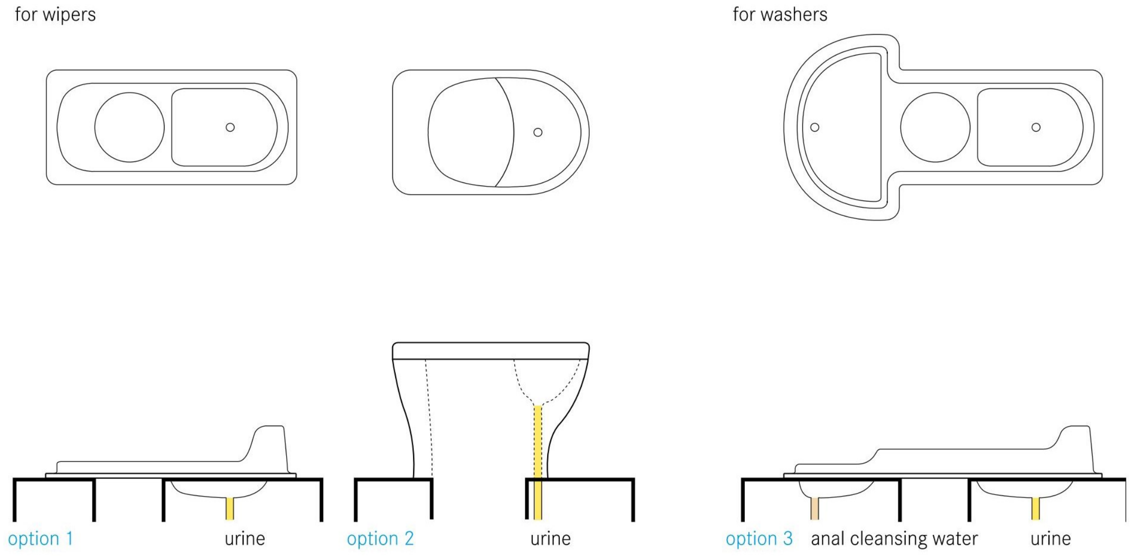

Figure 3-10: User interface for UD toilets (Tilley *et al.,* 2014)

Maintenance

Typical maintenance respectively operational intervals are dependent on the date of the last fecal matter contribution to the heap. In Table 3-6 the suggested fecal storage times are outlined.

Table 3-6: Suggested storage times for fecal destruction process (Schönning & Stenström, 2004)

Boundary conditions	Storage time *	Comment
Ambient temperature 2-20°C	1.5 – 2 years	Will eliminate most bacterial pathogens; regrowth of E. coli and Salmonella not considered if re-wetted; will substantially reduce

		viruses, protozoa and parasites. Some soil-borne ova may persist
Ambient temperature 20-35°C	> 1 year	As above
Alkaline treatment (pH > 9)	> ½ months	If temperature > 35 °C and moisture < 25%, lower pH and/or wetter material will prolong the time for absolute elimination

* From last fecal matter contribution

3.1.2.1 Urine diversion dehydration latrines

A urine diversion dehydration (UDD) system or dry UD latrine generally works with two separated chambers, one for the liquids in the front and another for solid excreta in the back. Liquids must not enter the processing chamber at any time. In case of anal cleansing water usage, a system with a third chamber might be a possible solution or cleansing water gets discharged together with urine (see

Figure 3-10). In the latter case, the mixture of urine and anal cleansing water must not get deployed on agricultural land. It rather has to be evaporated into designated evapotranspiration beds (see chapter 3.4.3) or discharged to a secondary treatment facility (see chapter 3.2). If anal cleansing water gets collected separately it may also be discharged to an affiliated evapotranspiration bed, whereas unpolluted urine can still be re-used as agricultural fertilizer. (Otterpohl, 2002; Lienert & Larsen, 2010; Kabir Das Rajbhandari, 2011) Little amounts of flush-water (approximately 0.1 - 0.2 liters per usage) for the urinal is permitted but still has to be avoided for the fecal gap (Hu *et al.,* 2016).

Dehydration

UDD systems follow the method of <u>dehydrated processing</u> which assumes that urine and feces are always getting diverted right at the origin. Its purpose is a radical reduction of the moisture content to less than 25%. This shall be attained by natural evaporation and due to adding dry cover material after every usage (see Cover and bulking material, p. 26). To assist the drying process, solar heaters can be assembled in the digestion chamber in order to favor the process of evaporation. Despite the low moisture content, a minimal decomposition of the organic material is preexisting. As the moisture content is low, pathogenic organisms can be destructed, fly-breeding prevented and acrid odors avoided. As the breakdown of organic material is low, toilet paper cannot be disintegrated completely and therefore should not be disposed into the processing vault. As soon as the dehydration process is completed, a small crumble pile, rich on nutrients, carbon and fibrous material remains to be deployed on farmland as valuable humus. (Kabir Das Rajbhandari, 2011)

Construction

There are two possible types of UDD systems: single-vault UDD toilets and double-vault UDD toilets. The following examples represent these diverse types of UDD systems, which are distinguished by the avoidance of flush-water and minor observed pile aeration.

Figure 3-11 shows the construction of a single vault UDD toilet. The urine is collected at the front hole and gets discharged to a separated tank, whereas feces drop down at the backward hole into an exchangeable barrel. As soon as the barrel is fully filled it gets replaced and moved beneath the solar heated cap. There, the increased temperature favors the fecal destruction process. To enable continuous toilet usage, another empty barrel is placed under the defecation hole. Depending on the size of the barrels and the amount of toilet users, two or three barrels can be in use at the same time. Hence one barrel is continuously active collecting fresh excreta, the others are set in a passive dehydration mode. (Kabir Das Rajbhandari, 2011)

Source: ECOSAN programme GTZ

Figure 3-11: Single vault UDD toilet (Kabir Das Rajbhandari, 2011)

Figure 3-12 shows an example for a double vault UDD toilet. At this system either the left or the right side is in use for at least one year. When the first processing vault is fully filled with feces, the hole designated for the feces gets sealed with lime mortar or clay. Then the other vault becomes active for the next year until the destruction process in the first chamber is completed or the second chamber is filled up too. Then the sandy dehydrated matter of the first digesting chamber should be free of odors, can be handled safely and may be deployed as valuable humus on farmland soil. After emptying, the first vault gets switched into active mode again and thus is applied for defecation for the next year. (Kabir Das Rajbhandari, 2011)

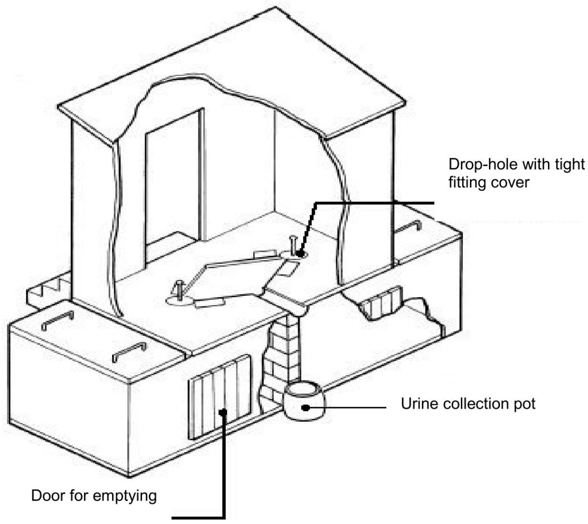

Figure 3-12: Double vault UDD toilet (Christine Werner *et al.,* 2006)

Maintenance

A UDD toilet system is slightly more difficult to maintain than other toilets since water must not be used and solid and liquid excreta need to be separated. It is important to regularly clean the toilet, though water may not enter the dehydration chamber where the feces are stored. Cleaning the toilet with a wet towel should be sufficient. Feces should remain separate and dry at all times. (Eawag/Sandec, 2008; Tilley *et al.,* 2008)

Since urine is collected separately from feces and consist of calcium- and magnesium-based minerals and salts, it may precipitate and accumulate in pipes and on surfaces. Mild acid (e.g. vinegar) and hot water respectively can be used for washing the bowl in order to avoid accumulation of material deposits and scaling. Blockages in the pipes can be dispensed by stronger acids (> 24% acetic) or a caustic soda solution. Nevertheless, in some cases manual removal is still necessary. (Tilley *et al.,* 2008; RIeck *et al.,* 2012)

Cost consideration

The construction can generally be done with locally available material and local labor. The toilet seats or squatting pans may be prefabricated and, if not imported from abroad, may even be cheaper than a self-designed squatting pan made from cement. Ceramic squatting pans are another cheap alternative, which is easy to clean. The costs for single-vault UDD systems are similar to those of VIP latrines or pit latrines. Double-vault UDD latrines are slightly more expensive compared to these technologies. Costs may be reduced if the digester design is well deliberated and the construction material is available locally. (RIeck *et al.,* 2012)

Review

UDD latrines can be constructed in areas that are prone to flooding and are most likely appropriate for all types of users. The main advantages and disadvantages are listed in Table 3-7.

Table 3-7: Advantages (+) and disadvantages (-) of UDD latrines (www.sswm.info, 2016)

+ Suitable for all types of users (sitters, squatters, washers and wipers)	– Prefabricated components are not available everywhere
+ Suitable for hard rock soil areas, areas with a high groundwater level as well as for areas that are prone to flooding	– Cultural conflicts are possible when handling feces and then the technology may be refused
+ No water is required for flushing	– Training is required to ensure the toilet will be used correctly
+ If used and maintained correctly there won't be serious problems with odors or flies	– Prone to misuse and clogging with feces
+ Can be built with locally available material and labor	– The pile of excreta is visible from inside the shelter
+ Low investment and operational costs	– Difficult usage for small children
+ Easy treatment of feces and direct re-utilization of urine as fertilizer	– Double-vault UDD latrines require large surface area for construction
+ No risk of groundwater contamination as the collection compartment is sealed	– Single-vault UDD systems require regular shifting of the collection basins
	– Transport of not yet stabilized matter to secondary storage or processing technology may be required

3.1.2.2 Composting toilets

The main difference between CTs and a UDD system is the moisture content of the feces within the vault and hence the required time for destruction of pathogenic matter. The moisture content of CTs is approximately 50%, whereas in UDD systems it is around 25%. CTs are usually designed for collecting urine and feces separately. Generally, the usage of anal cleansing water is permitted inasmuch as excess liquid is drained away constantly. Water for flushing is prohibited, as it would increase the moisture content of the pile and lead to a disturbance of the compostable matter. For re-utilization of the degraded compost, the organic content needs to be destructed completely. (Kabir Das Rajbhandari, 2011)

Composting / decomposition process

Composting at household level is an important task in order to manage organic wastes. These are contained in multiple products of the daily life. Composting is a natural process but by optimizing the environment for microbial activity, the process can be accelerated. Composting can be split in three processing steps: preparation of the waste by defining the quantity, moisture content and carbon to nitrogen ratio; the type of facility where the matter gets decomposed; and the final preparation of the compost by curing and screening. When the composting process is completed, the matter can be deployed on agricultural farmland as fertilizer. (Kabir Das Rajbhandari, 2011)

The process generally permits initial mixing of urine, feces and anal cleansing water. Nevertheless, additional water for flushing should ideally be avoided. The more liquids enter the composting vault, the more difficult and protracted the progress of detoxification will turn out. The composting process itself is strongly influenced by several environmental factors such as the amount of oxygen, temperature, the moisture content, pH-value, the ratio of carbon to nitrogen, competition among microorganisms for nutrients and the toxic byproducts of decomposing organisms. In the following, some of these factors, which can directly be influenced by customer behavior or constructive design, are announced: (Bond & Templeton, 2011; Kabir Das Rajbhandari, 2011)

- Aeration of the heap is essential for the development and survival of micro-organisms. The present bacteria in the fecal heap are significant for any activity in regard to composting. They have the ability to burrow holes through the pile and thereby facilitate fundamental oxygen supply to the decomposable matter. Aerobic conditions result in an odor-free decomposition process, whereas anaerobic conditions cause slower and foul-smelling destruction.

- Temperature is an important factor for the progress of decomposition. If the time period for desiccation is too short and pathogens possibly survived the drying phase, they can still be eliminated by rising temperatures above 50 °C for several days. To increase the temperature within the digester, an external energy unit could be installed, whereby heated air can be circulated through the chamber. Pathogens will anyway die over time if kept without water and left undisturbed by weather or animals. The dependency of processing temperature over time and its influence on the pathogen destruction process is discussed in chapter 2.3. If the degradation is executed at ideal thermophilic conditions (see Table 3-11), the destruction process would only take a couple of weeks until feces or urine were decomposed.

- The moisture content can be regulated by adding appropriate bulking agents (see Cover and bulking material, p. 26). A moisture content of 50 - 60% defines perfect condition for the composting progress and accordingly the process of pathogenic destruction. This can be achieved by minimizing liquids entering the processing chamber and adding dry bulking material. Consequently, aerobic decomposition takes place within the pile. In comparison to anaerobic processing, aerobic decomposition processes are odor-free.
- Carbon-nitrogen-ratio (C-N-ratio): Micro-organisms feed on organic matter containing nutrients, carbon and nitrogen. The organisms obtain energy from carbon, while nitrogen accelerates growth. A carbon-nitrogen ratio within the range of 15:1 to 30:1 provides ideal conditions for microbial processing. Urine for instance is rich on nitrogen and, if processed together with feces, carbon containing additives are required. These can either be green grass clippings, vegetable scraps, straw, husks, chipped wood or a combination of these. If urine gets separated at the point of origin, the amount of nitrogen in relation to carbon decreases and fewer additives are required. Anyway, adding carbon-rich material provides oxygen to the pile and this improves the degradation process.

The CT is regularly designed as a two-vault system. Similar to the example of the double-vault UDD system (see Figure 3-12), the hole down to the digestion chamber of the CT also has to be sealed accurately when the chamber is set into passive composting mode. Nevertheless, it is essential that the air can circulate through the pile so effective ventilation has to be guaranteed. As soon as the composting process is completed, which should not last less than one year, the compost can be utilized as soil conditioner (Otterpohl, 2002). Anyway it must be considered that the finished compost is still contaminated with some pathogens. These can be eliminated by spreading out the odorless composted mass on the soil so as to dry it in the sun for a few hours. (Schölzel & Bower, 1999; Kabir Das Rajbhandari, 2011)

Dimensioning

CTs are designed for a retention time of at least 12 months when the processing temperature can be held between 20 – 35 °C. If not, and the average processing temperature is only between 2 – 20 °C, one processing vault has to be dimensioned for at least 2 years of usage. (WHO, 1992; Kabir Das Rajbhandari, 2011)

Construction

CTs can be built above ground level, which benefits groundwater not being endangered to contamination by harmful pathogens. An important issue is the layout of the ventilation system. The better the air can circulate through the composting mass, the better will be the performance of the decomposition process and the less unpleasant odors will occur. This can be achieved by mounting semi-circular corrugated iron sheets into the digestion chamber, so that feces can still drop down through the spacing to the bottom of the structure. A false floor close to the basement may bring additional ventilation to the heap and excessive liquids can drain away. The air inlet to the chamber should be located at a low point of the structure in order to facilitate regular air flow form the very bottom up to vent-pipe outlet. CTs can either be designed as a one vault system with a removable compartment for collection or with two chambers. One is active and the other one in undisturbed composting mode. The former assumes that the mass gets extracted and decomposed at a centralized collection point whereas the latter allows on-site composting. For reasons of reliability and sustainability, on-site composting can be a welcome treatment solution. Making people responsible for their own toilet may improve the system efficiency and its life span. (Kabir Das Rajbhandari, 2011) Figure 3-13 shows the principle of an operating CT.

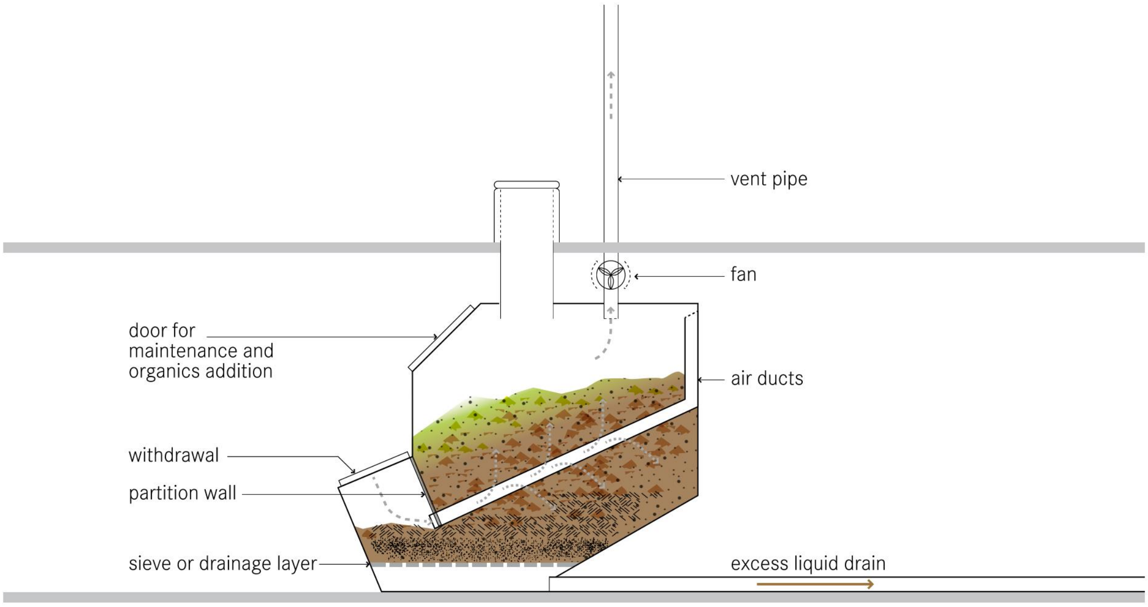

Figure 3-13: Cross section of a CT (Tilley *et al.,* 2014)

Furthermore, CTs can either be constructed with or without UD. If UD is not applied, more bulking material will be necessary to control the moisture content and to increase the C-N-ratio simultaneously. (Kabir Das Rajbhandari, 2011)

Maintenance

CTs are not that easy to operate. The moisture content has to be checked regularly, the C-N-ratio must be well balanced and the processing temperature of the compost pile should be high in order to achieve pathogen reduction. However, if the system is well designed, the effort of maintenance can be reduced. Composting systems require the regular addition of bulking agents such as wood chips, wood shavings, sawdust, dry leaves, shredded paper or cardboard to achieve aerobic decomposition. Additives like degradable kitchen wastes and composting accelerating earth worms are most welcome. Besides, regular turning of the pile results in an improved oxygen supply. As mentioned above toilet cleaning with flush-water has to be avoided, whereas little amounts of cleansing water is acceptable. It's always important to close the toilet lid after usage. (Schölzel & Bower, 1999; Kabir Das Rajbhandari, 2011)

To ensure the moisture content of the pile being in the range of 50 – 60%, a squeeze test may be helpful. For this, some compost has to be squeezed in the hand. If the matter neither feels dry like crumble nor wet like a sponge the moisture content is ideal for decomposition. The compost should rather leave a few drops of water in one's hand. Otherwise, either more bulking material or some water should be added to the mass. (www.sswm.info, 2016)

Regular emptying of the composting chamber should be done every 2 to 10 years. It mainly depends on the size of the chamber, the feeding rate and the rate of volume reduction and pathogen removal. However, only mature compost should be removed and laborers should wear protective cloths, especially if the material is not fully stabilized. Additionally, normal hand washing with soap is of course important after handling the compost. Over time, salt and solids accumulate in the tank, pipes and drainage system. Clogging can be dissolved by cleaning with hot water or scraping it out. (WHO, 2006; Tilley *et al.,* 2014)

Review

CTs are highly effective in reducing pathogens and the residual matter can be used as soil conditioner or fertilizer. The main advantages and disadvantages are listed in Table 3-8.

Table 3-8: Advantages (+) and disadvantages (-) of CTs (Tilley *et al.,* 2014)

+ No water is required for flushing + Reliable technology in both wet and dry season + Volumetric reduction of fecal matter up to 30% is possible + Significant reduction of pathogens	– Bulking material and careful operation is required – Training is required to ensure the toilet will be used correctly – Transport of not yet stabilized matter to secondary storage or processing technology may be

Advantages	Disadvantages
+ Compost can be used as soil conditioner + If used and maintained correctly there won't be serious problems with odors or flies + Long life span + Low operating costs if the compost is removed by the users + Suitable for hard rock soil areas, areas with a high groundwater level as well as for areas that are prone to flooding + No risk of groundwater contamination as the collection compartment is sealed + Low-tech CTs can be built with locally available material and labor	required – The leachate requires treatment or further treatment – Manual removal of compost is required – Cultural conflicts when handling feces are possible and then the technology may be refused – Expert design and knowledge is required for the construction – Prefabricated components are not available everywhere

Filter bag CT

An alternative to the conventional design of a CT can be the implementation of a filter bag system. The primary sedimentation of incidental fecal matter can be achieved by a simple filter bag system. Thereby solids, liquids and bulking material drop onto a suspended filter bag, which itself functions as a separator. The liquids trickle through the pile and the permeable bag down to the bottom of the system, whereas the solids get restrained. Therefore, one bag is clipped under the defecation hole of the toilet until it is fully filled. Assisted by a conveyor rail the bag may be moved to another place of the chamber where it can be decomposed undisturbed. Simultaneously, an empty bag again gets clipped under the defecation hole. Due to these exchangeable bags, the system capacity is quite variable because several bags can be restrained in composting mode. Presuming undisturbed conditions, the destruction process should at least last one year per bag. As soon as the destruction process is completed, the residual material can be composted as soil conditioner like that from CTs. The collected liquids on the basement of the structure need to be further treated in a secondary treatment step. (Verena Menz, 2008)

3.1.2.3 Urine diversion flush toilet

Wet (water-flush) UD toilets are separated into a front and a back drain like any other UD toilet (see Figure 3-14). In the front drain urine is collected and can directly be deployed as fertilizer. The back drain gets filled with feces, flush-water and maybe some anal cleansing water. With a system of pipes, the fecal compounds together with flush water are transferred to a secondary treatment facility (see chapter 3.2). (Lienert & Larsen, 2010)

Construction

The system requires dual plumbing, thus urine and brownwater (see p. 5) is separately collected. When designing the toilet, care should be taken of narrow points which may be prone to clogging. For the discharge of urine, plastic pipes are suitable since they do not get corroded by acids. In order to save costs, the length of the pipes should be kept as short as possible. Its slope should be steeper than 1% and the inner diameter should not be less than 5 cm (for steep slopes respectively 7.5 cm for rarely inclined sections). (Tilley *et al.,* 2014) Figure 3-14 shows the user interface of a wet UD toilet:

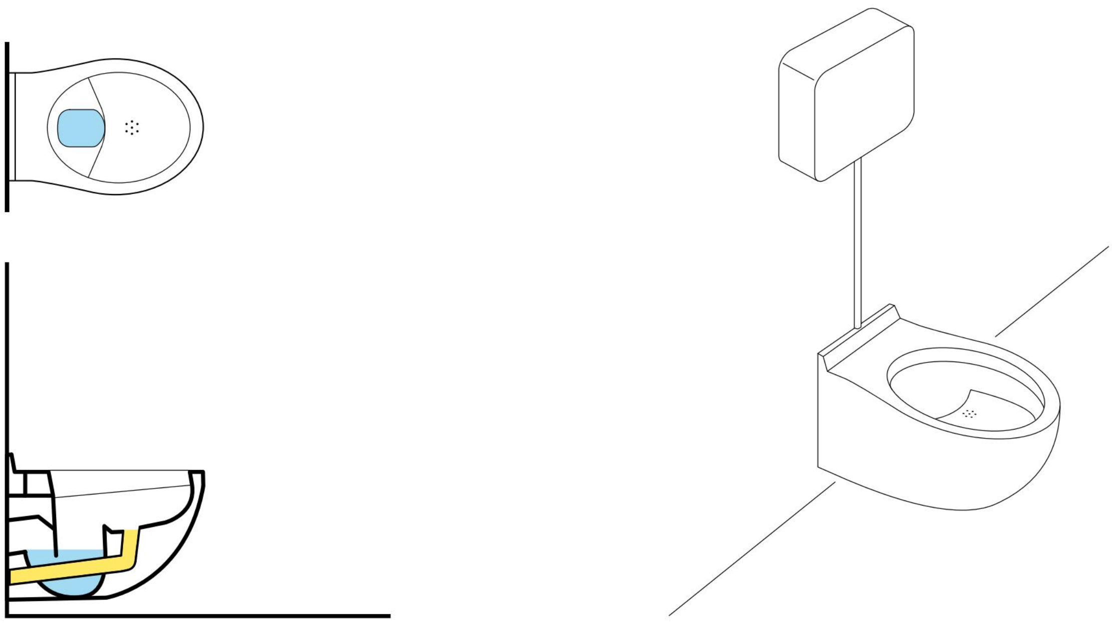

Figure 3-14: UD flush toilet (Tilley *et al.,* 2014)

Maintenance

Since urine is collected separately, salt, calcium- and magnesium-based minerals may precipitate and accumulate in the pipes. This can be prevented by washing the bowl with mild acid (e.g. vinegar) or flushing hot water through the pipes. If one pipe got clogged, stronger acid (> 24% acetic) or a caustic soda solution can remove blockages. In some cases, manual removal of deposits is however unavoidable. (Tilley *et al.,* 2014)

Review

Generally, eco-san technologies count to improved sanitation technologies. Wet UD systems are very user-friendly in operation and the collected urine may be used as fertilizer. The main advantages and disadvantages are listed in Table 3-9.

Table 3-9: Advantages (+) and disadvantages (-) of wet UD systems (Kabir Das Rajbhandari, 2011)

+ Simplicity of operation and comfortable usage + No problematic odor risks in case of inadequate usage + Water consumption may be less compared to conventional flush toilets but this mainly depends on user habits. + Urine may be used as fertilizer	– The toilet requires a connection to reliable water supply and in any case, a sewer and furthermore a secondary treatment system – Limited availability inasmuch as construction and repair work cannot be executed by unskilled laborers – The user interface requires prefabricated components – The system is prone to misuse and clogging – A constant source of water is required – If gravity flow is impossible, effluent pumping will be necessary – With all its treatment and connection components it's a highly cost-intensive solution. – High effort of maintenance

3.2 On-site storage and treatment

Human life residues such as excreta or kitchen waste compose the main contamination sources of infections and environmental contamination. It has to be the objective of any sanitary approach to prevent infections and avert health hazards from the population. Furthermore, ecological consequences require a sophisticated approach. This includes the choice of a suitable treatment facility and subsequently considerations on how its residuals and the outflow can be handled ecologically. (Hu *et al.,* 2016)

In Figure 3-15 a number of treatment steps in order to reach targets of effluent purification and environmental relief are illustrated. It shows the progression of very basic sedimentation facilities up to more extensive post-treatment technologies. In this thesis only those technologies are reviewed, which are theoretically implementable in the remote areas of DCs. When considering essential rating factors, such as system complexity, system reliability and electrical energy requirements, some technologies that are prone to failure or require excessive energy supply are not examined subsequently. In the following studies wastewater treatment facilities such as activated sludge units, trickling filters, aerated lagoons, rotating biological contactors etc. will be excluded. All these systems are highly cost intensive and prone to errors, which may cause deadlocks and consequently cannot be repaired by local laborers.

