CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT AND REUSE IN NORTHERN-THAILAND

BACHELOR THESIS ENVIRONMENTAL SCIENCES

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FOREWORD

The thesis that lies before you is the result of a two months of literature research. It has been written to fulfill the graduation requirements of the major Environmental Sciences for the Bachelor Liberal Arts and Sciences at Utrecht University.

The decision to write my bachelors thesis on constructed wetlands was made quickly. Within environmental sciences my main interest is in hydrology and water management. I am especially interested how we, as scientist, can use our knowledge on these subjects to create safer living situations all across the world. The concept of constructed wetlands, and their potential for the developing world, immediately interested me. Not only because constructed wetlands are complicated systems where abiotic and biotic factors play huge roles but also because it brought the possibility to design a wetland. This, to me, is very important because the design is the utilization of knowledge that the scientific world acquired.

Looking back on the writing process of this thesis it has been an interesting, challenging experience. During this process I had support from several people that I would like to thank. First of all I would like to thank Leontien Kraaijeveld for her comments and guidance about how best to approach the research and writing process. I also want to thank my Intervision Group for their insightful comments during presentations and meeting.

I hope you enjoy your reading,

Marijke Ronduite

Utrecht, June 27, 2017

ABSTRACT

In rural, developing areas surface waters are increasingly polluted by wastewater discharge. For these areas constructed wetlands (CWs) are seen as a suitable method for wastewater treatment. However, current knowledge on implementation of CWs in developing regions is limited. This study therefore aimed to design a suitable CW for rural regions in Northern-Thailand, with an additional focus on wastewater reuse possibilities. A literature review was conducted along with k-C* model based calculations. The study showed that it is necessary to make several adaptions in CW for optimal pollutant removal in Northern-Thailand. The use of a diverse selection of macrophytes is advised. A storage unit should be used for climate adaption in the hydrology component. Additionally it is advised to use a separate soil filtration unit for optimal phosphorus removal. A hybrid CW design with sub-surface flow elements should be used for optimal pollutant removal. This study found that, based on the proposed design, agricultural reuse of the treated water is possible.

In plattelandsgebieden van ontwikkelingslanden worden oppervlaktewateren steeds meer vervuild door afvalwater lozing. Voor deze gebieden worden zuiverende moersassystemen, ofwel 'Constructed Wetlands (CWs)'*, gezien als een geschikte aanpak voor