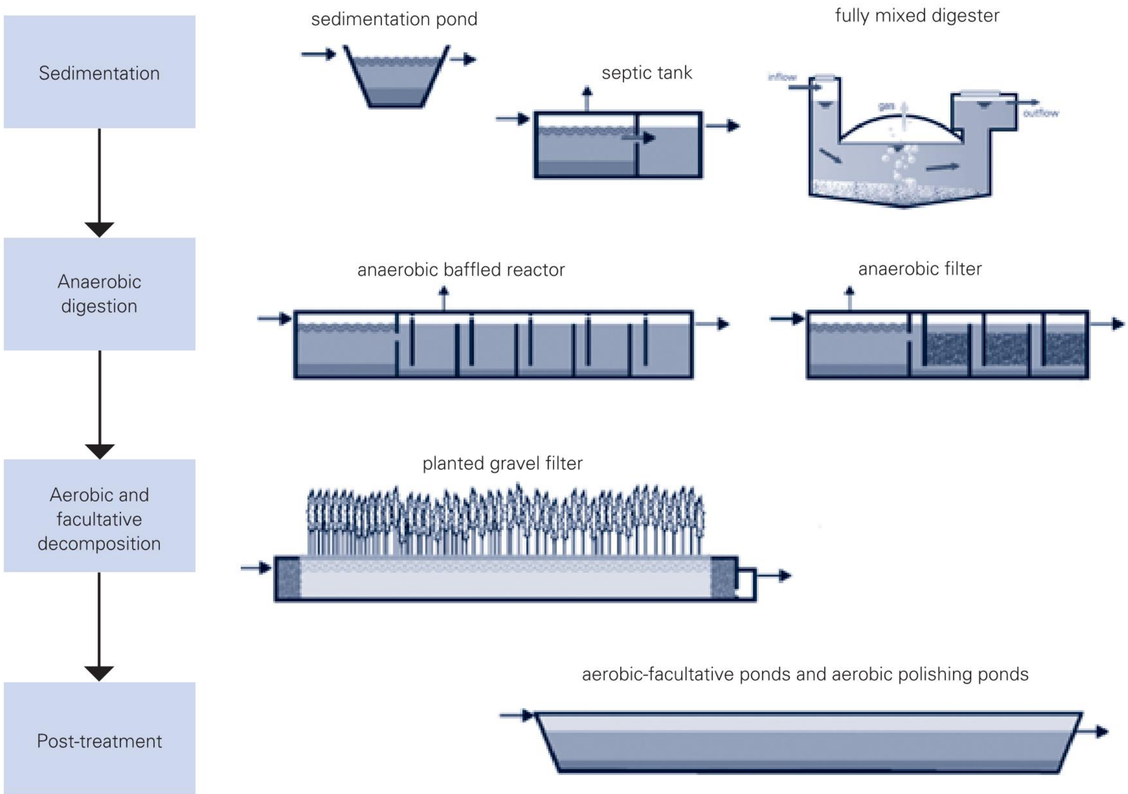

Figure 3-15: Step approach to treated wastewater (Gutterer *et al.,* 2009)

3.2.1 Cesspit

A cesspit is the most rudimentary form of a dry sanitation system. It is similar to a conventional pit latrine with the difference that no superstructure is mounted. In the same manner as a pit latrine, a cesspit can easily be constructed with locally available materials. The pit excavation must end minimum 2 meters above the highest groundwater level. The system should be designed such that usage of 20 years is guaranteed without the need of emptying. Hereby, an annual excreta cumulative rate of 40 – 60 liters per person can be assumed. The degradation process in the pit is very limited and hence the pathogenic destruction and the reduction of organic matter are insignificant. Further treatment steps are recommended in order to avoid human health risks and ensure safe reuse. Especially in rural and peri-urban areas, where water is a scarce resource, cesspit constructions are commonly used (Hu *et al.,* 2016).

Review

Cesspits are very simple to operate and hazardous risks are low. The main advantages and disadvantages are listed in Table 3-10.

Table 3-10: Advantages (+) and disadvantages (-) of cesspits

+ Simple to operate + Collection in closed tank is possible + Minimized health risks if emptied by a vacuum truck	– Costs for desludging may be significant compared to initial costs – Vacuum truck is required for emptying – Risk of groundwater pollution – Acrid odors and gas formation – No specific reuse of urine and feces – Sludge requires further treatment and/or appropriate disposal

3.2.2 Biogas digester

Mesophilic biogas digesters rejoice in high acceptance within DCs. This technology's advantages are ease of use, possible gas yields and re-utilization of residual matter as fertilizers. Its entire system functionality is based on anaerobic treatment conditions (see p. 5).

In order to generate biogas only fresh excreta is suitable, whereas primarily stored or pre-treated effluent from pit latrines or septic tanks is not, because its gaseous emission is not sufficient anymore. Further, biogas production relies on anaerobic conditions. In order to run the system, domestic sewage, agricultural residues or industrial wastes with a high proportion of anaerobically degradable biomass are particularly favored for biogas recovery technologies. (Bond & Templeton, 2011)

Biogas is contributed of 50-70% methane (CH_4) and 30-50% carbon dioxide (CO_2) respectively, as well as small amounts of hydrogen (H), nitrogen (N_2) and traces of hydrogen sulfide (H_2S). The high content of methane is responsible for producing a calorific value of 6 kWh per cubic meter. A part of the biogas yield depends on the type of digester and the kind of organic matter used. In order to convert biogas into electricity two fundamental methods are commonly used, scilicet gas turbines and combustion engines. The latter is more suitable for small-scale solutions because it's less expensive and more efficient than gas turbines. Gas turbines are advantageous when operating a cogeneration cycle producing heat and electricity simultaneously. (Bond & Templeton, 2011; Spuhler, 2014; Khan & Martin, 2016)

DC municipalities often use solid fuels like wood, dung, agricultural residues or coal for cooking and heating their houses. Commonly used open fireplaces emit gasses that are responsible for hazardous diseases. Negative effects on human health can be abolished by using biogas as a green source of energy, which provides an alternative to conventional solid fuels and provokes air pollution. It is mostly utilized for cooking, heating, lighting or electricity generation, whereby cooking is the simplest form of recirculation. To power a stove with biogas the gas-to-air-ratio has to be 1:6. Compared to conventional gasses like butane and propane, where the combustible gas-to-air-ratio is 1:31 and 1:24 respectively, biogas is hardly flammable and requires larger gas jets for burning. Despite these deficiencies, biogas accumulates as a waste-product and its re-utilization is free of charge. It burns with a clean, blue flame and stoves are proven to be the most convenient facilities for application in rural areas of DCs. Furthermore, biogas can alternatively be converted to electricity using fuel cells, which on the one hand require investments into these fuel cells and on the other hand clean and accurate mixed gas to operate. Well-skilled users are a necessity to run and maintain such kind of systems. Due to these technological and user-specific needs, henceforward this study focuses on biogas as a combustible and lighting device. (Weiland, 2010; Bond & Templeton, 2011; www.who.int, 2016)

The processing temperature is a key parameter for degradation and biogas production and must not fall below 10 °C in any case. Depending on the temperature, typical substrate retention times for destruction processes are designated to deviate between 20 to 100 days, whereby psychrophilic digestion occurs at temperatures between 10 – 20 °C and hence require a minimum of 100 days for destruction, whereas mesophilic digestion takes place between 20 – 35 °C and only takes 30 to 60 days retention time respectively. Furthermore, an increase of temperature by 10 °C may double the yield of biogas. The temperature is the most significant factor for successful gas production and may result in people lacking gas during cold winter months due to low system potential. To operate a biogas digester in colder and more arid regions, designs incorporating solar-powered heating and insulation can be contemplated. In summary, Table 3-11 outlines the ideal conditions for diverse bacterial growth and the according HRTs for the destruction processes. (Chen *et al.,* 2010; Weiland, 2010; Bond & Templeton, 2011; Spuhler, 2014; Khan & Martin, 2016)

Table 3-11: Range of temperatures for anaerobic fermentation and particular retention times (Werner *et al.,* 1989)

Digestion	Minimum	Optimum	Maximum	Retention time
Psychrophilic	4 – 10 °C	15 – 18 °C	25 – 30 °C	> 100 days
Mesophilic	10 – 20 °C	28 – 33 °C	35 – 45 °C	30 – 60 days
Thermophilic	25 – 45 °C	40 – 60 °C	75 – 80 °C	10 – 16 days

The carbon-nitrogen-ratio (C-N-ratio) has to be well balanced to avoid failures by ammonia accumulation, whereas CTs can have C-N-ratios within the range of 15:1 to 30:1. Studies by Shah (1997) have found that the mixture of multiple substrates in the digester have synergetic effects that can increase biogas production even though the methane potential of the feedstock is lower. Nevertheless, admitted material should contain carbohydrates, proteins, fats, cellulose or hemicellulose in order to have gaseous transformation potential. Especially fats have a high potential for biogas yields but in return require long retention times within the digester caused by its poor biodegradability. (Weiland, 2010; Bond & Templeton, 2011)

The fermentation process can take place in wet or dry conditions within the digester. The process of dry digestion presumes a solid content of 15 – 35% of the total matter, whereas wet digestion works with solid- content values between 5 – 10%. For low-rate digesters, the optimal ratio of solids to liquids is between 1:10 to 1:20. If a biogas digester is attached to public toilets, the amount of water for flushing or cleaning should thus be limited to 0.5 - 1.0 L per usage. (Bond & Templeton, 2011)

As can be seen in Table 3-12, pig manure provides the highest additional value in terms of biogas potential. To facilitate two warm meals per household per day, approximately 1.5 m^3 of biogas is necessary. In order to illuminate one lamp for one hour, 0.1 to 0.15 m^3 biogas is required. Next to fundamental livestock manure, harvest residues such as organic agricultural wastes, household residues or energy crops are valuable co-substrates to optimize the gas yields. (Weiland, 2010; Bond & Templeton, 2011; Spuhler, 2014; Khan & Martin, 2016)

Table 3-12: Biogas production from selected substrates (Bond & Templeton, 2011)

Substrate	**Daily production** [kg/animal]	**DM** %	**Biogas yield** [m³/kg DM]	**Biogas yield** [a] [m³/animal/day]
Pig manure	2	17	3,6-4,8	1,43
Cattle manure	8	16	0,2-0,3	0,32
Chicken manure	0,08	25	0,35-0,8	0,01
Human excrements	0,5	20	0,35-0,5	0,04
Straw, grass		80	0,35-0,4	
Rice straw		87	0,18	
Rice straw husks		86	0,014-0,018	

DM = dry matter. a = based on mean biogas yield (m^3/kg DM).

Digested sludge is rich in ammonium and can be deployed as organic compost in fields. This may increase agricultural yields up to 20% under ideal conditions. However, due to insufficient destruction of helminth eggs, tapeworms, roundworms, E. coli and Enterococci by mesophilic anaerobic digestion, the WHO (WHO, 2006) suggests no further use of the sludge as fertilizer before being filtered by appropriate post treatment plants. (Bond & Templeton, 2011; Khan & Martin, 2016)

Dimensioning

The volume of biogas latrines mainly depends on the number of livestock kept per household. These contribute most to the digestible matter. Small digesters start with volumes from 2 m^3, whereas larger digesters can reach up to 10 m^3. Per cubic meter digester volume 0.5 m^3 of biogas can be yielded, which results in an energy production of about 6 kWh. Therefore, 1.2 - 1.6 m^3 of the tank volume per person can be estimated. (Bond & Templeton, 2011; Reed & Shaw, 2015)

Construction

Digesters in DC are generally classified as low-rate digesters, having a simpler constructive design, skimping on insulation, heating units or stirring devices. Basically, three types can be distinguished: a Chinese fixed dome digester, an Indian floating drum digester and a balloon digester. All of them are designated to collect human excreta and animal manure as well as other biodegradable wastes. After the anaerobic transformation, the biogas sits atop of the sludge and is harvested via an outlet pipe for utilization. Between the tank outlet and the gas supply for the end-user, a flame trap facility has to be implemented by all means. It functions as a safety device to prevent an explosion of the gas reactor by reversal flame propagation from gas jets. The diameter of the gas outlet pipe from the digester is 12 - 25 mm and has to be fabricated from copper or galvanized iron. (Bond & Templeton, 2011; Reed & Shaw, 2015)

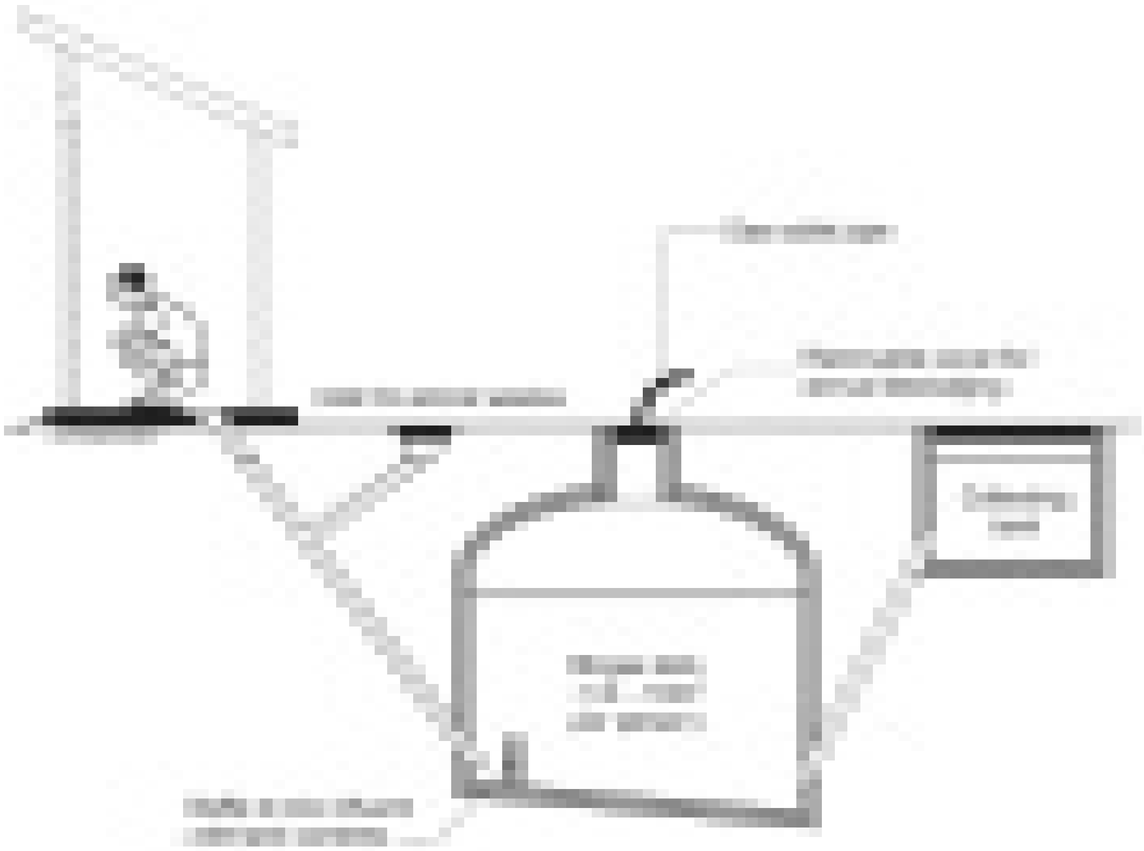

Figure 3-16: Biogas tank with latrine (Reed & Shaw, 2015)

Floating drum digesters are generally constructed from concrete and steel, whereas fixed dome digesters can be made from variable locally available materials. The third type of biogas digesters compounded off-site from pre-fabricated polyethylene foils has to be delivered and setup on site subsequently. The principle of a livestock inlet, yield of biogas and outlet for sludge ultimately, is very much identical for all types of biogas digesters. Figure 3-16 illustrates the main important components necessary for the implementation of a biogas digester. Nevertheless, even a simple pit might function as digester if biogas can be captured at the top of the structure. The designs of most conventional Chinese fixed dome and Indian floating cover digesters, as well as the rarely installed balloon digesters, will be dealt with in the following subchapters. (Sasse L., 1988; Khan & Martin, 2016)

Maintenance

In general, the maintenance activities for biogas reactors are low. Depending on the type of digester, the emptying intervals vary between 2 to 5 years, where the accumulated sludge may get removed by vacuum trucks. The overall operation requirements of anaerobic biogas digesters are very low. As long as the system is maintained by skilled users, the regular usage of the technology is simple. The initial start-up phase can be accelerated by additional sludge inoculation from other anaerobic digesters and thus also acidification of the digester can be prevented. (Sasse, 1998)

Review

Biogas digesters generate biogas and organic fertilizer, it’s got a long lifespan and is effective in pathogenic destruction. The main advantages and disadvantages are listed in Table 3-13.

Table 3-13: Advantages (+) and disadvantages (-) of biogas digesters

+ Generation of biogas and organic fertilizer	– Experts needed for reactor construction to accomplish a gas-tight tank.
+ Long life span	– Users handle explosive mixture of gas and air
+ Destruction of pathogens causing typhoid, cholera, dysentery, schistosomiasis and hookworm diseases	– Incomplete bioconversion (e.g. helminth eggs and diverse hazardous worm populations cannot be killed effectively) which possibly requires further treatment of sludge before re-utilization
+ Biogas can be produced when needed and stored easily	– Shortages of feedstock and temperatures less than 15 °C cause low methane yields
+ Reduction of greenhouse gas emissions	– Heating or insulation in cool climates necessary
+ Low operational costs	– Relatively high investment costs
+ Recoup of investment costs within 2 - 3 years	– If system design is too complex to operate and maintain, biogas
+ Low space requirements due to underground construction	
+ High public acceptance	
+ Possibly governmental subsidies	

contributed + Rapid and sustainable public health upgrades due to improvement of indoor air quality. + Retention times of only a few weeks at mesophilic conditions is possible + Sealed off waste storage leading to low odor problems	recovery technologies may easily fail in DC – Long start-up phase due to slow anaerobic bacteria growth possible

3.2.2.1 Fixed dome digester

The fixed dome digester is typically constructed as a round airtight underground reactor. Therefore, mostly concrete or bricks are used for construction. At the top's center a fixed and airtight dome is responsible for the gas collection and discharge to the consumption point. The gas pressure is absorbed by the sludge which thereby gets displaced into a compensation tank (outlet). As mentioned before, a flame trap between digester gas outlet and gas consumption facility is highly important in order to prevent reversal flame propagation and therefore the possible explosion of the gas tank. One possible design of a fixed dome digester is shown in Figure 3-17. (Bond & Templeton, 2011; Spuhler, 2014)

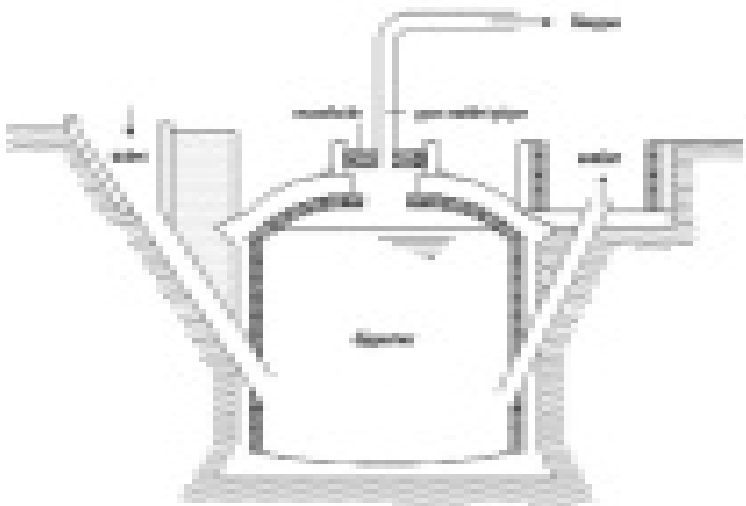

Figure 3-17: Fixed dome digester; Chinese type (Bond & Templeton, 2011)

Due to its subsurface construction, changes of ambient temperature have less impact on the processing temperature and land space requirements are relatively low. The digester's lifespan is high but still, construction and investment costs are complex and high. The effort of maintenance for the fixed dome digester is generally low. Proving the digester's manhole for gas-tightness and frequent disposal of exited sludge from the compensation tank are the main tasks for failure-free operation. (Spuhler, 2014)

3.2.2.2 Floating cover biogas digester

The floating cover digester consists of an underground digester with a floating gas cover. Between the in- and outflow of the tank, a partition wall can be installed to extend the retention time of the sludge. The vertically movable floating gas-cover either directly sits on the fermentation sludge or on its own water jacket. Anyhow a surrounding guiding frame prevents the cover from tilting. Depending on the amount of gas contained, the cover moves up- or downwards. By reason of the movable gasholder, the gas pressure stays constant within the digesters. As mentioned above, a flame trap between digester gas outlet and gas consumption facility is highly important in order to prevent reversal flame propagation and the possible explosion of the gas tank. In Figure 3-18 the principle design of a floating cover digester is illustrated. (Bond & Templeton, 2011; Spuhler, 2014)

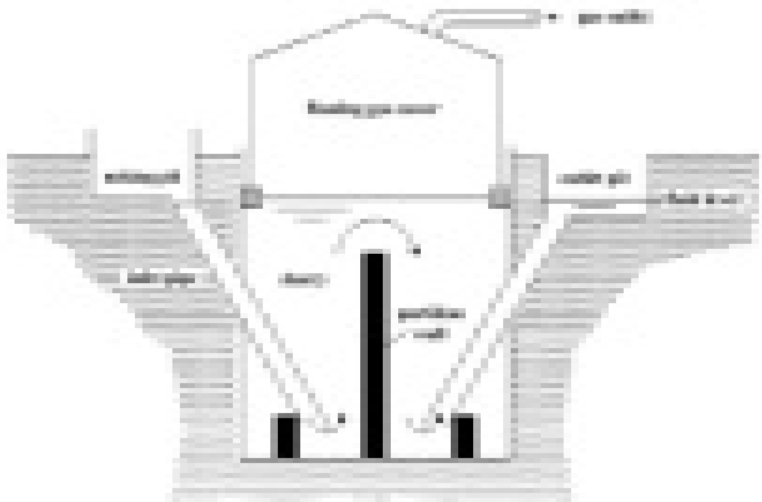

Figure 3-18: Floating cover digester; Indian type (Bond & Templeton, 2011)

The construction of the digester is relatively simple and even if mistakes are made, these usually do not cause restrictions in gas yields. Typically, the floating cover's construction material is steel, whereas pit lining can be realized with brick or concrete. The connection pipes from the in- and outlet are generally made of PVC with a diameter of approximately 100 mm. Regarding construction material requirements, the initial costs for the floating cover digester compared to the fixed dome digester are high. As the drum and many parts, which ensure the drums movability, are made of steel and thus are prone to corrosion, the costs for construction and maintenance increase. Furthermore, due to corrosion, the lifespan of the digester decreases. Anyway, as the system is operating, it is easy to handle without worrying to cause errors by incautious utilization. (Spuhler, 2014)

3.2.2.3 Balloon biogas digester

The balloon or tube digester is generally pre-fabricated and delivered on site. Alternatively, if the necessary material is available and the fusing of PVC foils on-site is possible, costs can be reduced dramatically, which makes this technology more affordable. The principle design is very simple but the system is prone to impermeability. Therefore, the depth of soil excavation should at least be half the diameter of tube and free of any sharp-edged components that could damage the foil. As for all other types of digesters, a flame trap between gas outlet and gas consumption facility is highly important in order to prevent reversal flame propagation and the possible explosion of the gas tank. Figure 3-19 shows the principle design of a balloon or tube digester. (Bond & Templeton, 2011; Spuhler, 2014)

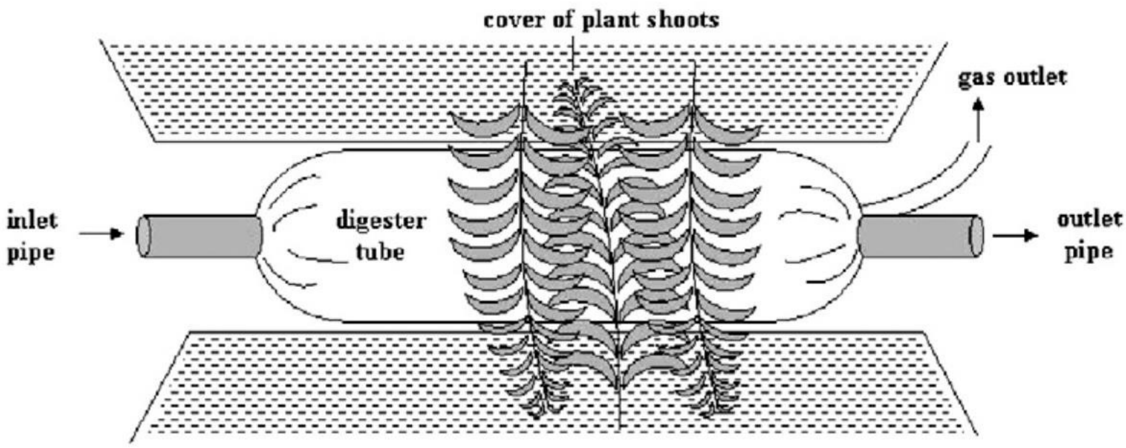

Figure 3-19: Balloon or tube digester (Bond & Templeton, 2011)

Due to its exposed surface, the balloon digester can be naturally heated by the sun. This increases its efficiency in pathogenic destruction process and supports the generation of biogas. During cold periods the digester should be covered with plant shots to prevent the processing temperature decreasing 10 °C. The digester is simple in operation and easy to maintain. Emptying the balloon once every few years is sufficient. The life span of balloon digesters is limited by reason of PVC corrosion due to UV radiation. This may be prevented by using polyethylene foils instead. (Bond & Templeton, 2011; Spuhler, 2014)

3.2.3 Septic tank

A conventional septic tank (CST) is a facility to store and treat black- and greywater from households anaerobically. They generally separate solids from liquids by gravity settling, meaning as liquids flow through the chamber, solids and heavy particles slag to the bottom and form a layer of sludge (see Figure 3-20). On the surface a layer of floating scum, formed by oils and greases develops simultaneously. The tanks are most efficient if the content of settleable solids is high. The sludge gets decomposed with time but since the destruction process is slow, it has to be excavated periodically. The system is quite robust against hydraulic and organic shock loads. Depending on the characteristics of the wastewater, conditions of the tank and the HRT (24-72 h), the destruction efficiency for BOD, COD and TSS similarly vary between 30-60%. E. coli can be reduced by 90% if an HRT of 48 hours can be met. The treatment performance mainly depends on the HRT and just a little on the accessible processing temperature. With time bacteria and microorganisms formed within the sludge start to digest the settled sludge anaerobically, whereof the by-products CO_2 and CH_4 (biogas) are produced. The inflow intensity into the septic tank is important for several aspects. If the inflow is turbulent and effluent gets into contact with old settled sludge, biological anaerobic degradation is supported and overall destruction efficiency increases. In return, the separation of liquids and solids is restricted and a smooth effluent inflow would hence be more appropriate. The outflow of the septic tanks can either be dispersed in soak pits, evapotranspiration beds, leach fields or further treated in constructed wetlands (CWs; see chapter 3.4 and 3.3.2). Accumulated sludge has to be dried or composted before extracting as agricultural fertilizer. (Sabry, 2010; Nasr & Mikhaeil, 2014)

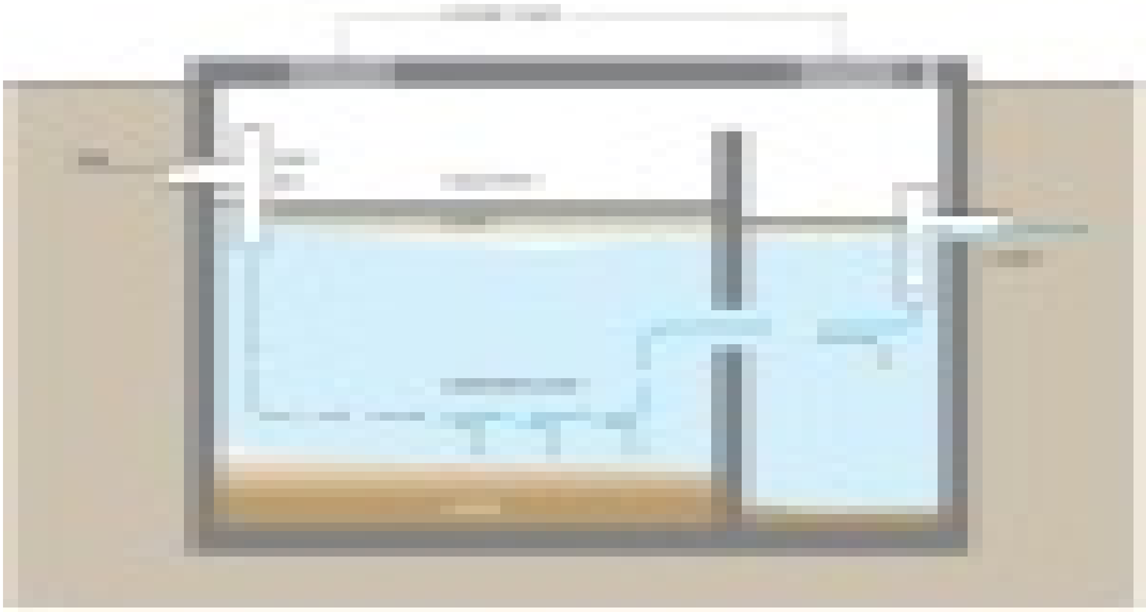

Figure 3-20: Cross section of a CST (Tilley *et al.,* 2008)

Generally, anaerobic treatment systems are distinguished by their ease of use, low operational costs and independence of electricity. Since biogas can be yielded and CO_2 emission reduced simultaneously, anaerobic decomposition is of special interest in terms of environmental sustainability. Water is needed to provide effluent transportation from point of origin into the tank and despite rather long HRTs destruction performance is comparatively poor. (Nasr & Mikhaeil, 2014; www.sswm.info, 2016)

Dimensioning

For the dimensioning of any septic tank the number of users, the amount of water used per capita, the average annual temperature, desludging frequency and general wastewater characteristics are significant. Usually, the depth of a septic tank varies between 1.5 and 2.5 m. Among the particular chambers, different levels with different depths are possible too. To define a guiding value for dimensioning the tank volume, 80 - 100 liters per capita can be estimated. (Sasse, 1998; Nasr & Mikhaeil, 2014)

Construction

A CST consists of a watertight chamber made from concrete, brickwork, fiberglass, PVC or plastic. In order to increase HRT at least one baffle, thus dividing the tank into a minimum of two chambers, is recommended. Depending on the number of baffles and thus the number of chambers, the first compartment should capture 50 - 70% of the total space from the tank. The more baffles are installed, the better the progress of effluent-solid separation. To install the diagonally arranged in- and outlet pipes from the digester, Tshaped components are recommended by reason of operation and maintenance (O&M) simplicity. The inspection openings need to be accessible for maintenance activities. The formed gasses in the tank have to be deflected safely so that people are not pledged by acrid odors. This can either happen by a connection to a preexisting vent pipe from a previous facility or by deflection of a separated screened vent pipe directly from the tank itself. (Nasr & Mikhaeil, 2014; www.sswm.info, 2016)

Maintenance

Starting up a new CST "seeding" with sludge from another septic tank, which is already in operation mode, is recommended. Due to that procedure, microorganisms responsible for the process of digestion, can be cultivated from the start. Consequently, short start-up times can be achieved and full performance is possible after a few days. (WHO, 1992)

Because of the sensitive microbial strain, harsh chemicals shouldn't be discharged into the tank. As soon as the digester is half to maximum 2/3 filled with sludge and scum, the tank has to get emptied. If the inlet pipe is deep inside the sludge, it could happen that the inflowing effluent has already scoured a channel through the solid matter and passes through the tank within a minute instead of remaining in the digester for the required retention time. (Sasse, 1998) Generally desludging should be executed every 2 to 5 years and can either be done by motorized or human-powered equipment. The extracted sludge has to be dehydrated by planted or unplanted drying beds, settling or thickening ponds. Desludging activities require skilled laborers to prevent health hazards. In addition, frequent system checks are important to ensure the system being watertight, remove floating debris from the chamber, avoid blockages of in- and outlet pipes and to check whether desludging is needed. (www.sswm.info, 2016)

Cost consideration

Construction costs for CSTs are comparatively low to other water based treatment systems but still much more expensive than toilets utilizing dehydration or composting for effluent treatment. The constructive design must be prepared by engineers, whereas constructive work can be executed by unskilled laborers while supervised accordingly. Operational costs are depending on water consumption, which is in any case required for transportation of solids. Therefore, greywater should be used as transportation media instead of clean drinking water. Furthermore, manual or mechanical desludging has to be done periodically and excavated scum and sludge require post-treatment subsequently. (www.sswm.info, 2016)

Review

Septic tanks persuade by their ease of use, robustness to hydraulic shock loads and a long life span. The main advantages and disadvantages are listed in Table 3-14.

Table 3-14: Advantages (+) and disadvantages (-) of septic tanks (www.sswm.info, 2016)

+ Construction and repair work can be realized with locally available material	– Cost intensive compared to dry or CT systems
+ If used correctly there won't be problems with flies or odors	– Water required for solid transportation into the tank
+ Simple technology	– Low reduction of pathogens, solids and organics
+ Robust against organic and hydraulic shock loads	– Regular desludging has to be ensured
+ No electricity required	– Area must be prone to flooding, require low groundwater level and low housing densities
+ Little land requirements because of underground construction	– Manual desludging is a highly hazardous and dirty work, whereas mechanical cleaning requires access to suitable machines
+ Low operational costs	– Effluent and sludge require post-treatment and appropriate discharge respectively
+ Long life span	

3.2.4 Anaerobic baffled reactor

An anaerobic baffled reactor (ABR) is an upgrade of the CST system. It consists of several chambers operating in series where effluent seeps through continuously. Due to accumulating sludge at the bottom of each chamber and a vertical transmission of effluent causing contact with this active biomass, the level of purification is increased. Figure 3-21 shows the longitudinal section of an ABR and its compartmentalized design into several chambers. ABRs can be loaded with greywater, blackwater or even industrial wastewater. As any septic tank, this also works by physical and biological treatment, thus settling of solids and anaerobic digestion. (Tilley *et al.,* 2014)

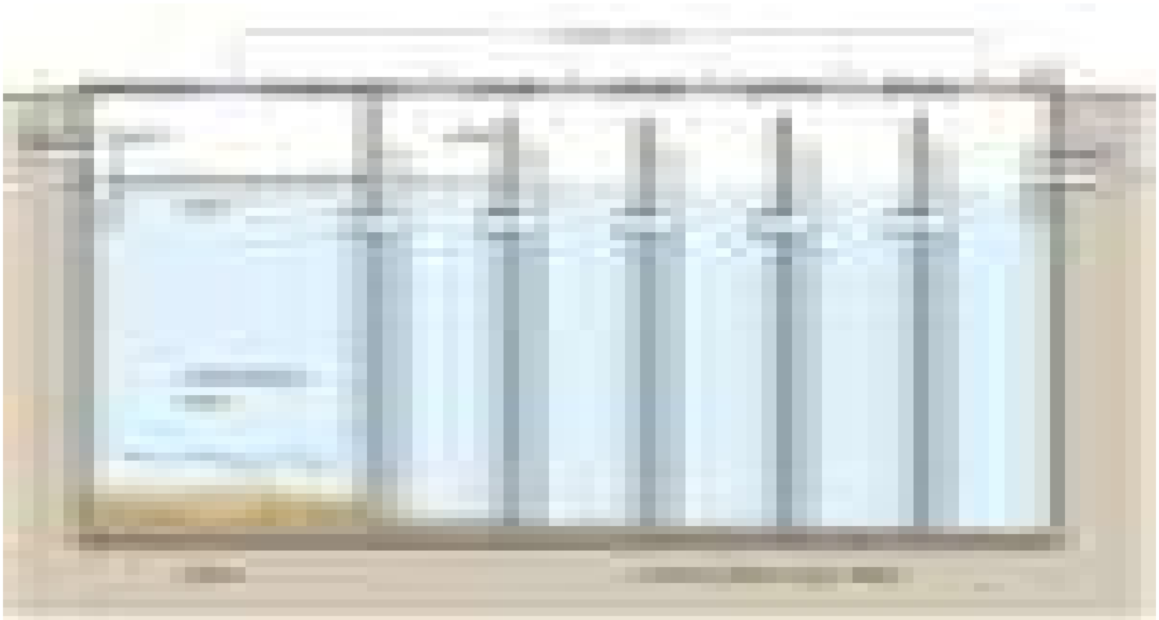

Figure 3-21: Cross section of an ABR (Tilley *et al.,* 2014)

The compartmentalized design of this system with its multiple vertical connection pipes enforces liquids to flow up and down causing increased contact with organic sludge. Once active sludge gets washed out from one chamber it traverses to the next. An increased treatment performance compared to CSTs is possible. HRTs of 48 – 72 hours should be aspired but shouldn't fall below 8 hours at all times. The system is characterized by its simple construction and ease of operation as well as its resistance to hydraulic and organic shock loadings. The higher the organic content of the effluent, the better the system's treatment performance. Nevertheless, exited effluent and excavated sludge must be further treated aerobically. Treatment efficiencies considering BOD and COD removal rates of 70 to more than 90% can be achieved. In addition, TSS can be detached by 50% within sedimentation zones and may achieve total removal efficiencies of up to 90%. Biogas yields increase as effluent passes through the individual chambers but total production, however, is low and recovered gas is thus best used for kitchen applications. (Sasse, 1998; Foxen *et al.,* 2004; Morel & Diener, 2006)

The treatment performance of ABR can be increased by the installation of an anaerobic filtered compartment at the end of the system. (WSP, 2008)

Dimensioning

The most critical parameter when dimensioning an ABR is to limit the maximum up-flow velocity to 2 m/h. This is important in order to avoid washout of accumulated sludge and might be critical when hydraulic shock loads occur. ABRs can be designed for a daily inflow of just a few cubic meters up to several hundreds of cubic meters per day. (Sasse, 1998; Morel & Diener, 2006; Tilley *et al.,* 2008)

Construction

The basic construction of an ABR is quite similar to CSTs (see chapter 0). Additionally, ABRs mostly consist of 3 to 6 up-flow compartments which are syndetic either by vertical pipes or baffles. The maximum length of one chamber should exceed 0.75 m and its corresponding height should anyway be twice as much as the length of the compartment. In order to retain floating scum formed in the up-flow chambers, the openings for the footpath from one compartment to the next should be arranged slightly below the liquid surface. The inlet pipe into the system has to be arranged higher than the opening for the outlet. Furthermore, each chamber has to be accessible for maintenance activities and thus appropriate openings at the top of the structure are necessary. (Sasse, 1998; Tilley *et al.,* 2014)

Maintenance

ABRs require long start-up periods of several months to reach full treatment performance. This time span can be shortened by inoculating the system with anaerobic bacteria contained in sludge from other treatment facilities or cow dung. The added stock of bacteria can multiply as soon as wastewater seeps through the tank and comprised solids get separated. During the start-up phase, system loading should approximately be only 25% of total capacity, whereby washout of bacteria can subsequently be avoided. In addition, feeding with harsh chemicals should anyway be prevented. (Sasse, 1998; Tilley *et al.,* 2008)

A regular monitoring of the sludge and scum layers is important to ensure the system functioning well and to realize the point for desludging activities. As soon as the first chamber is half to maximum 2/3 filled with sludge and scum, the tank has to get emptied. The assumed time interval is between 1 to 3 years. When extracting the sludge, care has to be taken to always keep some sludge within the system, allowing a continuous and efficient treatment. The process of desludging can either be executed by motorized or human-powered equipment, whereat human contact with the sludge has to be avoided completely. Regular checks to prove that the system is watertight are important. (Sasse 1998; Tilley et al. 2008)

Cost consideration

In general, ABRs are cheap solutions compared to more mechanical and centralized technologies. They can be built from locally available material, are simple to construct, do not require electricity input, and are uncomplicated in operation. Still the system design has to be carried out by an expert. (www.sswm.info, 2016)

Review

ABRs persuade of a long life expectancy, are simple in operation and robust against organic and hydraulic shock loads. The main advantages and disadvantages are listed in Table 3-15.

Table 3-15: Advantages (+) and disadvantages (-) of ABRs (www.sswm.info, 2016)

Advantages (+)	Disadvantages (-)
+ Robust against organic and hydraulic shock loads	– Long start-up phase
+ No electricity requirements	– Experts required for constructive design
+ Low operational costs	– Poor pathogen and nutrient reduction rates
+ Long service life	– Further treatment for effluent and sludge required
+ Effective in BOD, COD and TSS reduction	– Water is required for system feeding
+ Little sludge production which finally is stabilized in the end	– Fecal sludge management is important in order to avoid deterioration of effluent quality
+ Moderate land requirements due to underground construction	
+ Simple to operate	

3.2.5 Anaerobic filter

Anaerobic filtered (AF) septic tanks generally consist of two compartments. The first functions as a regular septic tank and the second as a polishing filter unit. To avoid massive contamination and blockage of filter media, the content of suspended solids within the incoming effluent should be low. Though as wastewater seeps through the chambers it gets anaerobically degraded by active biomass adherent to the filter media. Figure 3-22 shows the compartmentalized design of an AF. The effluent flows through the filter media bottom-up and thus a bacterial washout can be avoided. AF systems are an advancement of CSTs and can be fed by both black- and greywater. Since AFs treat the effluent anaerobically, incidental biogas can be reclaimed. AFs catch similar effluent quality like centralized wastewater treatment plants (WWTPs) but are much more cost-effective. They are generally characterized by little land occupation, little O&M requirements executed by minor skilled users, comparatively low construction costs, and little sludge and methane gas production. The latter can be recovered in form of biogas. (Sabry, 2010; www.sswm.info, 2016)

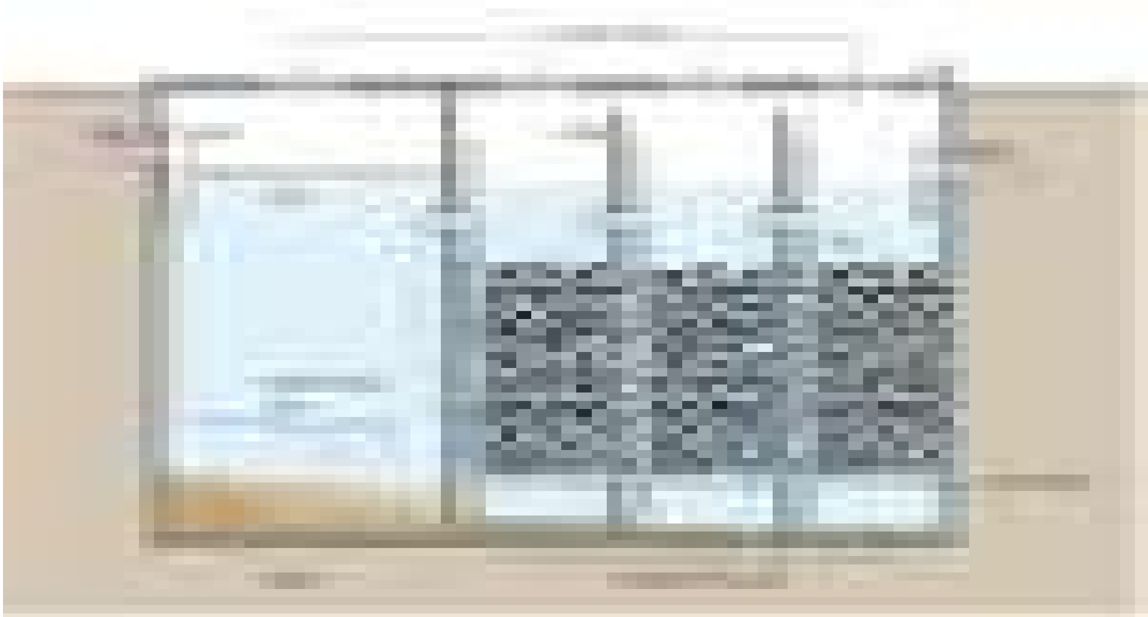

Figure 3-22: Cross section of an AF (Tilley *et al.,* 2014)

AFs combine the physical and biological treatment. Like any other type of septic tank, the initiated effluent is separated in a fatty scum layer on top, a major layer of liquids, and a sludge layer settled to the bottom due to gravity flow. Residual fatty acids get converted into biogas and are either directly detracted to a user interface or buffered in a biogas holding tank. If none of these forms of biogas recovery is chosen, the gas can be deflected by ventilation pipes. In doing so, the foul smelling odors have to be considered. In the start-up phase, the system has a low treatment performance, since the biological purification is inexistent.

Hence, a start-up period of 6 – 9 months is required to effectively fix the bacteria on the filter media. The performance is highly influenced by the processing temperature and the HRT. The higher the processing temperature, the more effective the pathogenic reduction efficiency. Typical HRTs are 1.5 - 2 days for blackwater or 0.7 - 1.5 days for greywater. It can be enlarged by the number of vertical walls installed, so that the flow path of wastewater is extended. From the economical point of view two to a maximum of four polishing chambers are recommended, because as HRT exceeds 72 h no significant effects on destruction efficiencies can be constituted. COD, BOD and TSS removal rates typically vary between 50 - 80% at temperatures exceeding 20 °C. Coliform reduction rates reach 90% and higher. If the polishing stage should work efficient at temperatures of only about 10 °C, HRT has to increase to 6 – 8 days in order to meet analog removal rates. However, this operational state causes high sludge production and hence requires frequent tank emptying up to once a year. (Sasse, 1998; Morel & Diener, 2006; Sabry, 2010; Nasr & Mikhaeil, 2014)

AF treatment systems neither are sensitive on hydraulic nor they are on organic/solid shock loads, meaning removal efficiencies of BOD, COD and TSS will thereby be unaffected (Sabry, 2010). The digestion process is similar to one of ABR systems, but at AF organic destruction takes place due to contact with fixed bacteria on filter material rather than by deeply immerged pipes into the sludge.

Dimensioning

For basic dimensioning of AF systems, the same standards as for CSTs are significant. In addition, when treating domestic wastewater, filter media volume of 0.5 m^3 per capita can be estimated, whereby smaller entities even require 1 m^3 per capita. (Sabry, 2010)

Construction

An AF system is assembled by two watertight compartments and thus generally is fabricated out of concrete or brick work. The first compartment functions as a sludge sedimentation tank, whereas the second is responsible for polishing the wastewater. In order to decrease adverse solid loadings to the filter media, the first cleaning stage may consist of several chambers, thus it rather functions as a primary ABR. Another way to minimize solid transportation from the sedimentation tank into the polishing compartment is achieved through the installation of plate settlers linking the settler and filter unit. These are embedded with an inclination of 60 degrees to horizontal projection and hinder solid particles penetrating into subsequent filter layers. To connect the individual sections of the polishing compartment, either vertical baffle walls or vertical pipes may provide an appropriate footpath. Their arrangements are important for the effluent flow direction. To avoid elutriation of filter bacteria the flow direction should be upwards, whereas down-flow systems relieve cleaning the chambers with a drawback to risk to flush out valuable bacteria. However, a combination of up- and down-flow is possible. To facilitate solids settling without clogging the filters, a perforated concrete slab may divide each chamber into an upper filter and a lower sludge settler part. The filter itself may consist of a diverse material which can be crushed rocks or bricks, gravel, cinder or pumice sized between 12 to 55 mm in diameter. Ideally, the filter material provides a surface area of 90 - 300 m^2 per cubic meter, whereby a rough edged material is more likely to settle microorganisms. The filter should be layered from rough to fine ascending from bottom to top and have a minimum total height of 0.8 to 1.2 m. The first polishing compartment may consist of crushed rock with 5 – 15 cm in diameter. (Sasse, 1998; Morel & Diener, 2006; Sperling & Lemos Chernicaro, 2006; Sabry, 2010; Nasr & Mikhaeil, 2014)

AF systems can be built above or below ground. To reduce health risks, save space and in order to provide insulation and protection against cold climates, a subsurface structure is beneficial. Regular openings at the upside of the tank are necessary to enable frequent monitoring of the state of the biofilm as well as to check the volume of accumulated sludge. The selected location should be prone to flooding and areas with high groundwater level should be avoided. (Tilley *et al.,* 2008; www.sswm.info, 2016)

Maintenance

As mentioned initially, the start-up period may take between six and nine months. To accelerate ordinary system operation, the filter media may get inoculated with anaerobic bacteria. For this purpose, the septic tank sludge can be deposited onto the filter material. In order to avoid a flush out of filter bacteria, the initial loading should be 1/4 of the full system capacity. The loading rate may then be slowly increased over time. (Tilley *et al.,* 2008)

Like with CST systems, harsh chemicals must not enter the AF tank due to the sensitive ecology. To ensure a proper functioning, regular monitoring of sludge and scum layers is necessary. The pores of the filter will clog over time and need to be cleaned. This can be done either by running the system in reverse mode (backwashing) or by abstracting and washing the filter material. Regular desludging of the primary settling tank is inevitable. It is important that service laborers wear protective clothing when working with the hazardous sludge. (Sasse, 1998; Morel & Diener, 2006; Tilley *et al.,* 2008)

Cost consideration

The structure for biological treatment is very similar to the ABR and thus can be constructed at low cost from locally available material. Depending on the local situation, pre-fabricated systems may be a cost efficient alternative. Since different filter material may be utilized, the local cheapest alternative is recommended. For desludging activities, vacuum trucks generally depict the safest way of disposal. The construction costs of USBR systems make 40 - 60% and O&M 10%, which are 4.5 US$ per cubic meter of treated sewage, compared to activated sludge treatment solutions respectively. (Sabry, 2010; www.sswm.info, 2016)

Review

Up-flow sludge blanket reactors are distinguished by a little sludge production and the possibility of biogas yields. The main advantages and disadvantages are listed in Table 3-16.

Table 3-16: Advantages (+) and disadvantages (-) of AFs (Sabry, 2010; www.sswm.info, 2016)

+ Low sludge production and the sludge is stabilized	– Long start-up period
+ Biogas recovery	– Connection to the treatment unit with tubing necessary
+ High BOD and TSS reduction rates	– Experts required for constructive design
+ Little land area requirements	– Risk of filter clogging caused by insufficient pre-treatment
+ No electricity requirements	– Elaborate removing and cleaning of clogged filter media
+ No special skilled laborer for operation required	– Low reductions of pathogens and nutrients
+ Moderate construction and M&O costs	– Further effluent and sludge treatment is required
+ Long service life	– Only suitable for low-density areas with low water tables and no danger of flooding
	– Effluent pumping may be required

3.2.6 Imhoff tank

The Imhoff tank is a primary treatment technology to treat black- and brownwater. Since the tanks are available at low costs and due to their simple operation and low maintenance requirements, they are well applicable for small communities. Unfortunately, treatment performance is low with the drawback that sludge and wastewater require further treatment. Figure 3-23 shows the cross section of an Imhoff tank. The effluent enters the structure in the centered flow tank, settles by gravity and subsequently forms a layer of sludge at the bottom as well as a layer of scum on top of the tank.

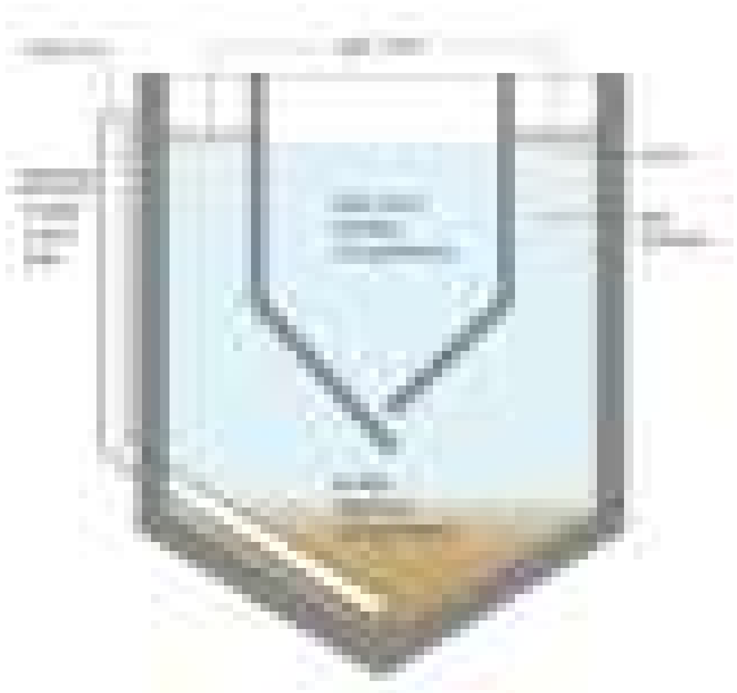

Figure 3-23: Cross section of an Imhoff Tank (Tilley *et al.,* 2014)

An Imhoff tank works similar to a septic tank. As the flow tank/settling compartment is deducted with wastewater, solids settle into the digestion compartment where the sludge gets destructed anaerobically. Due to the fermentation process of the sludge, gas bubbles are formed start floating upwards together with sludge particles. Due to the V-shaped settler in the center of the tank, the composition of gas and sludge gets deflected from inclined walls and subsequently form a layer of scum on top of the liquid surface. This allows the collection and reutilization of biogas. During upward movement of gases and sludge, the settling process stays undisturbed. The common HRT for liquids of only 2 - 4 hours is short, whereas settled solids remain in the tank for 4 - 12 months and longer in colder climates. (Sasse, 1998; WSP, 2007)

The system is able to treat high organic loads and is resistant against organic shock loads. Treatment performance is moderate and further purification is necessary. Effluent can be transferred to leach fields, soak pits or any form of CWs, whereas sludge may get dried or composted before deploying as soil fertilizer. After the effluent exits the tank, both BOD and COD reduction rates range between 30 - 50%, TSS can be reduced by 50 - 70%. Still pathogen removal is very low. (WSP, 2007; Tilley *et al.,* 2014)

Dimensioing

The Imhoff tank is most suitable to treat domestic and mixed wastewater for 50 to 20.000 PE (person equivalent). Minimum feeding of 3 m^3 per day should be warranted. System dimensioning mainly depends on the sludge production per population equivalent, the targeted degree of sludge stabilization and the processing temperature. A minimum HRT of 2 hours at peak flow and a maximum hydraulic load of 1.5 $m^3/h/m^2$ surface area have to be considered. A volume of minimum 50 to 120 L per user should be provided in the tank for domestic wastewater treatment. (Sasse, 1998; WSP, 2007; Tilley *et al.,* 2014)

Construction

Imhoff tanks are generally underground constructions but above ground solutions are possible as well. The spatially separated settling compartment, similar to the digestion compartment, is usually built from reinforced concrete. The outer walls need to be assembled watertight to avoid contamination of the surrounding. Especially with tank heights up to 9 m, the groundwater level should be low and placed at a designated land area free from flooding. The length of the tank approximately equals three times its width. Biogas is recovered on both longitudinal sides of the tank. A vertical pre-installed pipe reaching from top to the bottom of the collection compartment may serve for regular desludging. Figure 3-24 shows different views of Imhoff tanks and gives an impression of the aspired flow direction. The tank construction is typically made of reinforced concrete. The in- and outlet pipes, as well as the pipes for desludging or gas deflection, can be fabricated from cast iron and PVC, respectively. (WSP, 2007)

Figure 3-24: The principle of the solid settlement in Imhoff tanks (Sinimas, 2005)

Maintenance

Flow paths need to be cleaned weekly to prevent clogging of in- and outlets. Scum floating on the liquid surface has to be removed daily, whereas accumulated sludge needs to be removed once to twice a year. This depends on the constructive design of the collection compartment. The latter may be executed with a primarily installed pipe and appendant pump or by providing access to vacuum trucks. Desludging is needed when the space between sludge level and the slot of the settling chamber gets less than 0.5 m. If desludging is ignored the sludge level may reach the funnel. Longitudinal arising gas bubbles on the surface of the settling compartment are indicators for initiating tank evacuation. However, it is important not to remove the entire sludge ensuring to keep some active sludge within the system. To recognize the point of evacuation, a constant monitoring of the sludge’s status is required. In order to control pathogens, evacuated sludge should be transferred to a drying bed or composting pit immediately. For any laborers with potential contact with effluent, sludge or scum protective clothing is necessary. To maintain the system skilled personal is required. (Sasse, 1998; WSP, 2007; Tilley *et al.,* 2014)

Cost consideration

Both construction and operational costs of Imhoff tanks are higher than those for septic tanks. Moreover, an Imhoff tank is still a pre-treatment facility and thus requires further purification steps. As the construction is embedded underground, the effluent may get discharged by gravity flow. For desludging either a pre-installed suction pump or evacuation by vacuum trucks is necessary.

Review

Imhoff tanks are robust against organic shock loads, low in construction and operational costs and biogas recovery is possible. The main advantages and disadvantages are listed in Table 3-17.

Table 3-17: Advantages (+) and disadvantages (-) of Imhoff tanks (WSP, 2007; Tilley *et al.,* 2014)

Advantages	Disadvantages
+ Biogas can be yielded	– Very deep excavation for tank construction required and thus groundwater level has to be low
+ Applicable for small settlements and house clusters	– Expert required for system design and construction
+ Robust against organic shock loads	– Daily checks required to avoid clogging plus short desludging intervals
+ Little land requirements	– Low reduction of BOD, COD and pathogens
+ Moderate costs for O&M	– Further treatment required
+ Simple O&M	– Odors from escaping gases
+ More efficient settling of solids than CSTs	

3.3 Semi-centralized wastewater treatment

Semi-centralized treatment technologies are appropriate for multiple households or even small city applications. The maintenance operation effort and energy requirements are relatively higher than for small-scale technologies at the storage level. In the following chapter a number of semi-centralized treatment technologies are examined. With respect to the rural areas of developing countries, a selection of the most suitable technologies is compiled.

3.3.1 Up-flow anaerobic sludge blanket reactor

Up-flow anaerobic sludge blanket (UASB) reactors treat high-strength (see wastewater strength, p. 6) black- and brownwater anaerobically. It is thus most appropriate for effluent with high organic loads. Due to anaerobic digestion, no input of electrical energy is required for the aeration of the sludge. Nevertheless, effluent pumping is necessary to feed the system. As shown in Figure 3-25, the wastewater is pumped into the reactor at the bottom of the structure. Because of pump pressure and gas formation the sludge is spun within the digester. The sludge is comprised of microbial granules that provide habitat to beneficial microorganisms assisting the progress of organic degradation. Biogas is produced as incidental end product of this process. At the structural top of the reactor, the gas gets recovered by passing through the gas-liquid-solid separator for further utilization. Biogas can be converted into electricity and the produced heat, which is rather an inevitable by-product, can be reused for reactor heating in order to support anaerobic digestion. Anyway, the rising gas bubbles increase bacterial activity and contribute to continuous destruction of the sludge. The upstream velocity and speed of sludge settling has to be balanced so that a locally rather stable layer of suspended sludge can be formed. At the upper part of the reactor, inclined walls are arranged in order to deflect upraised sludge back downwards. After the expiration of an appropriate HRT, the purified effluent gets discharged at the top of the structure. (Sasse, 1998; Rose, 1999)

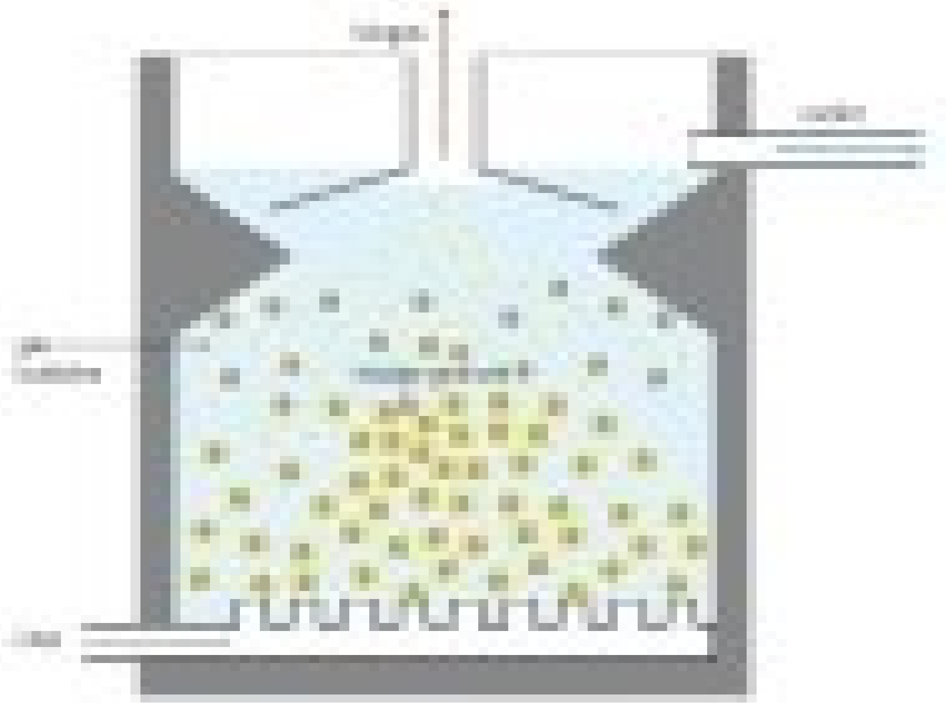

Figure 3-25: Cross section of an UASB reactor (Tilley *et al.,* 2014)

The main influencing parameters for the treatment are pH-value, temperature, ammonia concentration, COD, HRT, up-flow velocity and start-up phase. Ideally the pH-values range from 6.3 to 7.8 in order to guarantee continuous bacterial activity. This range can be met by the addition of hydrogen carbonate. The processing temperature needs to be held between 35 – 38 °C. A decrease of one degree in temperature leads to a digestion quality fall-off of 11%. As long as the temperature is higher than 20 °C, anaerobic digestion is possible. To ensure stable microbial degradation and avoid acidification of the process, the processing temperature must not fall below 15 °C. Formation of ammonia (NH_3) during the fermentation process may cause process inhibition. It is generated once the pH-value exceeds 7.5 and its formation accelerates in correlation with high temperatures. Only when the pH-value can be held within its defined range, the accumulation of ammonia can be avoided. In contrast, in order to catch low NH_3 concentration rates, high COD values of the effluent intake are significant for excellent anaerobic performance. In general, a minimum concentration of > 250 mg COD/l is necessary. The treatment efficiency hits an optimum as if more than 400 mg COD/l is contained within the wastewater. Another significant factor to ensure high treatment performance is the HRT. It should not be less than 2 hours in order to avoid washout of biomass and to provide microbial bacteria growth. To yield optimum outcome, the HRT is held within the range of 2 - 20 hours. In order to avoid bacterial washout, the upper limit of up-flow velocity should not exceed 1.0 m/h. That is necessary to assure effectual dilution and contact between sewage and sludge. The lower limit is defined by 0.6 m/h. At the start-up phase an overloading and acidification utterly needs to be prevented. Generally speaking, municipal wastewater is more appropriate than industrial wastewater since the required nutrients for bacterial activity are contained in significant higher concentration. Initial inoculation for running the degradation process is not necessary. (TWB, 2001)

When considering the limiting factors, treatment efficiencies of 75 - 90% BOD plus 60 - 80% COD and TSS removal rates are possible. In return, the reduction rates of pathogens and nutrients are low. (TWB, 2001; Sinimas, 2005)

Dimensioning

A reactor height of 4 to 6 m is typical. This assumption is based on the bounds of up-flow velocity, which depends on the inflow, water surface, reactor-height and targeted HRT.

Construction

The reactor is built from concrete, brick work or any other material that is proved to be watertight. Both circular and rectangular designs are possible. A certain wastewater inlet distribution, the phase separator as well as the effluent outlet are the most critical elements within a UASB reactor. (TWB, 2001)

The phase separator is primarily responsible for separation of gas, liquids, solids and functions as a biogas recovery facility. Furthermore, it facilitates the settling of suspended solids above the separator to hold back process-supporting bacteria from being discharged. Additional space on top of the structure may absorb high hydraulic loads. In exchange, a hydraulic seal according to the gas outlet is necessary in order to supply sufficient pressure and thus prevent the separator from getting entirely filled up. A submerged installation of the phase separator like shown in Figure 3-26 is possible and actually brings several advantages. The corrosion of the steel construction can be reduced, the entire reactor volume gets available for solids to settle, gas accessibility is improved by excess gas pressure and due to the downstream hydraulic seal the danger of reactor explosion can be prevented. (TWB, 2001)

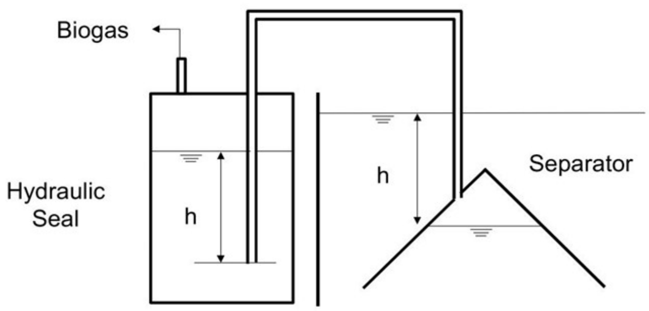

Figure 3-26: Submerged separator, deflector and hydraulic seal (van Haandel & Lettinga, 1994, modified)

Maintenance

UASB reactors generally require a start-up phase of several months. In order to speed up the progress and to attain full system performance in significantly less time, high organic loading, together with low hydraulic loading is needed. To hold the fluid surface on a constant level, hydraulic loading has to be in determined relation to upstream velocity and organic loading simultaneously. Organic loading is specifically responsible for the desired sludge production. (Sasse, 1998)

The sludge production is comparatively low. Subsequently only infrequent desludging, about every 2 - 3 years is required. When cleaning the tank, only excess sludge has to be abstracted so that residual matter still provides sufficient bacterial content to keep the reactor running. As accumulated sludge gets dried or composted in large-scale sludge treatment plants, it may subsequently be used as organic soil fertilizer. (Rose, 1999; WSP, 2008; Tilley *et al.,* 2014)

Cost consideration

Due to the fact that UASB reactors treat wastewater anaerobically and therefore do not require electricity input, the operational costs are comparatively low. But effluent pumping can be necessary to feed the system and thus, energy may be required anyway. The costs for construction are in the range of those of ABR systems. The highest expenses are owed to desludging and continuous operation (e.g. pump feeding).

Review

UASB reactors are highly effective in BOD and TSS reduction. Additionally, biogas can be yielded and the residual sludge can be used as an agricultural fertilizer. The main advantages and disadvantages are listed in Table 3-18.

Table 3-18: Advantages (+) and disadvantages (-) of UASB reactors (TWB, 2001)

+ High BOD and TSS removal rates + Low sludge production and thus infrequent desludging + Biogas recovery + Little land area occupation + No aeration required + Treated effluent is rich in nutrients and can be deployed as organic fertilizer + Construction from locally available	– Experts required for constructive design – Skilled laborers for O&M required – Long start-up period to reach full system performance – Pumping unit requires constant electricity supply – Not all parts for the construction might be locally available – Sensitive to diverging hydraulic

	materials		and organic loads
+	Little CH_4 and CO_2 losses into the atmosphere	–	Further treatment or appropriate discharge of effluent and sludge is necessary

3.3.2 Constructed wetland

CWs can be established after a primary sedimentation cycle to treat liquid effluent. An appropriate primary sedimentation therefore can be carried out in septic tanks or any other technology where liquids are primarily separated from solid contents. The loading of the CW from the upstream pre-treatment takes place either by intermitted pumping or gravity flow. CWs are one option of biological treatment and work through biochemical reactions.

Generally, three types of CWs can be distinguished: horizontal surface-, horizontal subsurface- and vertical-flow wetlands. A sequence of different CW ponds, so called hybrid CWs, is also possible. It is a combination of two or even all three types of CWs and hence, combines their advantages. Vertical-flow wetlands are generally characterized by high rates of nitrification together with low rates of denitrification, whereas this is just reversed at horizontal flow wetlands. Horizontal surface-flow wetlands are comparable to naturally appearing wetlands and hence offer perfect conditions for mosquito breeding. As long as the topography allows gravity flow, none of the CWs are dependent on electric energy supply. Additionally, there is no need to add chemical additives or use any other high-tech infrastructure.

CWs performances may spread a lot considering the high amount of different factors. Influencing factors can either be the location, the type of wastewater, the quantity and the variability of runoff, climate, weather, the wetland design, or unwished functional disturbances. Taking into account all these parameters is a difficult task. Respecting the following some guidelines will increase the chance of successful wetland implementation: (Luise Davis, 1994)

- The design should be as simple as possible because highly complex technologies raise the threat of errors.
- The design should be optimized for a minimum of maintenance.
- The wetland design should fit together with local landscape and natural topography, thus using natural energies such as gravity flow.
- Care should be taken to a nature-oriented design: rigid structures, artificial channels or rectangular basins should be avoided whenever possible.

- System layout should be designed for extreme on-site conditions of weather and climate and not for the average: Storms, floods and droughts need to be considered.
- An appropriate start-up period until the system reaches full efficiency has to be accepted. Strategies that try to abridge the process of development often fail.
- System design should be justified on functionality. Independent to whatever plants used for a wetland construction, while the overall system is functioning well and aspired objectives are satisfied, the system in its entirety has not failed even if some plant types failed.

Depending on the type of CW, the design of the effluent in- and outlets significantly vary. In case of horizontal flow wetlands, the effluent inlet is situated on one side, whereas the outlet is located at the opposite and at a lower elevation. Looking at vertical-flow CWs, surface distribution pipes and subsoil drainage pipes ensure the in- and outflow of the system. The intersections of the different types of wetlands are shown in the following chapters. (Luise Davis, 1994)

As learned by a Scandinavian study (Verena Menz, 2008), CWs function appropriately in alpine regions of Austria (e.g. Göppinger Hütte, Vorarlberg) even above heights exceeding 2000 m in altitude.

Nitrification, denitrification and eutrophication

Providing aerobic conditions to micro-organisms leads to a nitrification process, thus a transformation of ammonia (NH_4^+) to nitrate (NO_3^-). The oxygen gained by photosynthesis of the plants is transported to their roots, where diffusion with water in the soil takes place, which assists the development of microorganisms. These microorganisms again realize nitrification. This process takes place at vertical-flow CWs. If the outflowing water with its high rates of nitrate and phosphate was directly discharged into the next water body or great quantities of it are seeped away on agricultural farmland, an over-fertilization of nearby rivers would occur over time. The so called eutrophication would then cause serious ecological damages on the entire affected environment. To prevent these effects of eutrophication after nitrification, a denitrification process, thus a conversion of nitrate (NO_3^-) to elementary gaseous nitrogen (nitric oxide NO, nitrous oxide N_2O or nitrogen gas N_2) has to take place. This process presumes anoxic (low-grade oxygen availability) conditions to microorganisms and a source of carbon to initiate processing. Denitrification takes place close to topsoil in horizontal subsurface-flow CWs where microbial activity is highest. (Luise Davis, 1994; IPNI, 2015)

The first step of nitrification is carried out by bacteria called nitrosomonas:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$$ Equation 3-1

The second step of nitrification is carried out by nitrobacter bacteria:

$$2NO_2^- + O_2 \rightarrow 2NO_3^-$$ Equation 3-2

Denitrification is carried out by heterotroph and autotroph bacteria:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$ Equation 3-3

Aquatic plants

The aquatic plants, which are name giving to this treatment technology, consist of reed (phragmites australis) mainly and may be supplemented by diverse marsh plants, reed mace, rush or carices. The plants absorb valuable ingredients contained within the wastewater for natural plant growth, are aesthetically pleasant and serve as a habit for wildlife. Their roots grow through the artificial gravel or sandy soil filter and thus are responsible for improving its permeability. It ensures sufficient oxygen supply to the soil, which otherwise would be restricted because of the accumulation of natural sediments or soil consolidation by human trespassing. The deeper the roots may enter the filter bed, the better effects on the filter permeability and oxygen supply into deep soil layers can be obtained simultaneously. The roots offer good living conditions for microorganisms and bacteria, which are as well essential for the degradation process of effluent. As the plants die off they still function as a natural insulation layer and protect the filter bed from freezing during winter in cold climates. (Gauss, 2008; Tilley *et al.,* 2008; Hoffmann *et al.,* 2011)

Cost consideration

The investment costs of any CW are highly dependent on the costs of land and costs for the filter bed material, which either consists out of gravel or sand. Compared to other intensive aerobic treatment solutions, CWs are naturally and extensively working systems. That means treatment, in fact, requires more land area but then is less cost intensive over the life span. The effort of maintenance is low and labor, as well as repair work, can be executed by low-skilled labor. Furthermore, there is no demand for special equipment, expensive spare parts or the assignment of chemical additives. CWs are generally less expensive than high-rate aerobic plants as long as plan dimensions are not excessively high. In order to provide secondary and tertiary treatment solutions to up to 500 PE, CWs will generally be cheaper than high-rate aerobic plants. For large scale solutions with more than 10.000 PE connected, free surface flow wetlands and wastewater stabilization ponds (WSPs) are supposed to be less expensive concerning investment costs than subsurface flow CWs. This assessment assumes that land area is available at low costs. Subsurface flow CWs require high amounts of sand and gravel fills, which may be quite cost-intensive whenever these are locally unavailable. Additional costs may be provoked as plants and liners are locally unavailable and thus need to be obtained from off-site. However, the design and construction of any CW technically require skilled labor. (Eawag/Sandec, 2008; Gauss, 2008; Hoffmann *et al.,* 2011)

3.3.2.1 Horizontal surface-flow constructed wetland

Horizontal surface-flow CWs or free-water surface CWs (FWS) are a series of flooded planted channels or basins for advanced wastewater treatment after prior solid separation. It aspires to replicate the function of natural wetlands, marshes or swamps. As the water slowly flows through the wetland, residual solid particles settle down, pathogens get destroyed and nutrients are utilized by organisms and plants. The pathogen destruction is forced by natural decay, the activity of microorganisms, sedimentation and UV radiation. The plants grown on the wetland may be utilized as an energy source or can be composted. Moreover, the discharged effluent can be irrigated on agricultural land or used in aquaculture. As the land requirements for horizontal surface-flow CWs are comparatively high, the technology is commonly constructed in rural or peri-urban areas, where sufficient land is available and its costs low. However, due to the fact that the water flow is quite still, mosquito egg deposition can depict a negative side effect of FWS systems. Furthermore, the systems are prone to become inefficient at cold climates since surface water might freeze. If the wetland is designed poor and hence, water cannot run off properly the occurrence of aggravating odors is possible as well. Figure 3-27 shows the longitudinal section of a horizontal-flow CW. With time a layer of sludge forms on the soil filter media which contains a multitude of bacteria and hence contributes to a high level of wastewater purification. (Luise Davis, 1994; Morel & Diener, 2006; Sa'at, Siti Kamariah Binti MD, 2006)

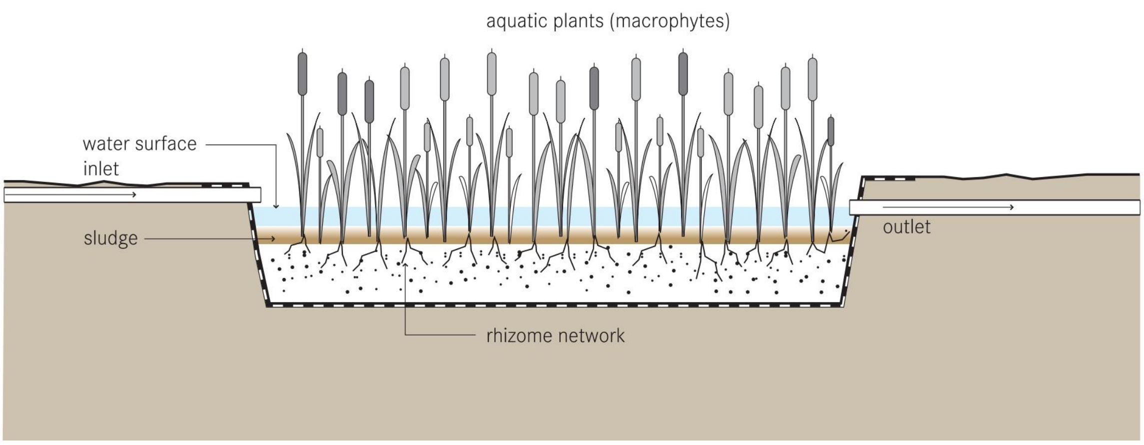

Figure 3-27: Free-water surface CW (Tilley *et al.,* 2008)

Dimensioning

Free surface-flow CWs generally require more surface than subsurface-flow CWs. This is because subsurface flow systems provide much more contact area with the filter media for running treatment activities. Consequently, Surface Flow CWs need to be designed bigger for the same amount of wastewater. (Sa'at, Siti Kamariah Binti MD, 2006)

Construction

The channel or basin is lined with an impermeable liner, either consisting of clay, PVC or geotextile. The ditch is filled with a layer of rocks, gravel and soil and then planted with native vegetation (see p. 73). The pond is filled up with wastewater to a depth of 10 - 45 cm above ground level. An FWS system is compartmentalized into at least two sections. However, the more compartments are arranged in series, the more efficient the treatment performance of the system. The wastewater inlet distribution is another important factor for the further treatment quality. An even feeding interval of the wetland can either be attained by drilled holes in the distribution pipe or by the installation of weirs. The plants for the horizontal surface-flow CW should ideally be locally available. In addition to the typical aquatic plants applicable (see p. 73), FWS technologies may also be planted with emergent, submerged and floating plants. (Sa'at, Siti Kamariah Binti MD, 2006; Tilley *et al.,* 2008)

Maintenance

The effort of maintenance, in general, is low for horizontal surface-flow CWs. However, the vegetation of the pond has to be cut out or thinned out regularly. In addition, it is important to prevent the in- and outlet from clogging. This includes the removal of accumulated solids and garbage dropped into the wetland. Free surface flow CWs are generally easier in operation than subsurface flow CWs since interval feeding is not necessary and the soil material is not prone to clogging. (Gauss, 2008; Tilley *et al.,* 2008)

Regular desludging of the pre-treatment facilities is essential in order to minimize sludge settlement in the wetland. The emptying can either be human-powered or motorized. It is important to absolutely avoid direct skin contact with hazardous sludge. However, also the filter bed of the wetland may be changed sometimes. The excavated material, full of earth and organic matter can directly be deployed as the soil amendment or else composted first. (Sa'at, Siti Kamariah Binti MD, 2006)

Review

Horizontal surface-flow CWs do not require an external energy supply, are easy to operate and maintain, and effective in BOD and TSS reduction. The main advantages and disadvantages are listed in Table 3-19.

Table 3-19: Advantages (+) and disadvantages (-) of horizontal surface-flow CWs (Tilley *et al.,* 2008)

+ Low effort of O&M	– Large land area requirements
+ Construction and repair work can be done with locally available material and local laborers	– Mosquito breeding
+ Natural purification process	– Little nutrient removal
+ High reduction of BOD and TSS; moderate pathogen removal	– If the system is poorly maintained clogging is possible
+ Can be combined with aqua- and agriculture	– Long start-up period until full system performance
+ No energy requirements	– Experts required for the system design and supervision for construction
+ Aesthetically pleasant and it provides animal habit	– System is not tolerant to cold climates
+ No problems with odors as long as system design and maintenance is good	
+ Low operational costs	

3.3.2.2 Horizontal subsurface-flow constructed wetlands

As effluent seeps through the CW, the filter material separates solid particles, while settled microorganisms degrade organic contents simultaneously. To prevent clogging of the filter material and to reach higher treatment efficiencies, appropriate pre- and primary treatment is important. Solid particles together with grease and oil need to be filtered out previously. Typical technologies therefor are septic tanks, ABRs, Imhoff tanks, biogas digesters or UASB reactors. Figure 3-28 shows the longitudinal section of a horizontal subsurface-flow CW. The lining all around the wetland prevents contaminated water from seeping into the ground uncontrolled. The bottom of the wetland is slightly sloped towards the outlet pipe. As soon as the water trickled through the soil filter it pours into a wet well to which the outlet is connected. (Morel & Diener, 2006; Hoffmann *et al.,* 2011)

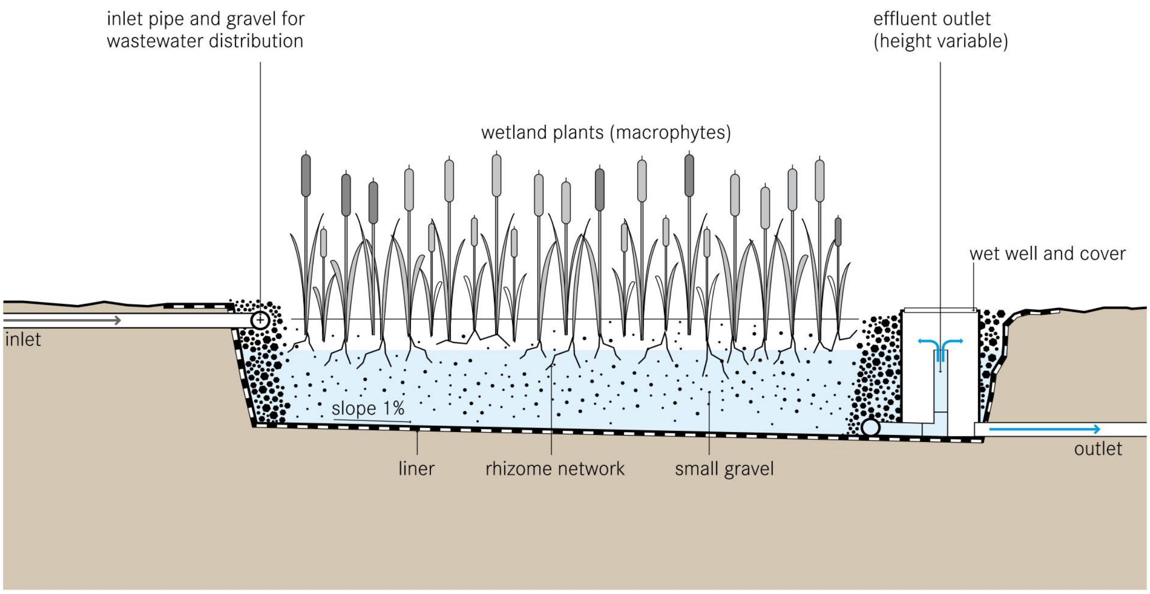

Figure 3-28: Horizontal subsurface-flow CW (Tilley *et al.,* 2014)

Removal efficiencies of horizontal subsurface-flow CWs considering BOD reduction values are between 80 – 90%, TSS are eliminated by 80 – 95%. The maximum reduction rate of nitrate by denitrification (see p. 72) reaches 40%. The removal of phosphorus is dependent on the filter material and the timespan the wetland has already been operating for. Maximum reduction rates of 45% are possible. (Hoffmann *et al.,* 2011)

Dimensioning

Dimensioning of a horizontal subsurface-flow CW is dependent on the treatment target as well as to the amount and quality of the influent. The removal efficiency is a function of the surface area (length multiplied by width), whereas the maximum possible flow is a function of the cross section (width multiplied by depth). Surface area requirements of 5 to 10 m^2 per PE are typical values when dimensioning a horizontal subsurface-flow CW. (Tilley *et al.,* 2008)

For the design of the filter bed, expert knowledge is required. The accurate filter size and the inserted filter substrate are dependent on the hydraulic and organic loads as well as on the findings and experiences of the designer. (Hoffmann *et al.,* 2011)

Construction

A horizontal subsurface-flow CW is basically a large with sand and gravel filled ditch that is planted with aquatic vegetation (see aquatic plants; p. 73). The water level is typically about 0.6 m from the bottom of the structure and maintained to be 5 to 15 cm below surface in order to ensure subsurface flow. Its treatment efficiency is highly dependent on a functioning oxygen supply. To enrich the inflowing wastewater with it and thus to enable BOD reduction and nitrification process, an inlet cascade may be provided. Nevertheless, external oxygen transfer at any horizontal filter bed is low and therefore larger land areas are required than for vertical-flow CWs. (Tilley *et al.,* 2008)

To avoid leaching of the basin an impermeable liner has to be installed at the bottom of the pond. It may be built out of clay, PVC, geotextile or concrete. For the filter media small, round, evenly sized gravel with a diameter of 3 to 32 mm is most appropriate. An alternative to conventional filter media can depict granules from PET, but eventually restricted availability and high costs may limit its implementation in DCs. To avoid clogging the material should be clean and free of fines. The bed is typically filled up 0.5 to 1 m with gravel filter, whereby in- and outlet zone should be designed with coarse gravel. Sand can be used as filter media alternatively but it is prone to clogging. If the topography allows water inflow by gravity, horizontal flow CWs are independent of electricity supply and hence can be operated with gravity flow. (Eawag/Sandec, 2008; Tilley *et al.,* 2008; Hoffmann *et al.,* 2011)

Appropriate aquatic plants are important to ensure soil permeability and oxygen supply to the filter bed. More information about possible diverse plant types and their functionality are described in the superior chapter (aquatic plants; p. 73).

Maintenance

Generally, the maintenance effort for CWs is low but some tasks are always required during their life time. However, these are not that complex and thus allow small-scale private or community based organization. During the first growing season, it is important to remove weeds that may hinder aquatic plant growth. Because of accumulated solids and bacterial film, the inlet filter will clog over time and hence requires replacement. The time span for the filter exchange-service shouldn't be more frequent than every 10 years. Maintenance should include regular inspections of the pre-treatment technologies so as to proof these are effective in solid content reduction. Besides, care should be taken not to grow trees close to the wetland as its roots may damage the liner. (Gauss, 2008; Tilley *et al.,* 2008)

If the wetland starts to smell like “foul eggs” it indicates anaerobic treatment conditions and defines a critical state for the aquatic plants. Then the filter should be rested and the system loading adjusted. (Hoffmann *et al.,* 2011)

Review

Horizontal subsurface-flow CWs are easy to operate and maintain, do not provide a breeding ground for mosquitos and are effective in pathogen reduction. The main advantages and disadvantages are listed in Table 3-20.

Table 3-20: Advantages (+) and disadvantages (-) of horizontal subsurface-flow CWs (Tilley *et al.,* 2008)

Advantages	Disadvantages
+ Fewer space requirements than free surface-flow CWs	– Large land area requirements
+ Low effort of O&M	– Little nutrient removal
+ Construction and repair work can be done with locally available material and local laborers	– Depending on the efficiency of solid separation by the pre-treatment, clogging of the system is possible
+ Natural purification process	– Long start-up period until full system performance
+ High reduction of BOD, TSS and pathogens	– Experts required for the system design and supervision for construction
+ No problems with mosquitos	– Moderate investment costs depending on land, liner, fill, etc.
+ No energy requirements	– System may be ineffective in cold climate regions
+ Low operational costs	

3.3.2.3 Vertical-flow constructed wetlands

A vertical-flow CW is able to treat both household and biodegradable municipal or industrial wastewater. As any CW facility, it requires appropriate pre-treatment so that solid contents are minimized and clogging of the filter bed is obviated. The feeding of the wetland is carried out at intervals between 4 to 10 times per day. This causes aerobic as well as anaerobic phases, thus alternating saturated and unsaturated bed conditions. During a flush phase, the water percolates through the unsaturated bed and drains away below. The arrangement of the in- and outlet pipes is shown in a longitudinal section in Figure 3-29. To ensure sufficient permeability of the filter bed, the roots of aquatic plants provide the necessary porosity. In addition, the vegetation transfers small amounts of oxygen into the filter bed so that aerobic bacteria can colonize in the root zone and degrade organics aerobically. The primary objective of the aquatic plants is to secure permeability of the filter medium and provide a habitat for microorganisms. As the plants die off, they may be used for composting or biomass production. By means of alternate feeding cycles, the microorganisms can be forced into a starvation diet, which reduces the biomass growth but increases the filter porosity. (Morel & Diener, 2006; Sa'at, Siti Kamariah Binti MD, 2006; Hoffmann *et al.,* 2011)

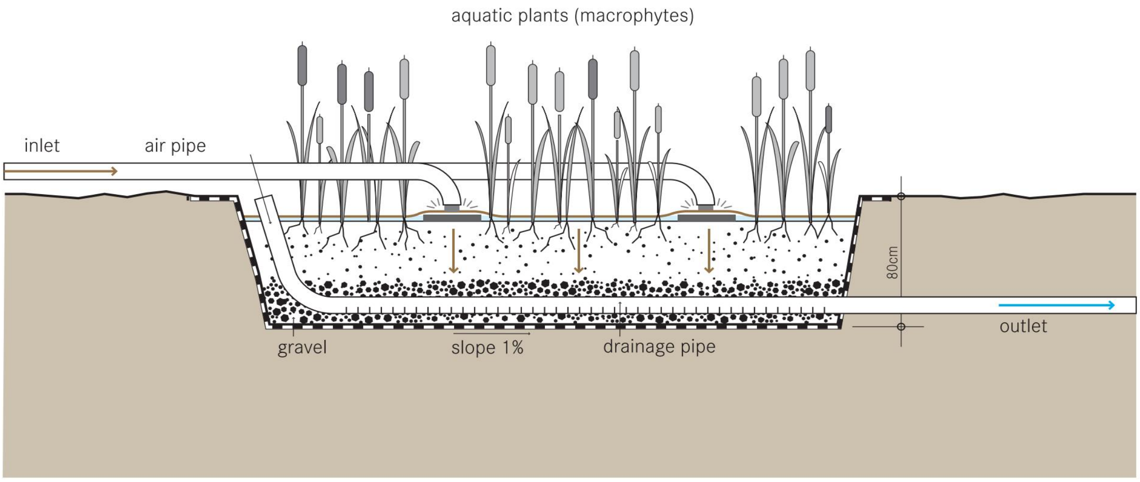

Figure 3-29: Cross section of a vertical-flow CW (Tilley *et al.,* 2008)

Vertical-flow CWs can achieve BOD and TSS removal efficiencies of 90 to 99%. Due to nitrification, ammonia oxidation up to 90% is possible. However, the nitrification process is highly dependent on a functioning oxygen supply (see p. 72). In return, vertical-flow CWs do not provide high denitrification rates and hence nitrate within the effluent can hardly be reduced. Therefore, total nitrogen removal rates of only around 30% are achieved. If enhanced nitrogen removal is favored, a consecutive arrangement of horizontal and vertical-flow CWs with recirculation is possible. It is then called a hybrid CW and is mentioned in chapter 3.3.2.4. (Hoffmann *et al.,* 2011)

Maintenance

In general, O&M for CWs is simple and can be executed by community organizations or small-scale entrepreneurs. (Gauss, 2008) Anyway, regular maintenance will be required over the entire life span of the CWs.

The distribution pipes should be rinsed once a year in order to remove sludge and biofilm that might block the outlet holes. By that time, the spacing between the grains becomes clogged by accumulated solids and bacterial film. Resting intervals may re-establish the hydraulic conductivity of the bed. If this measure is insufficient, the clogged parts of the filter need to be excavated and replaced. This exchange has to be done regularly every 8 to 15 years or even more often. To avoid problems with filter clogging, it is important that the pre-treatment facilities remove suspended solids effectively. It is important that trees must not grow close-by to the wetland so as to prevent the liner from damage. (Hoffmann *et al.,* 2011)

If the wetland starts to smell like “foul eggs”, it indicates anaerobic treatment conditions and defines a critical state for the aquatic plants. Consequently, the filter should be rested and the loading of the system adjusted. Generally, vertical-flow CWs require more technical expertise than other wetland technologies, such as surface flow CWs or WSPs. (Hoffmann *et al.,* 2011)

Dimensioning

A vertical-flow CWs should be designed to provide 1 – 3 m^2 surface area per PE. The design and size of the wetland is dependent on hydraulic and organic loads as well as the particular feeding intervals. (Sasse, 1998).

Construction

The design of the inlet area has to assure uniform distribution of wastewater to the particular distribution pipes. These pipes are perforated with small holes to ensure equal distribution along the length. (Hoffmann *et al.,* 2011)

The total depth of the wetland should be somewhere between 0.8 to 1.3 m. To keep the water in the basin, an impermeable liner at the limit of the wetland can be mounted. If the groundwater level is low and there are no intentions for a re-utilization of the water, the liner can be omitted. Otherwise, several perforated drainage pipes need to be installed at the ground of the structure to provide a collection- and outflow facility for leached water. The pipes are embedded in gravel filter medium with a minimum thickness of 0.2 m. Ventilation pipes connected to the drainage system may contribute reaching aerobic treatment conditions in the filter. The upper part of the fill consists of a sand layer with a thickness of 0.4 – 0.8 m and constitutes the actual filter bed of the wetland. On top of the sand layer, there's another layer of gravel (about 0.1 m thick) that provides the washout of sand by wastewater influent loads. The top layer does not contribute to the filtering process. Additionally, a freeboard of 0.15 m is recommended. (Hoffmann *et al.,* 2011)

To ensure sufficient HRT, the sand layer should have a hydraulic conductivity (kf-value) of about 10^{-4} to 10^{-3} m/s. The filter substrate should neither consist of sharp-edged material nor contain clay, silt or other fine grained material. The grain size distribution of the filter material is important to ensure sufficient permeability. Ideally, the sand and gravel consists of particles with varying grain size. The d10 value defines the minimum grain size of the filter media, where only 10% of the grains may be smaller than this size. For vertical-flow CWs ideally 0.4 mm is chosen for the d10 value, so as to receive a relatively high portion of pores. Figure 3-30 shows two typical grain size distribution curves, which are suitable for vertical-flow CWs. The planting of the vertical-flow CW is equal to any other CW and thus, it is referred to aquatic plants on page 73. (Hoffmann *et al.,* 2011)

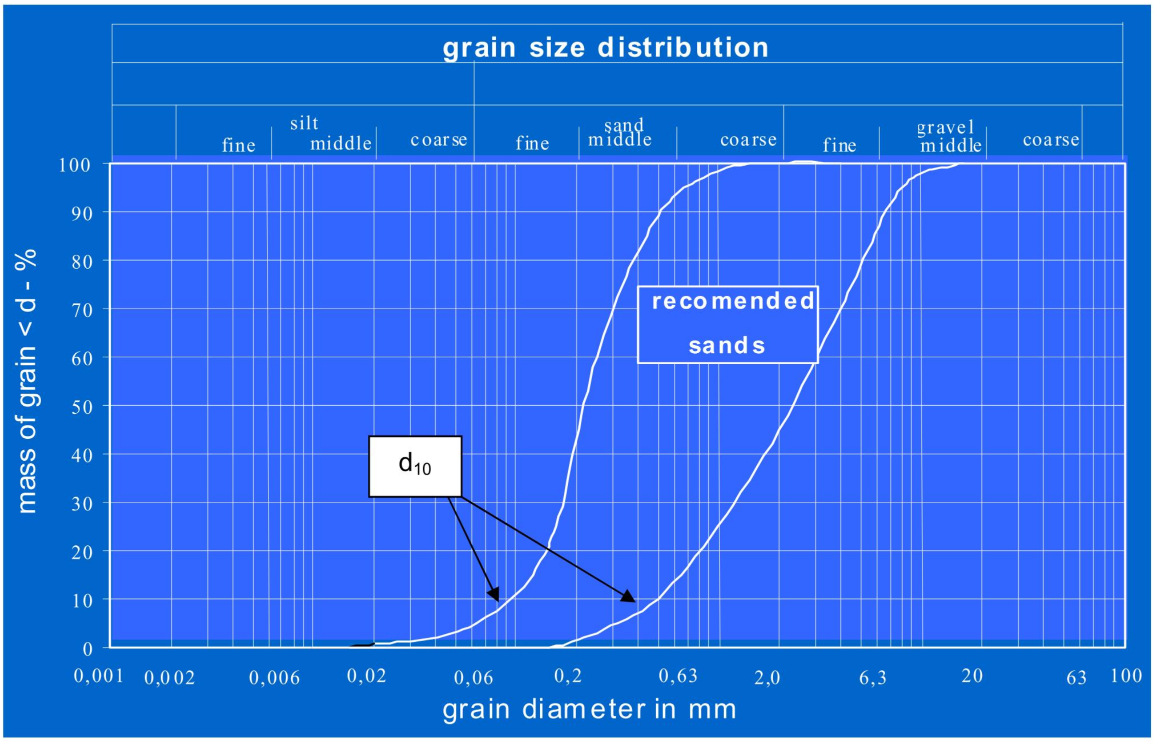

Figure 3-30: Grain size distribution (Hoffmann *et al.*, 2011)

Review

Vertical-flow CWs are easy to operate and maintain, effective in BOD, TSS and pathogen reduction and may be operated at low costs. The main advantages and disadvantages are listed in Table 3-21.

Table 3-21: Advantages (+) and disadvantages (-) of vertical-flow CWs (Tilley *et al.*, 2008)

+ Less space required than for free-surface and horizontal-flow CWs + Construction and repair work can be done with locally available material and local laborers + Natural purification process + High reduction of BOD, TSS and pathogens + Nitrification process is possible if oxygen supply is functioning well + No problems with mosquitos + Low operational costs	– Depending on the efficiency of solid separation by the pre-treatment; clogging of the system is possible – Long start-up period until full system performance – Experts required for the system design and supervision for construction – Dimensioning system requires complex engineering – High quality filter material is not always available locally and then can be expensive – More frequent maintenance required than for subsurface flow

	CWs – Moderate investment costs depending on land, liner, fill, etc. – System may be ineffective in cold climate regions – Due to alternate system feeding, the technology may require a constant source of energy supply

3.3.2.4 Hybrid constructed wetlands

Hybrid CWs combine the above mentioned different types of wetlands in order to achieve higher treatment efficiencies. Typically, a combination of horizontal subsurface-flow and vertical-flow CWs is selected. They treat household as well as, biodegradable municipal or industrial wastewater. A pre-treatment facility is, however, necessary to prevent high amounts of solid contents from entering the wetland.

Construction

Mostly horizontal- and vertical-flow CWs are combined together to a hybrid CW. Ideally, the transfer of wastewater between the wetlands can be arranged in a staged manner by gravity flow. As mentioned above, horizontal subsurface-flow CWs cannot provide nitrification because of their limited oxygen transfer capacity. In return, vertical-flow CWs do provide good conditions for nitrification but the process of denitrification is very low. In hybrid CWs the advantages of these two systems can be combined. If a recirculation of the final outflow water is existing and if the wastewater is passed through the wetland several times, the level of purification can be increased. Consequently, the effluent is low on BOD, fully nitrified and partly denitrified and hence the content of total nitrogen is low. (Vymazal, 2005)

A classical hybrid system was developed by Seidel (1978) at the Max Plank Institute (Germany). It is designed to provide several parallel vertical-flow beds in the first stage, followed by two or three in series operating horizontal subsurface-flow beds. The vertical-flow beds get loaded with pre-treated wastewater for 1 – 2 days and are then dried out for 4 – 8 days. The solid particles retained on the surface are mineralized during the period the bed is not loaded. (Kröpfelová & Vymazal, 2011)

Another approach is introduced by Johansen and Brix (1996) and describes a hybrid CW composed of a horizontal subsurface-flow bed followed by a vertical-flow bed (see Figure 3-31). If denitrification shall take place some outflowing wastewater needs to be collected and pumped back to the inlet distribution so as to pass through the horizontal flow bed. Otherwise, if the outflowing wastewater does not provoke environmental damage, the water recirculation back to the inlet can be neglected. (Kröpfelová & Vymazal, 2011)

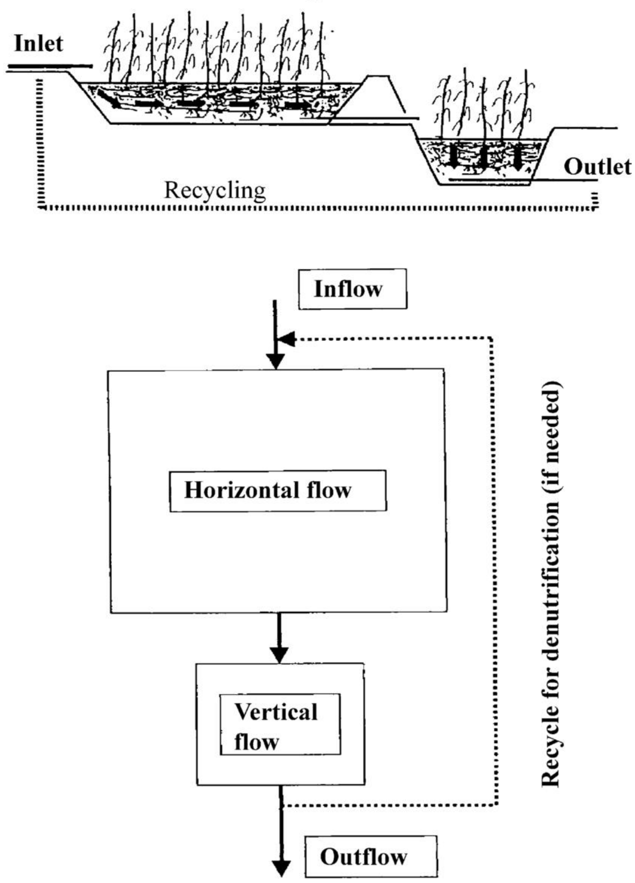

Figure 3-31: Arrangement of a hybrid CW (Vymazal, 2005)

The costs for a hybrid CW can be estimated by simply adding the costs of the particular beds. Possible additional costs incurred for a pumping device, including a pipe connection, need to be considered. The effort of O&M is equal to the particular beds as if these were operated individually.

Review

Hybrid CWs can be maintained and repaired by any local laborer, effectively reduce nitrogen compounds and are stable in operation. The main advantages and disadvantages are listed in Table 3-22.

Table 3-22: Advantages (+) and disadvantages (-) of hybrid CWs (Tilley *et al.*, 2008)

+ Since the advantages of different filters can be combined, higher treatment efficiencies in terms of BOD, TSS, pathogens and	– Space consuming construction – Depending on the efficiency of solid separation by the pre-

nitrogen reducition can be achieved	treatment, clogging of the system is possible
+ No problems with mosquito breeding as long as no surface flow beds are designed	– Long start-up period until full system performance
+ Construction and repair work can be done with locally available material and local laborers	– Experts required for the system design and supervision for construction
+ Natural purification process	– Moderate investment costs depending on land, liner, fill, etc.
+ Process stability	– System may be ineffective in cold climate regions
	– If system loading is not possible by gravity flow, electrical energy may be required

3.3.3 Wastewater stabilization pond

WSPs are large semi-centralized man-made basins and can be arranged right after a collection facility. Since WSPs are able to treat greywater, blackwater as well as fecal sludge, there is no need for another treatment facility between the point of collection and the first pond. Nevertheless, a grid or some screening is required in front of the inlet towards the first basin, so as to avoid loading with large or heavy solids. To achieve high treatment efficiencies, three or even more ponds should be arranged in series. The effluent is transferred from the initial anaerobic pond to the facultative pond and further to the aerobic pond. The depth of the ponds always declines from one treatment stage to the next, starting from up to 5 m and going down to at least 0.5 m in the aerobic pond. (Varon, 2004; Tilley *et al.,* 2014) The particular ponds and how they are arranged in series is depicted in Figure 3-32.

The primary anaerobic stage mainly reduces the organic contents of the wastewater. The anaerobic bacteria convert organic carbon to methane, which can also be collected by covering the pond with a floating plastic membrane, yielding biogas. However, biogas collection is only feasible if the WSPs are of large size. Anaerobic ponds may achieve removal efficiencies of up to 60%. Important factors are the sedimentation process and anaerobic digestion. Generally, anaerobic ponds are able to treat wastewater of high strength. At this first stage, algae are rarely contained in the pond. (Varon, 2004; Eawag/Sandec, 2008; Tilley *et al.,* 2014)

At the second stage, the facultative pond, further BOD reduction takes place. As this pond is of less height, the upper part of the wastewater receives oxygen from natural diffusion, natural airstream and photosynthesis by algae. Algae production can expand close to the surface of aerobic ponds, where light can still penetrate (typically down to 0.5 m). Additional oxygen supply can be provided by natural airflow. However, sunlight is indispensable to ensure photosynthesis of algae and thus aerobic treatment conditions. That’s why at the morning anaerobic treatment conditions are predominant. The facultative as well as the maturation pond can be combined with aquaculture to locally produce animal feed or fish. When fish get settled in the pond they can prevent mosquito breeding on the one hand and may provide excessive algae growth on the other hand. The latter assumes that the fish are herbivores. The lower section of the pond provides anoxic or anaerobic conditions and thus favors solid settlement and digestion. Together anaerobic and aerobic organisms achieve BOD removal efficiencies of up to 75%, which corresponds to a BOD reduction of 10 to 40 $g/m^2/day$ at temperatures above 20 °C. (Tilley *et al.,* 2014)

At the third stage, the aerobic or maturation pond, a majority of nitrogen and phosphorus can be removed from the effluent. If multiple aerobic ponds can be arranged in series, pathogen and BOD removal efficiencies can be increased. The main factors for the removal of fecal bacteria are HRT, temperature, pH-value (> 9) and a high light intensity. WSPs are able to remove nitrogen by more than 80%, ammonia even up to 95%. (Varon, 2004; Tilley *et al.,* 2014)

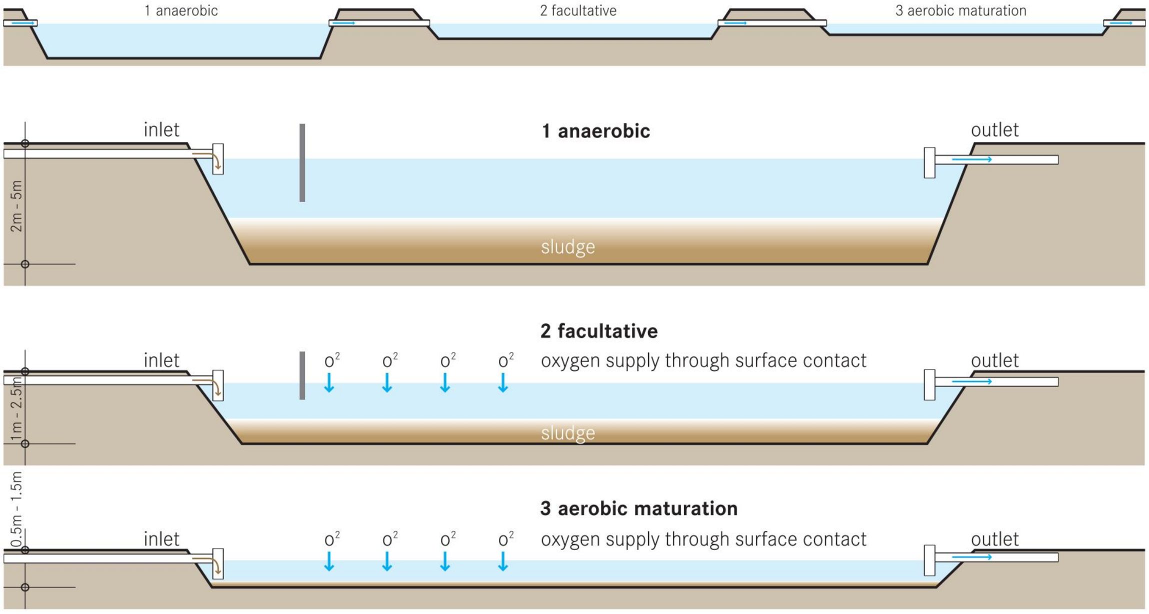

Figure 3-32: Cross section of different WSPs arranged in series (Tilley *et al.,* 2008)

The theorem by Marais (1974) states that ponds arranged in series achieve maximum efficiency when the retention time in every pond is the same. Table 3-23 summarizes the required land areas, pond depths, BOD reduction potentials and the estimated HRTs of wastewater within the particular ponds.

Table 3-23: Summary of the particular stages of a series of WSPs (Sinimas, 2005; Eawag/Sandec, 2008; Tilley *et al.,* 2014)

	Area requirements per person	**Pond depth**	**BOD reduction**	**HRT**
Anaerobic pond	1 – 3 m^2	2 – 5 m	up to 60%	1 – 7 days
Facultative pond	2 – 4 m^2	1 – 2.5 m	up to 75%	5 – 30 days
Aerobic pond	3 – 7 m^2	0.5 – 1.5 m^2	Reduction of pathogens	10 – 15 days

Dimensioning

Arranging a facultative pond after a primary anaerobic pond causes total land area savings between 45 – 70% over a single facultative pond, arranged as the only initial treatment stage. (Sperling & Lemos Chernicaro, 2006)

The formulas for detailed pond dimensioning can be found in Sperling & Lemos Chernicaro (2006).

When choosing the appropriate site for the construction of a WSP, some boundary conditions need to be considered: (Luise Davis, 1994)

- The construction should be as close to the source of wastewater as possible but at least 500 m away from housings.
- Sufficient space for several ponds has to be available.
- Ideally, the sole is gently sloped so that water can flow through the system by gravity.
- The sole of any pond has to be impermeable in order to minimize seepage of wastewater into the groundwater. If soil permeability is more than 10-6 m/s, a lining of the pond is necessary.
- The facility has to be built above the groundwater level and out of areas that are prone to flooding in any case.

Construction

WSPs can either be constructed by excavating basins or raising an earth embankment (dike). A combination of these two design options is possible. When dikes are built, the embedded soil consistency is an important factor for ensuring a long life span of the structure. It has to consist of adequate fine-grained material so that the embankment in its final state is stable and impervious. The embankment slope must be no steeper than 1 in 3 for any pond design. In addition all the ponds should be lined in order to avoid wastewater leaking into the groundwater. The liner can be clay, asphalt, compacted earth, PVC etc. The excavated soil can be reused as a berm around the ponds so as to prevent overflow and to protect surroundings from flooding. (Luise Davis, 1995; Sinimas, 2005; Eawag/Sandec, 2008)

When constructing a WSP the following issues need to be considered: (Luise Davis, 1994; Varon, 2004)

- The design for the ponds require expert knowledge, the construction can be realized by unskilled laborers as long as it is supervised by the expert
- Roads have to be built to easily access the treatment system for desludging activities
- Pond depths of less than 1 m encourage the growth of macrophytes and hence benefit mosquito breeding
- The selected area has to be cleared of trees and other vegetation
- Basins and dikes have to be constructed with appropriately dense earth fillings
- Pumps may be necessary if water transfer by gravity is impossible

- Lining of the embankment and the sole often is required.

Maintenance

As long as the system is well balanced, there won't be serious problems with odors. However, if occasional operational problems occur this can lead to a release of hydrogen sulphide (H_2S), which indeed is responsible for obnoxious smells. (Sperling & Lemos Chernicaro, 2006)

Regular removal of floating debris from the surface and the inlets is necessary. Desludging activities additionally require an efficient community organization or a called in external service provider. For the anaerobic pond, this has to be done every 2 to 5 years, once the accumulated sludge occupies one third of the pond volume. Facultative ponds rarely and maturation ponds hardly ever need desludging. Desludging can be executed by pumping devices, mechanical scraper at the bottom of the pond or by releasing water from the pond and removing the sludge with a front-end loader. The latter requires a by-pass to temporary deflect incoming wastewater. To avoid mosquito breeding and facilitate solar radiation penetrating the water simultaneously, aquatic plant growth should be prevented. (Sinimas, 2005)

Cost consideration

WSPs are the most cost-effective semi-centralized treatment facility for the removal of pathogenic microorganisms. Since WSPs are low-tech infrastructure and do not require external energy supply, operational costs are low. The costs for construction are mostly dependent to the land availability and its price. However, construction requires expert design in order to guarantee sufficient retention time within the particular ponds. Desludging activities may require an external service provider. (Varon, 2004)

Due to their low operational costs, their simplicity of usage together with high treatment efficiencies, WSPs are a promising treatment technology for DCs, especially when low priced land is available.

Review

WSPs are robust against hydraulic and organic shock loads, effective in pathogen destruction and operational costs are low. The main advantages and disadvantages are listed in Table 3-24.

Table 3-24: Advantages (+) and disadvantages (-) of WSPs (Sinimas, 2005)

+	Robust technology against hydraulic and organic shock loads	–	Very space consuming construction
+	High treatment efficiencies concerning BOD, TSS and	–	High investment costs depending on the price of land

pathogen removal	– Desludging is required every few years and therefore external service providers may be attracted
+ High nutrient removal if combined with aquaculture	– Sludge has to be removed and treated properly
+ No problems with flies and odors as long as the system is designed and maintained correctly	– Long HRT within the system
+ Construction and repair work can be done with locally available material and local laborers	– Experts are required for the system design and supervision for construction
+ Low operational costs	– System may be ineffective in cold climate regions
+ No electricity requirements	– If loading of the system is not possible by gravity flow, pumping may be required
+ A reutilization of effluent in aquaculture or for irrigation in agriculture is possible	
+ Natural purification process	
+ Process stability	

3.4 Greywater disposal

In this chapter, a short outlook on simple on-site greywater disposal technologies is given. Soak pits, leach fields and evapotranspiration beds are some possible technologies to dispose greywater on-site. These facilities are described in the following subcategories.

Technologies for sludge disposal will not be outlined along this thesis since all of these are large-scale solutions and thus, require appropriate infrastructure and an extensive effort on coordination among the involved parties. However, there are many opportunities but this would extend the frame of this thesis, which anyway focuses on treatment solutions in rural areas. Nevertheless, some technologies for sludge removal shall be announced: Unplanted and planted drying beds; thickening ponds; large-scale composting; destruction by incineration. All of these technologies require an increased effort of maintenance, high capital investment or large land area availability. An association of at least several villages is necessary to sustainably operate one sludge disposal technology. More information about this topic is provided on the website www.sswm.info.

3.4.1 Soak pit

A soak pit is a covered, perforated-walled, subsurface chamber, where pre-treated wastewater may slowly percolate into the subsoil. The pre-treatment may be facilitated by simple collection and primary treatment technologies, or on-site respectively semi-centralized storage and treatment facilities.

Construction

Generally, there are two different designs for soak pits. The first presumes an empty pit, in which the water gets discharged. In order to prevent collapse, the pit should be lined with porous material. The second possible design is a coarse rock-gravel-filling of the pit. According to this filling, the pit does not require additional lining since a collapse of the pit can be prevented thereby. Nevertheless, Figure 3-33 shows a combination of a lined and gravel-filled soak pit. However, sand and gravel should be spread on the bottom of the pit in order to disperse the flow and to slow down the percolation. The pit depth ranges from 1.5 to 4 m depending on the groundwater level. The minimum distance between the bottom of the pit and the maximum height of the groundwater level is 1.5 m. (Tilley *et al.,* 2008)

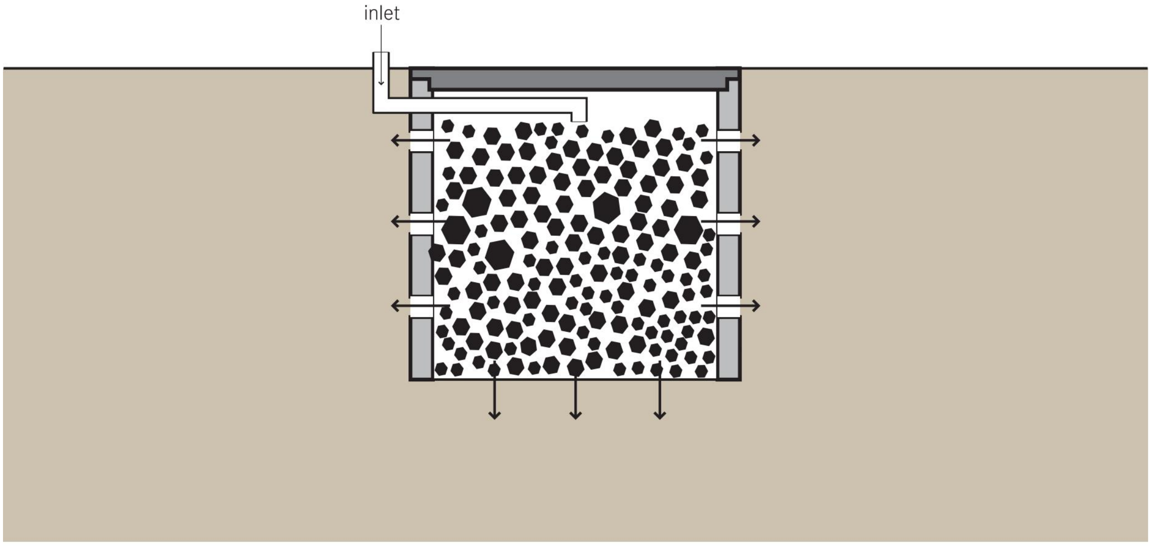

Figure 3-33: Soak pit (Tilley *et al.,* 2008)

As the wastewater seeps through the soil matrix around the soak pit, small particles get restrained and organic contents are degraded by microorganisms. Soak pits are ideally suitable for absorptive soils, whereas clay, hard packed or rocky soils are absolutely unsuitable. The location of the pit should ideally be away from high-traffic areas so that a compaction of the surrounding soil can be avoided. The soak pit can be covered with a concrete lid, which may be opened and thus provide access to maintenance activities. (Tilley *et al.,* 2008)

Maintenance

A well designed soak pit should be able to operate free of disturbance for 3 to 5 years. Of course, this depends on the efficiency of the pre-treatment stage. The more solid particles are contained in the incoming wastewater, the higher the risk of blockages and the less the soak pits' life expectancy. As soon as the performance of the soak pit deteriorates, the material can be excavated, cleaned and recouped into the pit or replaced by a new gravel-rock-filling. (Tilley *et al.,* 2008)

Review

Soak pits can be operated at low costs, are simple to apply for several users and do not require large land areas. The main advantages and disadvantages are listed in Table 3-25.

Table 3-25: Advantages (+) and disadvantages (-) of soak pits (Tilley *et al.,* 2008)

+	Low capital and operational costs	–	Depending on the efficiency of the pre-treatment technology, clogging or overflow is possible
+	Construction and repair work can be done by locally available material and labor	–	Risk of pollution from soil and

+ Little land area requirements + The technology is simple to apply for several users	groundwater – Soak pits are only applicable if the soil conditions allow infiltration; the groundwater level is low; the area is not prone to flooding; the next water well is at least 30 m away – Soak pits may not function in cold climate regions

3.4.2 Leach field

A leach field is conducted with pre-treated wastewater from a water-based collection and storage/treatment or semi-centralized treatment technology. It consists of several perforated pipes, which deviate contaminated effluent into the soil. Hence, it is important that the groundwater level is at least 3 m under the outlet pipes, 30 m from drinking water sources and 15 m from streams respectively. (Hammond & Tyson, 1999)

If a re-utilization of wastewater is not required, leach fields depict an opportunity for a save disposal of greywater. The pre-treated effluent is either conducted by gravity or may be pumped to the leach field. There it gets passed into several parallel channels, which distribute the flow to the subsurface soil for percolation. As the wastewater seeps through the soil, the dissolved organic material within the effluent is degraded by bacteria living in the upper soil layers. A part of the discharged wastewater moves upwards to the surface by capillary action. It either gets absorbed by plants or is evaporated on the surface. (Tilley *et al.,* 2014)

As the wastewater should be discharged by gravity, each leaching line has to be sufficiently sloped (> 1%). In order to ensure the water is discharged over the entire length of the pipes, a dosing respectively pressurized distribution has to be utilized. Then the dosing system may release the pressurized wastewater into the leach field (up to 3 - 4 times a day). (Tilley *et al.,* 2008)

Construction

The perforated tubes should be buried between 0.3 and 1.5 m into the soil, but anyway beneath the frost covering. The width of the trenches ranges from 0.3 to 1 m and their length should not exceed 20 m. The distance between the parallel arranged trenches is in the range of 1 to 2 m. A clean rock fill with a thickness of 15 cm underneath each plumbing, is required in order to guarantee undisturbed seepage. As soon as the pipes are installed, more rock filling is used to cover the plumbing. To prevent small particles clogging the pipes, a layer of geotextile covers the rock filling. On top of the geotextile fabric, sand or topsoil build the top layer of the earthwork. The area of the leach field should be kept free of trees and plants and heavy traffic has to be avoided in any case, by reason of not crushing the plumbing or compacting the soil. Figure 3-34 shows the principle design of a leach field. (Tilley *et al.,* 2008)

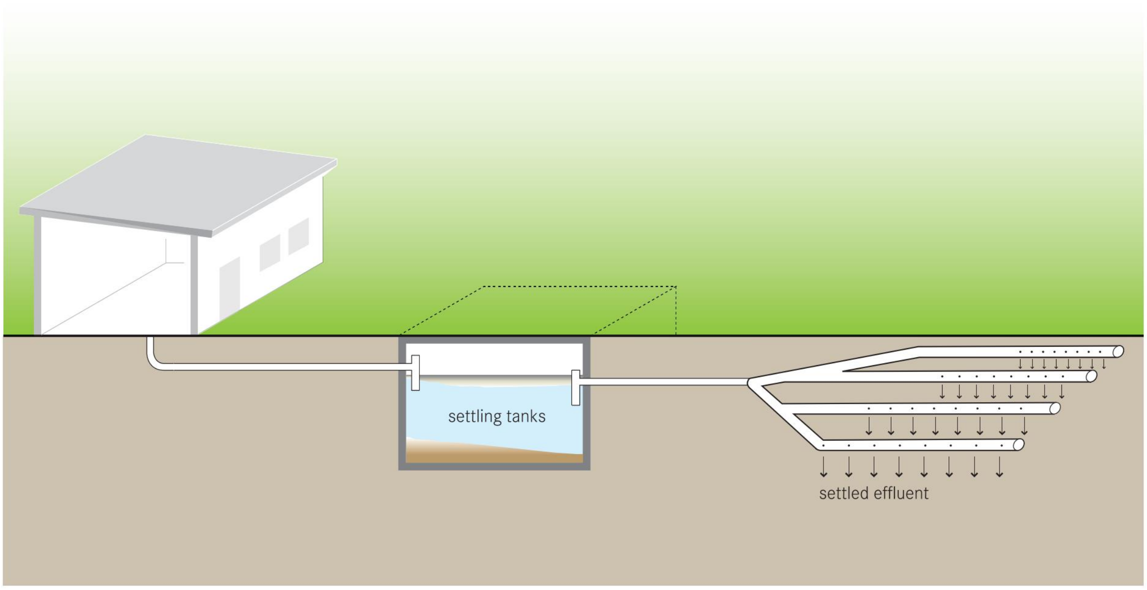

Figure 3-34: Leach field (Tilley *et al.,* 2008)

Maintenance

Independent from constructive arrangements (e.g. insertion of geotextile or well-functioning pre-treatment technologies), the pipes will become clogged over time. The life span of leach fields should be warranted for at least 20 years and the effort of maintenance is supposed to be minimal. As soon as the system discharge capacity is strongly restricted, the pipes need to be cleaned or removed and replaced. (Tilley *et al.,* 2008)

Review

Leach fields are low cost technologies and simple to apply for several users. The main advantages and disadvantages are listed in Table 3-26.

Table 3-26: Advantages (+) and disadvantages (-) of leach fields. (Tilley *et al.,* 2008)

+ Low capital and operational costs + Usable in almost all climates as long as the ground does not freeze + Long life span + Maintenance requirements are	– Dependent on the efficiency of the pre-treatment technology, clogging or overflow is possible – Expert knowledge is required for the design and construction – Not all parts and material may be

low, whether the system is operated without mechanical equipment	locally available – Large land area requirements – Risk of pollution from soil and groundwater

3.4.3 Evapotranspiration bed

Evapotranspiration beds are low cost solutions that allow minor treated greywater to percolate in a predefined transpiration bed. The bed can be fed by greywater from kitchen and showers (anal cleansing water or even septic tanks at a larger scale). The applied water can either be evaporated from the surface or be transpired by plants growing in the bed. Though the plants extract the nutrients from the effluent and dissolved organic material is removed by bacteria settled in the soil.

Construction

The evapotranspiration beds are variable in design and thus can simply be sealed up or consist of old barrels. The bed is filled with soil and mulch, where ornamental plants are grown. In return, the mulch functions as bulking material (see p. 26) and provides better ventilation for aerobic digestion. The plants take advantage of the nutrients contained in the wastewater. In order to avoid clogging of the inlet pipe, a perforated bin is paved upside down on the end of it and then buried in the bed. As the infiltration is arranged below the surface, acrid odors and risks for transmission of diseases are reduced. The bed should be constructed close to the point of occurrence of wastewater. Besides, if the area is well exposed to the sun, high efficiencies of evapotranspiration beds are possible. (Tilley *et al.,* 2008)

Review

Evapotranspiration beds can be operated at low costs, are simple in construction and easy to repair. The main advantages and disadvantages are listed in Table 3-27.

Table 3-27: Advantages (+) and disadvantages (-) of evapotranspiration beds

+ Low-cost solution + Very simple construction + Simple to use + Easy to repair	– Clogging or overflow is possible – May constitute a risk if small children get in contact with the contaminated soil – Slight smells are possible – Insect breeding cannot be neglected

	– Time consuming evaporation process – Only feasible in hot and dry climates

Part two: Rating system

4 Methodology

In order to compare the previously described technologies, a matrix with different properties is generated. The particular factors by which the rating is executed, are adopted by Duncan Mara (2004). Table 4-1 illustrates the selected issues by which the specific treatment technologies get rated. The dots within the table state the importance of different valuation factors. Generally, the more points are depicted, the more important the factor is for the particular surroundings. The rating within this table is an assumption and hence only serves as a guiding value. For the further technology selection process, these rating points can be modified individually, depending on the specific situation on site. The attached "C" highlights the critical issues with the highest rating of five points. The comparison of industrialized countries (ICs) and DCs serves to illustrate the different significance of different factors in different environments. For instance, the costs for construction and operation need to be kept as low as possible since otherwise its implementation will fail in DC by reason of unaffordability. It has to be well understood, that industrialized high-end solutions can hardly be implemented in DCs because of the fact that the technologies mostly cannot be properly adopted to the local circumstances. People on-site need to understand the functionality of the technology, how the system has to be conducted, maintained and in a case of failure how it can be repaired.

Table 4-1: Comparison of factors of importance in wastewater treatment in industrialized and developing countries (Duncan Mara, 2004)

	Industrialized countries	**Developing countries**
Construction costs	••	C•••••
Land requirements	C•••••	••
Pollutant reduction efficiency	C•••••	••••
Environmental impact	••••	••
Reliability	C•••••	C•••••
Sustainability	•••	C•••••
Operational costs	•••	C•••••
Maintenance costs	•••	C•••••

C, critical; •••••, very high impact; •, no impact

4.1 Description

Due to the numerical rating of factors that are difficult to evaluate, a comparison of a multitude of issues can be conducted. Therefore, the scoring method is a convenient tool in order to assess diverse factors and hence finally obtain a comparative value for every particular technology considered. This method was chosen because it allows a numerical evaluation of generally hardly assessable factors. In order to use the method correctly, it is important that just three to maximal five factors are incorporated in the evaluation process. Subsequently, this is ensured by the definition of groups of similar contents. Every technology is hence evaluated by a pre-defined rating system (see chapter 4.2.1).

The methodology is built on two separated rating matrices, one operating in the background and the other is adjustable by any individual user. "Rating matrix A" states the technical rating for the particular factors, whereas the "Rating matrix B" defines the value by which the factor ratings of "Matrix A" are weighed. “Matrix B” is consecutively adjustable by the individual user. This can define the specific importance of every factor. The distinct selection is hence variable since it highly depends on the user preferences as well as the current situation in the field. The interconnection between these two rating matrices is pictured in Figure 4-1. However, the higher the final score of one specific technology, the better it is eligible for the particular situation.

Figure 4-1: Flow chart showing the interconnection between “Rating matrix A” and “Rating matrix B”

Both rating matrices are assessed with values between “1” and “5” like suggested by (Duncan Mara, 2004). Since the value “5” does not necessarily state the better eligibility of the specific factor against another, the value has to be converted respectively. Therefore the relative equations are defined in Table 4-3. The according description to the variables is outlined in Table 4-2.

Table 4-2: Description of variables for the methodology

g	Group number (1..4)
f	Consecutive number of rating factors within one group (1..2)
Variables for the rating matrix A:	
$x_{g,f}$	Individual factor rating (1..5)
$q_{g,f}$	Converted rating factors for the scoring method in percent. All the ratings need to take a value in the range from “0” to “1”, whereat “1” always describes the best rating and “0” the worst.
Variables for the rating matrix B:	
$FOI_{g,f}$	User-specific rating factor of importance for the particular issue. “0” states that the factor is unimportant, whereat “5” specifies very high importance.
FOI_g	The sum of all factors of importance within one group (see Equation 4-4).
$i_{g,f}$	Internal rating value of certain factors within one group. All $i_{g,f}$ per group constitute 100% (see Equation 4-5).
$R_{g,total}$	Calculated rating value of the specific groups (see Equation 4-6). It is evaluated by comparison of each FOI_g with the overall sum of $FOI_{g,f}$ values.
CV	The comparative value (CV) is calculated for every single technology. Due to that factor, the particular facilities can be directly compared to each other. The higher the value, the better the technology is suitable for the explicit situation on site. (see Equation 4-7).

All equations, primarily outlined within Figure 4-1, are again listed in Table 4-3. The grey lodged equations state the formulas for conversion of the rating matrix A. The others are required to link the specific opposite factors and thus, serve to construct the interconnection between matrix A and matrix B.

Table 4-3: Equations to calculate comparative technology values (factor description see Table 4-2)

$q_{g,f} = \frac{x_{g,f}}{5}$	**Equation 4-1**
$q_{g,f} = \frac{(x_{g,f}-1)}{4}$	**Equation 4-2**
$q_{g,f} = \frac{5-(x_{g,f}-1)}{5}$	**Equation 4-3**
$FOI_g = \sum FOI_{g,f}$	**Equation 4-4**

$i_{g,f} = \frac{FOI_{g,f}}{FOI_g}$	**Equation 4-5**
$R_{g,total} = \frac{FOI_g}{\sum FOI_g}$	**Equation 4-6**
$\boldsymbol{CV = R_{g,total} * \sum(q_{g,f} * i_{g,f})}$	**Equation 4-7**

The comparative value is the final result of every technology rating. It is composed of the combination of rating matrix A and rating matrix B and is expressed in percentage. Therefore it states the level of the technology suitability for a specific situation on site. The higher its value, the better it is eligible for the particular circumstances.

4.2 Application

The technology selection is conducted by a scoring-method. This method has been chosen because many factors can hardly be quantified. Due to an analytic procedure, all the technology specific factors can be categorized and arranged from 1 to 5. As mentioned initially, the scoring method preferably deals with three to five factors and however should not exceed ten or more issues. For that reason, these eight specific technology rating factors by Duncan Mara (2004) get summarized in four superior groups. This can be done since some of the factors can hardly be seen as stand-alone aspects, as there is always a sort of connection to other issues. For instance, if the pollutant reduction efficiency is low, the environmental impact of one technology will be influenced in a negative way too. If the system does not work reliable, the technology most likely cannot work sustainably and so on. For that reason, these partly similar factors are merged in order to define one group. The superior groups and its individual factors comprised are outlined in Figure 4-2.

Figure 4-2: Technology selection by defining clusters

The technology selection is built-on two rating components. On the one hand, the technology rating and on the other hand the user-specific rating. The technology rating thereby states the rating matrix by which every particular technology gets evaluated. The user-specific rating provides the corresponding user interface with an input mask in order to define different importance to the individual factors.

The interconnection between these two rating matrices is constructed by the variables $q_{g,f}$, $i_{g,f}$ and the group specific rating $R_{g,total}$. The relative equations are comprised within Table 4-3. The corresponding flow chart is pictured in Figure 4-1 in an abstract from and then filled with data in Figure 4-3.

Group of purpose

The assessment is made on the comparison of several similar technologies combined in one group of purpose (GoP). The GoPs are defined by the main headings of chapter 3:

- Collection and primary sanitation
- On-site storage and treatment
- Semi-centralized wastewater treatment
- Greywater disposal
- Combined technologies.

For further observation only technologies comprised within one of these headings can be compared. Hence, because the technology rating factors within the groups may vary significantly from each other and so would adulterate the results. For instance, it does not make sense to compare SPLs with AF since these technologies are arranged successively. The comparative values of the specific technologies are thus representative within one GoP only.

Figure 4-3: Flow chart showing the interconnection between “Technology rating” and “User-specific rating”

4.2.1 Technology rating

The technology rating is consequently executed by allocating values between "1" and "5" like suggested by Duncan Mara (2004). Although it is not always the case that the higher value of one particular factor automatically states the better eligibility of the technology in this respect. For instance, the lower the construction- and recurring costs, the less expensive the specific technology and the less rating points are thus allocated. As the technology rating is directly faced with the individual user-specific rating by multiplication of the particular factor ratings, lower values would always state worse technology eligibility. Besides, in order to represent the calculation results consistently, the values furthermore get accounted in percent. For that reason, a conversion of all individual rating factors is required, which is described in Table 4-2. The differences among the rating factors and how they are converted are shown in Table 4-4, the according equations in Table 4-3.

Table 4-4: Factor-specific conversion of $x_{g,f}$ to $q_{g,f}$

	$x_{g,f}$		$q_{g,f}$	
Reliability	5	→	1	Equation 4-1
Sustainability	1	→	0.2	
Pollutant reduction efficiency	5	→	1	Equation 4-2
	1	→	0	
Construction costs Land area occupation Environmental impact Operational costs Maintenance costs	5 1	→ →	0.2 1	Equation 4-3

In general, every rating factor can be dedicated to a minimum of activity at least. Only the factor of pollutant reduction efficiency can actually turn zero, as a treatment facility is simply ineffective in purification performance and only serves as a collection device. For this special case, an additional equation is determined. All other rating factors may take a minimum value of 0.2 (see Equation 4-1 and Equation 4-3). The gap between the maximum and minimum $q_{g,f}$ is proportionately fragmented. This once cause rating steps of 0.2, respectively 0.25 in case the minimum $q_{g,f}$ may turn zero.

In the following technology selection process the group ratings are composited by the individual factor ratings. The higher the ratings of the factors within one cluster, the higher the weight of the particular group. Figure 4-4 again shows the hierarchy levels and the sub-items that are comprised of the specific factors. On this basis, the factors were evaluated in the technology rating.

Figure 4-4: Control hierarchy for technology selection

The technology rating represents the matrix, on which the technology selection process is based. It is categorized into superior groups and rating factors. Every rating factor is gradationally assessed. Accordingly, all technologies get characterized by one specific value of one rating factor. In the following subchapters, the groups with their specific rating factors are characterized.

4.2.1.1 Investment costs

Investment costs are principally important since the communities or individual people primarily need to finance a major part of the investment on their own. Certainly there may be some subsidies by the local government but however, the financial donation is mostly disbursed months or even years after completion of the building. For that reason, the financial capital has to be accessible when starting with the construction work.

Construction costs

The construction costs mainly depend on the applied material, the necessity of steel reinforcement, the total land area requirements, the design complexity and thus the estimated construction time, the need for skilled laborers as well as the additional necessity of a power unit installation. Table 4-5 states the ranting system, by which the specific technologies are evaluated with regard to construction costs.

Table 4-5: Rating points assigned for the estimated construction costs

•	The entire construction material can be obtained on site; very simple design; construction work can be done by unskilled laborers
••	The entire construction material can be obtained on site; simple design; can be built by unskilled laborers; double implementation may be required; no additional electricity supply necessary
•••	Externally delivered construction material may be necessary; moderate design and thus skilled laborers are required; no additional electricity supply necessary; installation of sewers may be necessary
••••	Externally delivered construction material may be necessary; complex design and thus skilled laborers are required; an additional power unit to ensure electricity supply may be necessary
•••••	Externally delivered construction material is necessary; complex design and thus expert knowledge is required; installation of sewers may be necessary; an additional power unit to ensure electricity supply may be necessary; very deep excavations may be necessary

Land area occupation

The land requirements are assessed by the occupied land area per person for the specific treatment facility. If further treatment is essential, the rating of technology's land area requirements is raised by at least one level. This is justified by eventually connected sewers and also as facilities cannot work sufficiently as a stand-alone technology. Table 4-6 states the rating system, by which the specific technologies are evaluated with regard to the estimated land requirements.

Table 4-6: Rating points assigned for the occupation of land area

•	< 1 m^2/person (and year); total area occupation: < 5 m^2
••	1 – 3 m^2/person (and year); total area occupation: 5 – 20 m^2
•••	3 – 10 m^2/person (and year); total area occupation: 20 – 100 m^2
••••	10 – 15 m^2/person (and year); total area occupation: 100 – 500 m^2
•••••	> 15 m^2/person (and year); total area occupation : > 500 m^2

4.2.1.2 Environment and ecology

All treatment systems aim to purify effluent water. Their objective is the reduction of compounds that may cause hazardous diseases or may negatively affect the surrounding environment. Especially the contamination of groundwater sources should be avoided and the pollution of streams reduced. Together the pollutant removal efficiency and the environmental impact define the superior category “Environment and ecology”. The following evaluations include the level of purification and the specific side effects on the environment.

Pollutant reduction efficiency

The pollutant reduction efficiency is a quite broad factor. It is dependent on the removal rates of BOD, COD and TSS but also the elimination of pathogenic contents like worms and eggs within the sludge and sludge. These may easily cause serious diseases if not being sufficiently destroyed. The reduction rates are generally declared in percent. Table 4-7 states the rating system, by which the specific technologies are evaluated with regard to the pathogen removal efficiency.

Table 4-7: Rating points assigned for the pollutant reduction efficiency

•	Only collection of polluted matter; no purification at this stage
••	Very low level of purification (BOD and COD reduction rates up to 50%); pathogens and hazardous substances comprised; no manual handling of effluents permitted; the sludge is not stabilized
•••	Medium level of purification (BOD and COD reduction rates up to 70%); some residual pathogens and hazardous substances comprised; manual handling of processed matter with appropriate protective equipment permitted; the sludge may be stabilized
••••	High level of purification (BOD and COD reduction rates up to 90%); very little pathogens and hazardous substances comprised; after skin contact hand washing with soap is sufficient; worms and eggs may be killed by spreading the matter in the sun
•••••	Very high level of purification (BOD and COD reduction rates greater than 90%); no more pathogens and hazardous substances comprised; manual contact with processed matter permitted; after contact hand washing with soap is sufficient;

Environmental impact

The environmental impact is defined by contamination of the outflow or the possibility of re-utilization from destroyed residues. If one technology requires further treatment, the standard rating of technology's environmental impact may be raised by one level. This is justified by eventually connected sewers and the increased risk of failure at an interaction between the technologies. Table 4-8 states the rating system, by which the specific technologies are evaluated with regard to environmental impact.

Table 4-8: Rating points assigned for the environmental impact

•	Low effluent contamination; no risk of unwished discharge of effluent by incorrect usage and hydraulic shock loads; no contamination of groundwater and no loading of streams; an ecological additional value may be generated; re-utilization of residual matter as soil conditioner, fertilizer or dung may be possible; no further treatment is required
••	Moderate effluent contamination; minor risk of unwished effluent discharge by incorrect usage and hydraulic shock loads; no contamination of groundwater; an ecological additional value may be generated; re-utilization as fertilizer or soil conditioner may be possible; no further treatment is required
•••	Moderate effluent contamination; residual risk of unwished effluent discharge caused by incorrect usage and/or hydraulic shock loads; no contamination of groundwater; further treatment may be required; an ecological additional value may be generated; re-utilization as soil conditioner may be possible;
••••	High effluent contamination due to poor destruction processes; increased risk of unwished effluent discharge caused by incorrect usage and/or hydraulic shock loads; possible contamination of groundwater and/or pollution of streams; further treatment required or seepage into low groundwater level soil; no re-utilization of contaminated matter
•••••	High effluent contamination due to very poor destruction processes; high risk of unwished effluent discharge caused by incorrect usage and/or hydraulic shock loads; high risk of groundwater contamination and pollution of streams; further treatment is absolutely necessary

4.2.1.3 Cultural acceptance

System's reliability is intimately connected with sustainability and hence, they constitute the superior group "Cultural acceptance". The robustness of the technology against faulty usage or sudden climatic impacts, are significant parameters for the technology rating process.

Reliability

The factor reliability concerns the system sensitivity on individual user handling and general adjustments of common user behavior. Table 4-10 states the rating system, by which the specific technologies are evaluated with regard to the system's reliability.

Table 4-9: Rating points assigned for reliability

•	High risk of technology deadlock; great adjustments in user behaviour may be necessary; high sensitive utilization due to system complexity; occasional faulty usage may easily cause technology inefficiency
••	Quite sensitive and challenging utilization; high adjustments in user behaviour may be necessary; sensitive utilization may require well educated users; occasional faulty usage may cause technology inefficiency
•••	Moderate, partly sensitive utilization; moderate adjustments in user behaviour may be necessary; utilization may require well educated users; occasional faulty usage is minor dramatic
••••	Simple utilization for educated users; very little adjustments in user behaviour may be necessary; utilization may require responsible users; occasional faulty usage is minor dramatic
•••••	Very simple utilization; very little or even no adjustments in user behaviour are necessary; faulty usage is not possible; non-restrictive usage of water is permitted

Sustainability

Sustainability is a very important issue when choosing a technology for a specific situation in developing countries. If one treatment facility is high sensitive to external influences like changes of climates or the efficiency of previous technologies, the permanent system functionality may be restricted significantly. Subsequently, very frequent maintenance and repair (M&R) work may be required and/or state a cost-intensive operation. If the effort of maintenance is high and even so technology inefficiency occurs easily, the technology sustainability is not warranted. Table 4-10 states the rating system, by which the specific technologies are evaluated with regard to the system's sustainability.

Table 4-10: Rating points assigned for sustainability

•	Difficult system recovery; permanent system functionality highly depend on efficiency of previous treatment facilities, system design complexity, and/or other technical components; little disturbances may easily cause technology inefficiency
••	Difficult system recovery; permanent system functionality may depend on the efficiency of previous treatment facilities, system design complexity, change of climates, sensitivity on hydraulic loads and/or deterioration of technical components; little disturbances may cause technology inefficiency
•••	System recovery may be done by well skilled users; permanent system functionality may depend on the efficiency of previous treatment facilities, system design complexity, change of climates and/or sensitivity on hydraulic loads; less than 20 years until system reconstruction
••••	System recovery can be done by individual users; permanent system functionality may depend on one specific factor; more than 20 years until system reconstruction
•••••	System recovery can be done by individual users; permanent system functionality can be warranted; the technology may be operated in cold and hot climates simultaneously

4.2.1.4 Recurring costs

Recurring costs are defined as a stand-alone category, as permanent expenses define a significant criterion for further observation. Ideally a technology should always operate on low costs. The recurring costs are composed of operational and maintenance costs. The time intervals for maintenance activities and the qualification of labor as well as the requirements of fresh water, electricity or fuel are comprised in this factor.

Operational costs

Depending on the estimated requirements on water, electricity and fuel the operational costs in- or decrease. Table 4-11 states the rating system, by which the specific technologies are evaluated with regard to the operational costs.

Table 4-11: Rating points assigned for the estimated operational costs

•	No electricity requirements; no requirements of water and no fuel requirements
••	No electricity requirements; little amounts of water may be applied
•••	Occasional pumping and thus some source of energy may be required for operation; some water may be applied
••••	Occasional pumping and thus some source of energy and/or fuel may be required for operation; continuous water supply may be necessary
•••••	Permanent electricity requirements for operation and/or continuous fuel requirements; continuous water supply may be necessary

Maintenance costs

The maintenance costs are composited of the estimated time intervals for desludging and the effort to exchange expended components. The costs are to be low if the maintenance activities can be carried out by any user. In return, if external service providers are required the costs rise. Table 4-12 states the rating system, by which the specific technologies are evaluated with regard to the maintenance costs.

Table 4-12: Rating points assigned for the estimated maintenance costs

•	Comparatively large time intervals for M&R work can be assumed; M&R may be executed by any individual user without mechanical equipment; little sludge accumulation;
••	Comparatively large time intervals for M&R work can be assumed; M&R eventually requires mechanical equipment (e.g. vacuum trucks); M&R may be executed by skilled users; moderate sludge accumulation
•••	Moderate time intervals (about once a year) for M&R work can be assumed; M&R eventually requires mechanical equipment; moderate sludge accumulation
••••	Short time intervals for M&R work can be assumed; M&R requires mechanical equipment and well skilled laborers; moderate to high sludge accumulation;
•••••	Short time intervals (about twice a year) for M&R work can be assumed; M&R requires mechanical equipment and excellent skilled laborers or external service company; frequent service of connected pumps and/or sewers may be necessary; high sludge accumulation

4.2.2 User-specific rating

In contrast to the technology rating, the user-specific rating may reach values between “0” (no importance) and “5” (high importance). The user has to select a value for every particular factor. If “0” is selected, the specific issue is not respected in the following calculation. Otherwise, the defined value is converted into a value between 0.2 and 1, whereas this states the quality by which the opposite factor from the technology rating is multiplied. Within one group, all rating factors together state 100%. In addition, the particular factor rating is integrated into the determination of the overall group rating. It is calculated by counting up all factors within one group and comparing this value with the overall sum of factors. The representative group rating states the value by which every group is weighted in the technology selection process (see Equation 4-6). The formulas and the flow chart showing the interconnection between the technology rating and the user-specific rating are shown in Table 4-3 and Figure 4-3.

The recommendations within the generated excel sheet outline the particular factor ratings assumed by Duncan Mara (2004). However, these values only state a recommendation and hence can be adjusted by any user to any situation on site.

4.2.3 Calculation example

The following example shall help to understand the technology selection process. Therefore Table 4-13 and Table 4-14 show the two interfaces of the technology rating on the one side and the user-specific rating on the other side.

For this example, all recommended factors of importance (FOI) by Duncan Mara (2004) are one-to-one adopted for further calculation. Besides, the internal rating factor ($i_{g,f}$) is built from the proportion of the specific $FOI_{g,f}$ comprised in one group. The importance of one group is evaluated by summing up the individual ratings within one group. Due to comparing this value with all other group values, the group rating factor ($R_{g,total}$) is assessed.

Table 4-13: Virtual example: User-specific rating

User-specific rating		Investment costs 1		Environment and ecology 2		Cultural acceptance 3		Recurring costs 4		Comperative value for technology selection
		Construction costs	Land area occupation	Pollutent reduction efficiency	Environmental impact	Reliability	Sustainability	Operational costs	Maintenance costs	
Recommended FOI referring to Duncan Mara (2004)		5	2	4	2	5	5	5	5	
Factor of importance	**$FOI_{g,f}$**	**5**	**2**	**4**	**2**	**5**	**5**	**5**	**5**	
Internal rating factor	$i_{g,f}$	0,71	0,29	0,67	0,33	0,50	0,50	0,50	0,50	
Group importance	FOI_g		7		6		10		10	
Group rating factor	$R_{g,total}$		0,212		0,182		0,303		0,303	
Collection and primary sanitation										
Simple pit latrines	CV		0,212		0,055		0,212		0,273	**0,752**
Pour-flush pit latrine	CV		0,212		0,024		0,242		0,242	**0,721**
Ventilated improved pit latrine	$q_{g,f}$	1	1	0,25	0,4	0,8	0,6	1	0,8	
Ventilated improved pit latrine	$q_{g,f} * i_{g,f}$	0,71	0,29	0,17	0,13	0,40	0,30	0,50	0,40	
Ventilated improved pit latrine	CV		0,212		0,055		0,212		0,273	**0,752**
Double-vault pit latrine	CV		0,182		0,085		0,182		0,273	**0,721**
Urine diversion dehydration toilets	CV		0,152		0,152		0,121		0,303	**0,727**
Composting toilets	$q_{g,f}$	0,6	1	0,75	1	0,4	0,8	0,8	1	
Composting toilets	$q_{g,f} * i_{g,f}$	0,43	0,29	0,50	0,33	0,20	0,40	0,40	0,50	
Composting toilets	CV		0,152		0,152		0,182		0,273	**0,758**
Urine diversion flush toilet	$q_{g,f}$	0,6	0,8	0	0,6	0,8	1	0,6	0,6	
Urine diversion flush toilet	$q_{g,f} * i_{g,f}$	0,43	0,23	0,00	0,20	0,40	0,50	0,30	0,30	
Urine diversion flush toilet	CV		0,139		0,036		0,273		0,182	**0,630**

The rating points $x_{g,f}$ range from 1 to 5 and are assigned for every rating factor for every single technology. For further calculation the converted rating factors ($q_{g,f}$) need to be determined and its values between 0 and 1 gets released to the user-specific rating (see Table 4-13). In Table 4-13 and Table 4-14 the converted factor ratings for VIP latrines, CTs and UD flush toilets are shown in detail. These three technologies are chosen for precise analysis since they state the best or rather the worst eligibility in consideration of the overall comparative value (CV). The green highlighted values define a very high technology suitability, whereas the red marks indicate very poor technology performance in this respect. The green and red marks facilitate the visualization of ratings within the upper 25% and the lower 25% of the scale respectively.

Table 4-14: Virtual example: Technology rating

Technology rating		Investment costs 1		Environment and ecology 2		Cultural acceptance 3		Recurring costs 4	
		Construction costs	Land area occupation	Pollutent reduction efficiency	Environmental impact	Reliability	Sustainability	Operational costs	Maintenance costs
Collection and primary sanitation									
Simple pit latrines	$x_{g,f}$	1	1	2	4	4	3	1	2
Pour-flush pit latrine	$x_{g,f}$	1	1	1	4	5	3	2	2
Ventilated improved pit latrine	$x_{g,f}$	1	1	2	4	4	3	1	2
Ventilated improved pit latrine	$q_{g,f}$	1	1	0,25	0,4	0,8	0,6	1	0,8
Ventilated improved pit latrine critical vaules		•	•	•• C	•••• C	••••	•••	•	••
Double-vault pit latrine	$x_{g,f}$	2	1	3	4	3	3	1	2
Urine diversion dehydration toilets	$x_{g,f}$	3	1	4	1	1	3	1	1
Composting toilets	$x_{g,f}$	3	1	4	1	2	4	2	1
Composting toilets	$q_{g,f}$	0,6	1	0,75	1	0,4	0,8	0,8	1
Composting toilets critical vaules		•••	•	••••	•	•• C	••••	••	•
Urine diversion flush toilet	$x_{g,f}$	4	2	1	3	4	5	3	3
Urine diversion flush toilet	$q_{g,f}$	0,4	0,8	0	0,6	0,8	1	0,6	0,6
Urine diversion flush toilet critical vaules		•••• C	••	• C	•••	••••	•••••	•••	•••

For the calculation of one group specific CV, every rating factor $i_{g,f}$ is multiplied by the related converted rating factor ($q_{g,f}$) and its group internal sum is multiplied by the group rating factor ($R_{g,total}$) (see Equation 4-7, p. 101). Summing up all group specific CVs of one technology results in the overall CV for the final technology selection. The results are displayed in the right column of Table 4-13 and hence, make all technologies comparable among each other. The higher the overall CV of one technology, the better it is eligible for the specific selection.

However, the technology with the highest comparative value is not automatically the most appropriate, but it indeed provides a basis for further discussion. Again, the green highlighted results are the most convenient solutions for the particular user-specific weightage.

4.2.4 Combined technologies

In order to combine different technologies expert knowledge is required. First of all, it is important that solids get separated from liquids in order to avoid clogging of further treatment facilities.

Table 4-15 shows some possible combinations of technologies. The disposal of sludge is an extensive task and thus, can hardly be executed on site. Vacuum trucks are appropriate facilities for suction cleaning and transportation of the contaminated matter to a large-scale treatment plant.

Table 4-15: Feasible combinations of technologies

	Collection and primary sanitation	**Post-treatment systems**
A1	Simple pit latrines	VT*
A2	Pour-flush pit latrine	VT*
A3	Ventilated improved pit latrine	VT*
A4	Double-vault pit latrine	VT*
A5	Urine diversion dehydration toilets	D3
A6	Composting toilets	D3
A7	Urine diversion flush toilet	B1, B2, B3, B4, B5, B6, B7, B8, C1, C6, D1, D2, D3
	On-site storage and treatment	
B1	Cesspit	VT*
B2	Fixed dome biogas digester	C2, C3, C4, C5, D1, D2, VT*
B3	Floating cover biogas digester	C2, C3, C4, C5, D1, D2, VT*
B4	Balloon biogas digester	C2, C3, C4, C5, D1, D2, VT*
B5	Septic Tank	C2, C3, C4, C5, D1, D2, VT*
B6	Anaerobic baffled reactor	C2, C3, C4, C5, D1, D2, VT*
B7	Anaerobic filter	C2, C3, C4, C5, D1, D2, VT*
B8	Imhoff tank	C2, C3, C4, C5, D1, D2, VT*
	Semi-centralized wastewater treatment	
C1	Up-flow anaerobic sludge blanket reactor	D1, D2, VT*
C2	Horizontal surface-flow constructed wetland	C4, C5, D1, D2
C3	Horizontal subsurface-flow constructed wetland	C4, C5, D1, D2
C4	Vertical-flow constructed wetland	C5, D1, D2
C5	Hybrid constructed wetlands	-

C6	Wastewater stabilization pond	-
	Greywater disposal	
D1	Soak pit	-
D2	Leach field	-
D3	Evapotranspiration bed	-

* Vacuum truck emptying and off site deposit; -, no further treatment required

In general, this rating tool is modeled to output a treatment facility for a specific stage of purification. Combinations of several technologies are conceivable but this thesis does not examine all possible options explicitly. Combining a number of technologies in series requires expert knowledge about the treatment facilities. In order to exemplify the model's suitability, two possible arrangements of treatment facilities are defined in Table 4-16.

Table 4-16: Technology combinations

Technology rating		Investment costs	1	Environment and ecology	2	Cultural acceptance	3	Recurring costs	4
		Construction costs	Land area occupation	Pollutent reduction efficiency	Environmental impact	Reliability	Sustainability	Operational costs	Maintenance costs
Combination of technologies									
Septic tank + Vertical-flow CW	$x_{g,f}$	3	2	4	2	4	3	3	2
Septic tank + Vertical-flow CW	$q_{g,f}$	0,6	0,8	0,75	0,8	0,8	0,6	0,6	0,8
Septic tank + Vertical-flow CW critical vaules		•••	••	••••	••	••••	•••	•••	••
Anaerobic baffled reactor + Horizontal subsurfac	$x_{g,f}$	4	3	4	2	4	4	2	3
Anaerobic baffled reactor + Horizontal subsurfac	$q_{g,f}$	0,4	0,6	0,75	0,8	0,8	0,8	0,8	0,6
Anaerobic baffled reactor + Horizontal subsurface-flow critical vaules		•••• C	•••	••••	••	••••	••••	••	•••

Table 4-16 shows a combination of a septic tank with a vertical-flow CW and besides, the arrangement of an ABR with a horizontal subsurface-flow CW. Ideally the inlet water entering the wetlands is not loaded with solid particles. This sometimes requires pre-treatment facilities for the settling of solids. The two alternatives vary in terms of incidental costs and the expected system sustainability. An example for the serial arrangement of technologies is discussed in chapter 5.3.4.

5 Case study: Rural village examination

In this chapter a case study is presented to show a practical example of how to apply the routine that is modelled in this thesis. The investigation generally considers the rural areas of Nepal and especially refers to the village Bhotechaur.

5.1 Boundary Conditions

Nepal is quite a diverse landscaped country, bordering India in the south and China in the north. Close to the Indian border, the terrain is fairly flat, whereas the Himalaya-mountains define the northern border to China. Thus the temperatures vary accordingly, depending on the altitude. Figure 5-1 shows the profile of Nepal and a mark determining the village Bhotechaur for this case study.

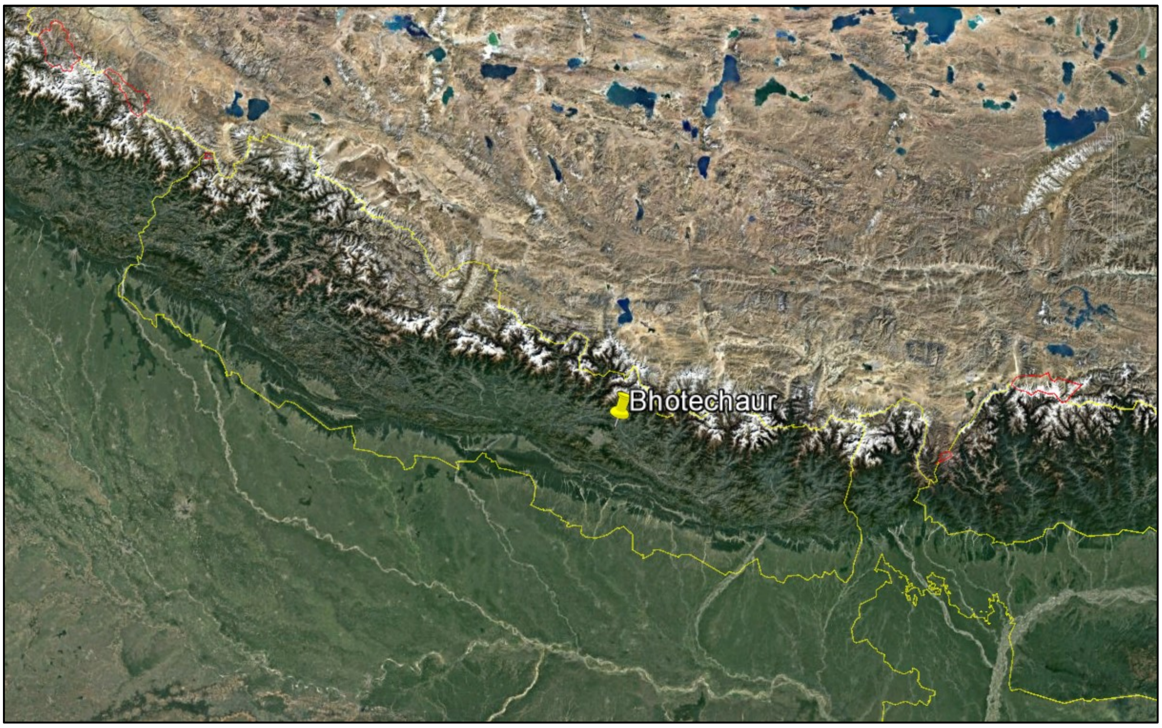

Figure 5-1: Map of Nepal (Google Earth, 2016)

Besides the topographic and climatic issues of Nepal there are many more important factors for further consideration. These include the level of education, major land use, cultural frame conditions, electrification etc. Some information about the social circumstances in Nepal is outlined in Table 5-1. Only about 4 million people live in Kathmandu valley, whereas the residual 25 million are scattered all over the country. The governmental investigation (www.cia.gov) also shows that more than 50% of the population in rural Nepal lack of satisfying sanitary conditions. So this affects about 14 million people. For that reason, decentralized wastewater disposal technologies are of particular interest for those who most likely do not have access to proper sanitation or public electricity supply. For the further investigation, these boundary conditions are important whenever determining a suitable collection or treatment facility in these regions.

Table 5-1: Hard facts about Nepal (www.cia.gov, 2016)

Capital city:	**Kathmandu**		
Total land area:	**147,181 km²**		
	Agriculture	Forest	Other
	28.8%	25.4%	45.8%
Total population:	**29.0 million**		
		Median age (total):	23.6 years
		Life expectancy (total):	70.7 years
Official language:	Nepali		
	123 languages are reported as mother tongue		
Ethnic groups:	125 caste/ethnic groups are listed		
Religion:	81.3% Hindu; 9% Buddhist; 4.4% Muslim; 3.1% Kirat; 1.4% Christian; 0.7% other		
Improved sanitation facility access:			
	Urban	Rural	Total
	56.0%	43.5%	45.8%
Unimproved sanitation facility access:			
	Urban	Rural	Total
	44.0%	56.5%	54.2%
Electrification:			
	Urban	Rural	Total
	97%	72%	76%
Literacy:			
	Male	Female	Total
	76%	53%	64%

5.2 Determining the factors of importance for Bhotechaur village

In this chapter the rating of the different factors of importance (FOI) is carried out. The rating is assigned with respect to the local circumstances in Bhotechaur village, which is located in Sindhulpalchok district. The area is known as the “Everest tea garden”. The area of Bhotechaur counts approximately 5000 inhabitants and the village is situated at about 600 m a.s.l.

Figure 5-2 gives an overview of Bhotechaur village, on which the assumptions for the further FOI determination is based. First of all the area is quite hilly and thus, the groundwater level is expected to be low. The financial resources are low at the current state but an upswing in the next years seems possible. The cultural beliefs of the people and the affiliation in a strict caste system is keenly developed. Besides, the literacy rate and the level of education in general are presumed to be moderate.

Figure 5-2: Bhotechaur (Andreas Kramer, 2016)

Table 5-2 shows an assumption of the FOI that may be worked out in a discussion with villagers. It respects the specific boundary conditions on site as well as the major doubts of the people involved. Every rating value assigned is discussed below.

Table 5-2: User-specific rating for Bhotechaur village

	FOI*		FOI*
Investment costs		**Cultural acceptance**	
Construction costs	4	Reliability	5
Land area occupation	3	Sustainability	5
Environment and ecology		**Recurring costs**	
Pollutant reduction efficiency	5	Operational costs	5
Environmental impact	2	Maintenance costs	0

* Factor of importance

Construction costs FOI: 4

After the heavy earthquake in 2015, people still need to spend a lot of money to rebuild their houses. For that reason, the financial resources are low and thus, the expenses for sanitation technologies should be low too.

Land area occupation FOI: 3

The area of Bhotechaur is quite hilly and thus, excessive land area is not available. Nevertheless, moderate sized constructions (e.g. up to 50 m^2) are possible.

Pollutant reduction efficiency FOI: 5

People understand the interconnection of high child mortality and infectious diseases caused by insufficient hygienic conditions. For that reason, the efficiency of pathogenic destruction has to be high.

Environmental impact FOI: 2

Since people suffer poverty after the heavy earthquake, they argue that the environment is minor important at the current stage. Nevertheless, governmental subsidies are only allocated for environmental sustainable projects. Due to the hilly landscape, low groundwater levels can be expected and thus, do not state a critical issue in that case.

Reliability FOI: 5

The technology shall absolutely be simple in operation. The level of education is low and the rate of illiteracy is high. The people do not want frequent technology deadlock caused by faulty usage. For that reason, the technology should be very simple in operation.

Sustainability *FOI: 5*

The technology should be robust and even withstand an earthquake or another naturally caused disaster and its sensitivity on errors should generally be low.

Operational costs *FOI: 5*

The costs for continuous operation necessarily have to be low in between the estimated time intervals for maintenance work. Electricity is only available for a few hours per day and during dry season water is scarce. For that reason, the particular treatment facility should avoid to come back to these limited resources.

Maintenance costs *FOI: 0*

Maintenance intervals of 2 years are accepted and their financing is guaranteed. The maintenance costs are not significant. In return, the expenses on operational costs are required to be kept low.

5.3 Model application: Comparison of technologies

Due to the interconnection between the facility-specific technology rating and the user-defined importance of every rating factor, a comparative value is calculated for every facility. Regarding the previous rating for each GoP a number of facilities are investigated on their suitability. Despite this rating, a critical discussion of the results is necessary. A combined rating of a number of technologies arranged in series is possible. In this thesis two possible combinations are examined. This list may get extended by experienced engineers since the technology rating has to be adopted properly.

The specific advantages and disadvantages of the technologies can be seen in the appendix (see Appendix A2). The green highlighted values define especially good technology properties, whereas red highlights state specifically bad technology eligibility.

5.3.1 Collection and primary sanitation

A family of four attends to build a toilet facility. They require a basic construction and do not have a lot of space available close to their house. They intend to stay aware of bacterial diseases and the technology has to be simple in operation.

After defining different FOIs (see Table 5-2), the comparative values for the specific technologies within the GoP “Collection and primary sanitation” are calculated. The comparative values are outlined in descending order in Table 5-3.

Table 5-3: Comparative values for a number of collection and primary sanitation technologies

	CV*
Composting toilets	**0,729**
Ventilated improved pit latrine	**0,726**
Simple pit latrines	**0,726**
Double-vault pit latrine	0,707
Urine diversion dehydration toilets	0,695
Pour-flush pit latrine	0,683
Urine diversion flush toilet	0,621

* Comparative value

Discussion

According to the pre-defined FOI rating, the SPLs, VIP latrines and CTs are the most eligible technologies. The UD flush toilet is hence the technology with the lowest score, since its pollutant reduction efficiency significantly differs from the other facilities and the FOI is rated with the maximum value “5”. The low comparative value of UD flush toilets is caused by the not existing treatment performance. In addition, the operational costs for UD flush toilets are high since effluent pumping may be required.

Figure 5-3 visualizes the particular advantages and disadvantages of different technologies. The FOI is expressed in percent. The red line in the graph defines the user specific importance and stays unchanged for the different technology selection processes in this example. When comparing the three technologies, CTs and VIP latrines are most suitable in terms of recurring costs, investment costs and environment and ecology. The cultural acceptance is the only factor where UD flush toilets are more applicable than the other technologies. Nevertheless, their poor eligibility relating to the other group ratings cause a low CV in this respect.

Figure 5-3: Visualized comparison of the results for collection and primary sanitation facilities

Result

If the people agree with low treatment efficiencies and digging a new pit every 10 years, VIP latrines are the most appropriate technologies. CTs are high effective in terms of pollutant reduction efficiency but may fail in consideration of reliability since people may not accept dealing with excreta.

5.3.2 On-site storage and treatment

Several family households intend to build a combined storage and treatment facility for incidental fecal and effluent disposal. The simplicity and sustainability are the central tasks for the technology selection. The effort of maintenance is of minor importance as long as the expectable time intervals can be met. Furthermore, the reduction of pathogenic content is significant.

After defining the different FOIs, the comparative values for the specific technologies within the GoP "On-site storage and treatment" are calculated. The comparative values are outlined in descending order in Table 5-4.

Table 5-4: Comparative values for a number of on-site storage and treatment facilities

	CV*
Balloon biogas digester	**0,764**
Fixed dome biogas digester	**0,736**
Floating cover biogas digester	0,702
Anaerobic baffled reactor	0,702
Septic Tank	0,698
Cesspit	0,676
Anaerobic filter	0,576
Imhoff tank	0,491

* Comparative value

Discussion

According to the pre-defined on-site conditions in Bhotechaur, the balloon biogas digester and the fixed dome biogas digester are the most eligible technologies. A cesspit is not suitable since its content does not get destructed and purified. Due to the high significance of the pollutant reduction efficiency caused by the high FOI, cesspits are not appropriate for these boundary conditions. If low cost solutions were the only task to fulfil, the result would be revolved and a cesspit would state the highest comparative value.

In Figure 5-4 the particular advantages and disadvantages of different technologies are visualized. The FOI is expressed in percent. The red line in the graph defines the user specific importance. The balloon biogas digester and the fixed dome biogas digester are equally rated in general. They only differ with regard to the estimated investment costs, which are higher for the fixed dome biogas digester.

Figure 5-4: Visualized comparison of the results for on-site storage and treatment facilities

Result

If people agree with slightly higher investment- and recurring costs, biogas digesters are environmental friendly solutions. Since balloon biogas digesters are little less expensive in construction than fixed dome biogas digesters, they are stated as the most eligible treatment technology.

5.3.3 Semi-centralized wastewater treatment

The villagers of Bhotechaur intend to clean the run-off water from the public standpipe in order to prevent groundwater contamination and to decrease the polluted matter. The solid contents of the effluent are minimal and hence, a pre-treatment technology for solid reduction is not required. The system reliability and sustainability are especially important for the technology selection.

After defining the different FOIs, the comparative values for the specific technologies within the GoP "Semi-centralized wastewater treatment" are calculated. The comparative values are outlined in descending order in Table 5-5.

Table 5-5: Comparative values for a number of semi-centralized wastewater treatment technologies

	CV*
Horizontal subsurface-flow constructed wetland	**0,709**
Vertical-flow constructed wetland	**0,660**
Horizontal surface-flow constructed wetland	0,603
Hybrid constructed wetlands	0,600
Wastewater stabilization pond	0,600
Up-flow anaerobic sludge blanket reactor	0,488

* Comparative value

Discussion

According to the pre-defined on-site conditions in Bhotechaur, horizontal subsurface-flow CWs and vertical-flow CWs seem to be the most eligible technologies. The cultural acceptance of these facilities is expected to be high and thus, the comparative values state the wetlands as most suitable solutions. Besides, the estimated expenses are moderate.

In Figure 5-5 the particular advantages and disadvantages of different technologies are visualized. The technology eligibility of horizontal- and vertical-flow CWs slightly vary within the different groups. While vertical-flow CWs are to be less expensive in the construction phase, horizontal-flow CWs are expected to be cheaper in operation. Anaerobic sludge blanket reactors are ideally equally rated to horizontal- and vertical-flow CWs and hence, cannot be realistically selected when respecting the comparative value.

Figure 5-5: Visualized comparison of the results for semi-centralized wastewater treatment facilities

Results

If the land area availability does not define a shortage, CWs seem to be the most appropriate treatment solution. Since the wetlands are expected to be cultural accepted technologies and they can be constructed and operated at low costs, they seem to be the most applicable solutions.

5.3.4 Combined technologies

Regarding the example outlined in chapter 5.2, a combination of different treatment technologies is requested. Assuming that the runoff from the standpipe contains a lot of solid particles, a CW would easily clog and fail subsequently. For that reason, the soil filter would require to be cleaned and renewed regularly in order to prevent technology deadlock. Solids need to be reduced in a previous treatment step. In this respect, the appropriate facilities therefore range from B2 to B8, listed in Table 4-15.

It is absolutely important to know about the specific treatment performances of the different technologies and how these can be combined reasonably. This requires expert knowledge and the availability of financial resource for the construction costs.

After defining the different FOIs, the comparative values for the arrangement of technologies within the GoP “Combined technologies” are calculated. Two examples for a technology combination are outlined in Table 5-6.

Table 5-6: Comparative values for a combination of technologies in series

	CV*
Anaerobic baffled reactor + Horizontal subsurface-flow constructed wetland	**0,716**
Septic tank + Vertical-flow constructed wetland	**0,695**

* Comparative value

Discussion

Despite the FOI for the investment costs are higher rated than those for the recurring costs, the combination of an ABR with a horizontal subsurface-flow CW is higher rated. By reason of high demands on the parameter cultural acceptance, the latter technology combination is expected to be more suitable. The technological differences and the composition of the comparative values are outlined in Figure 5-6.

Figure 5-6: Visualized comparison of the results for a combination of wastewater treatment facilities

Results

If slightly higher investment costs can be accepted, the solution with an ABR in combination with a horizontal subsurface-flow CW seems to be most eligible. Considering restrictions in the land area availability, however the combination of a septic tank with a vertical-flow CW may be more reasonable. Due to a multitude of variables and the minimal difference between the comparative values of the two combinations, an explicit recommendation is hardly possible.

6 Results and discussion

In order to achieve representative results, a collective determination of the FOI may be helpful. Most likely every user may define different importance to the specific factors, even when observing one and the same situation. For that reason, more than just one opinion should be respected for the technology selection process so that subjective assessments can be prevented. Nevertheless, after allocating specific importance to each factor, the most appropriate technologies examined by the calculation tool still require to be discussed on actual suitability.

As mentioned above, the results only provide a recommendation for the technology selection process. It cannot be guaranteed that the highest technology rating, in fact, states the best solution considering the specific situation on site. In the following, those facilities with the highest comparative values can be consulted as the most appropriate, whereas the lower estimations can rather be excluded from further consideration. Since deal-breaker criteria are not integrated into this calculation model, all technologies get weighted simultaneously. Due to cultural restrictions (e.g. against fecal handling or unacceptable changes in user behavior) some collection facilities are anyway unsuitable in these regions and thus, need to be ignored in further discussions. This has to be done by looking at the specific properties of one technology and cannot be carried out by this calculation tool. Nevertheless, issues like these are very well assessed within the rating but do not automatically depict a superordinate decisive factor.

Both the technology rating and the user-specific rating have inaccuracies in the evaluation. This is mainly caused by the fact that many factors are not measurable numerically and thus, a 100% objective rating is impossible. Assigning one rating factor up or down in the technology rating can hardly be argued since the constraints are fluent. For that reason, the technology evaluation factors most likely have to be compared inside one GoP to achieve reasonable disparities. Some technologies are actually rated worse or at least equal in every respect compared to other technologies. As a result, these poorly rated facilities cannot realistically get chosen in the technology selection process. Hence, it is important to discuss the results and not just appoint the technology with the highest score for implementation.

Adjustments in the rating structure of the technology rating are possible for further investigation. This includes adjustments in the rating structure as well as the insertion of additional treatment facilities in the model. However, this first requires practical proof and empirical values in order to adjust the actual assignment of rating points. Table 6-1 depicts the major advantages and disadvantages of the current calculation tool.

Table 6-1: Advantages (+) and disadvantages (-) of the methodology for technology selection

+ A uniform rating of hardly quantifiable factors is possible + The analytical procedure makes the process transparent and traceable + The data based rating contributes to a structured discussion + A numerical comparison of technologies is possible + A calibration of the system is possible + The technology rating can be adjusted and the table of technologies extended by experienced engineers	– The results only serve as a proposal and do not state a definite result – The result still require a critical discussion of experienced engineers in order to question the feasibility of the technology

7 Summary, conclusions and outlook

Summary

The first part of this thesis examines a multitude of collection and primary sanitation facilities. The selection is primarily based on technologies that require little or even no source of energy, are simple in operation, and are low cost in construction and operation. For every facility the technology research is fragmented in the subcategories dimensioning, construction, maintenance and cost consideration.

In order to achieve technology comparability a number of factors and a proper rating scale are defined. These factors are fragmented in four major groups: investment costs; pollutant reduction efficiency; environment and ecology; and recurring costs. After investigating a particular on-site situation, the planning engineer may assign different importance for each criterion. Depending on the stage of treatment a comparative value is calculated for each facility. It is important that only technologies of the same treatment level can be compared. The higher the value, the more suitable is the specific technology considering the defined boundary conditions.

Conclusion

The results can be used as basis in any decision-making process dealing with sanitary technologies in rural areas of developing countries. It is possible to picture individual treatment facilities as well as diverse combinations of several technologies arranged in series. Nevertheless, the results are to be discussed in order to identify the most suitable technology for the specific purpose. Next to the technical aspects considered, cultural habits are respected in the selection process as well. Due to the explicit rating system, the technologies can be clearly distinguished and the results are traceable for all events. In short, the tool serves as a data based concept in order to limit a multitude of treatment facilities to only a few suitable ones.

Outlook

The calculation tool is extendable and adjustable in any order. It is possible to adopt both, the rating scale and the rating points assigned for the specific factors associated with the technologies. Besides, the integration of more facilities in the model is feasible.

A practical implementation and system calibration is striking at the current stage of research. Therefore, application by experienced engineers is required and subsequently an incorporation of empirical values is needed in order to improve the calculation model. Since the subject is culturally crucial, a socio-scientific projection is recommended at this point.

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Appendix

Appendix A1

Table 8-1 shows the technology rating ranging from 1 to 5. The evaluation is based on the classification defined in chapter 4.2.1. The values are converted in a range from 0 to 1 by the formulas outlined in Table 4-3. Appendix A2shows the significant values for further calculation.

Table 8-1: Technology rating (1..5) for the particular technologies

Technology rating		Investment costs	1	Environment and ecology	2	Cultural acceptance	3	Recurring costs	4
		Construction costs	Land area occupation	Pollutent reduction efficiency	Environmental impact	Reliability	Sustainability	Operational costs	Maintenance costs
Collection and primary sanitation									
Simple pit latrines	$x_{g,f}$	1	1	2	4	4	3	1	2
Pour-flush pit latrine	$x_{g,f}$	1	1	1	4	5	3	2	2
Ventilated improved pit latrine	$x_{g,f}$	1	1	2	4	4	3	1	2
Double-vault pit latrine	$x_{g,f}$	2	1	3	4	3	3	1	2
Urine diversion dehydration toilets	$x_{g,f}$	3	1	4	1	1	3	1	1
Composting toilets	$x_{g,f}$	3	1	4	1	2	4	2	1
Urine diversion flush toilet	$x_{g,f}$	3	2	1	3	4	5	3	3
On-site storage and treatment									
Cesspit	$x_{g,f}$	2	1	1	5	5	3	1	2
Fixed dome biogas digester	$x_{g,f}$	4	2	4	2	4	4	2	2
Floating cover biogas digester	$x_{g,f}$	4	2	4	2	4	3	2	3
Balloon biogas digester	$x_{g,f}$	3	2	4	2	4	4	2	2
Septic Tank	$x_{g,f}$	3	2	2	3	5	4	2	2
Anaerobic baffled reactor	$x_{g,f}$	4	3	4	3	4	4	2	3
Anaerobic filter	$x_{g,f}$	4	2	3	3	3	3	3	3
Imhoff tank	$x_{g,f}$	5	2	2	4	4	2	3	4
Semi-centralized wastewater treatment									
Up-flow anaerobic sludge blanket reactor	$x_{g,f}$	5	2	4	3	3	1	4	4
Horizontal surface-flow constructed wetland	$x_{g,f}$	4	4	3	3	4	3	2	4
Horizontal subsurface-flow constructed wetland	$x_{g,f}$	3	3	4	2	4	3	2	3
Vertical-flow constructed wetland	$x_{g,f}$	3	2	4	2	4	2	3	3
Hybrid constructed wetlands	$x_{g,f}$	4	4	5	2	3	2	3	4
Wastewater stabilization pond	$x_{g,f}$	5	5	5	1	4	3	4	5
Greywater disposal									
Soak pit	$x_{g,f}$	2	1	2	4	4	4	2	2
Leach field	$x_{g,f}$	2	3	2	4	4	3	2	2
Evapo-transpiration bed	$x_{g,f}$	1	1	2	3	5	4	2	1
Combination of technologies									
Septic tank + Vertical-flow CW	$x_{g,f}$	3	2	4	2	4	3	3	2
Anaerobic baffled reactor + Horizontal subsurface-flow CW	$x_{g,f}$	4	3	4	2	4	4	2	3

Appendix A2

Table 8-2 shows the converted technology specific ratings. The values highlighted in green define very good technology eligibility on that score, whereas the highlights in red rather bad suitability. The table allows direct comparison of different technologies considering a specific rating factor.

Table 8-2: Converted technology ratings (0..1)

Technology rating		Investment costs 1		Environment and ecology 2		Cultural acceptance 3		Recurring costs 4	
		Construction costs	Land area occupation	Pollutent reduction efficiency	Environmental impact	Reliability	Sustainability	Operational costs	Maintenance costs
Collection and primary sanitation									
Simple pit latrines	$q_{g,f}$	1	1	0,25	0,4	0,8	0,6	1	0,8
Pour-flush pit latrine	$q_{g,f}$	1	1	0	0,4	1	0,6	0,8	0,8
Ventilated improved pit latrine	$q_{g,f}$	1	1	0,25	0,4	0,8	0,6	1	0,8
Double-vault pit latrine	$q_{g,f}$	0,8	1	0,5	0,4	0,6	0,6	1	0,8
Urine diversion dehydration toilets	$q_{g,f}$	0,6	1	0,75	1	0,2	0,6	1	1
Composting toilets	$q_{g,f}$	0,6	1	0,75	1	0,4	0,8	0,8	1
Urine diversion flush toilet	$q_{g,f}$	0,6	0,8	0	0,6	0,8	1	0,6	0,6
On-site storage and treatment									
Cesspit	$q_{g,f}$	0,8	1	0	0,2	1	0,6	1	0,8
Fixed dome biogas digester	$q_{g,f}$	0,4	0,8	0,75	0,8	0,8	0,8	0,8	0,8
Floating cover biogas digester	$q_{g,f}$	0,4	0,8	0,75	0,8	0,8	0,6	0,8	0,6
Balloon biogas digester	$q_{g,f}$	0,6	0,8	0,75	0,8	0,8	0,8	0,8	0,8
Septic Tank	$q_{g,f}$	0,6	0,8	0,25	0,6	1	0,8	0,8	0,8
Anaerobic baffled reactor	$q_{g,f}$	0,4	0,6	0,75	0,6	0,8	0,8	0,8	0,6
Anaerobic filter	$q_{g,f}$	0,4	0,8	0,5	0,6	0,6	0,6	0,6	0,6
Imhoff tank	$q_{g,f}$	0,2	0,8	0,25	0,4	0,8	0,4	0,6	0,4
Semi-centralized wastewater treatment									
Up-flow anaerobic sludge blanket reactor	$q_{g,f}$	0,2	0,8	0,75	0,6	0,6	0,2	0,4	0,4
Horizontal surface-flow constructed wetland	$q_{g,f}$	0,4	0,4	0,5	0,6	0,8	0,6	0,8	0,4
Horizontal subsurface-flow constructed wetland	$q_{g,f}$	0,6	0,6	0,75	0,8	0,8	0,6	0,8	0,6
Vertical-flow constructed wetland	$q_{g,f}$	0,6	0,8	0,75	0,8	0,8	0,4	0,6	0,6
Hybrid constructed wetlands	$q_{g,f}$	0,4	0,4	1	0,8	0,6	0,4	0,6	0,4
Wastewater stabilization pond	$q_{g,f}$	0,2	0,2	1	1	0,8	0,6	0,4	0,2
Greywater disposal									
Soak pit	$q_{g,f}$	0,8	1	0,25	0,4	0,8	0,8	0,8	0,8
Leach field	$q_{g,f}$	0,8	0,6	0,25	0,4	0,8	0,6	0,8	0,8
Evapo-transpiration bed	$q_{g,f}$	1	1	0,25	0,6	1	0,8	0,8	1
Technology combinations									
Septic tank + Vertical-flow CW	$q_{g,f}$	0,6	0,8	0,75	0,8	0,8	0,6	0,6	0,8
Anaerobic baffled reactor + Horizontal subsurface-flow CW	$q_{g,f}$	0,4	0,6	0,75	0,8	0,8	0,8	0,8	0,6

Appendix A3

Table 8-3 gives an example for a comparison of technology regarding to the inserted factors of importance. For each technology a comparative value is calculated and can hence be faced with other facilities at the same treatment level. The most eligible ratings on the specific conditions on site are highlighted in green.

Table 8-3: User-specific rating with adopted recommended factors of importance by Duncan Mara (2004)

User-specific rating		Investment costs 1		Environment and ecology 2		Cultural acceptance 3		Recurring costs 4		Comperative value for technology selection
		Construction costs	Land area occupation	Pollutent reduction efficiency	Environmental impact	Reliability	Sustainability	Operational costs	Maintenance costs	
Recommended FOI referring to Duncan Mara (2004)		5	2	4	2	5	5	5	5	
Factor of importance	**$FOI_{g,f}$**	**5**	**2**	**4**	**2**	**5**	**5**	**5**	**5**	
Group rating factor	$R_{g,total}$		0,212		0,182		0,303		0,303	
Collection and primary sanitation										
Simple pit latrines	CV		0,212		0,055		0,212		0,273	**0,752**
Pour-flush pit latrine	CV		0,212		0,024		0,242		0,242	**0,721**
Ventilated improved pit latrine	CV		0,212		0,055		0,212		0,273	**0,752**
Double-vault pit latrine	CV		0,182		0,085		0,182		0,273	**0,721**
Urine diversion dehydration toilets	CV		0,152		0,152		0,121		0,303	**0,727**
Composting toilets	CV		0,152		0,152		0,182		0,273	**0,758**
Urine diversion flush toilet	CV		0,139		0,036		0,273		0,182	**0,630**
On-site storage and treatment										
Cesspit	CV		0,182		0,012		0,242		0,273	**0,709**
Fixed dome biogas digester	CV		0,109		0,139		0,242		0,242	**0,733**
Floating cover biogas digester	CV		0,109		0,139		0,212		0,212	**0,673**
Balloon biogas digester	CV		0,139		0,139		0,242		0,242	**0,764**
Septic Tank	CV		0,139		0,067		0,273		0,242	**0,721**
Anaerobic baffled reactor	CV		0,097		0,127		0,242		0,212	**0,679**
Anaerobic filter	CV		0,109		0,097		0,182		0,182	**0,570**
Imhoff tank	CV		0,079		0,055		0,182		0,152	**0,467**
Semi-centralized wastewater treatment										
Up-flow anaerobic sludge blanket reactor	CV		0,079		0,127		0,121		0,121	**0,448**
Horizontal surface-flow constructed wetland	CV		0,085		0,097		0,212		0,182	**0,576**
Horizontal subsurface-flow constructed wetland	CV		0,127		0,139		0,212		0,212	**0,691**
Vertical-flow constructed wetland	CV		0,139		0,139		0,182		0,182	**0,642**
Hybrid constructed wetlands	CV		0,085		0,170		0,152		0,152	**0,558**
Wastewater stabilization pond	CV		0,042		0,182		0,212		0,091	**0,527**
Greywater disposal										
Soak pit	CV		0,182		0,055		0,242		0,242	**0,721**
Leach field	CV		0,158		0,055		0,212		0,242	**0,667**
Evapo-transpiration bed	CV		0,212		0,067		0,273		0,273	**0,824**
Technology combination										
Septic tank + Vertical-flow CW	CV		0,139		0,139		0,212		0,212	**0,703**
Anaerobic baffled reactor + Horizontal subsurface	CV		0,097		0,139		0,242		0,212	**0,691**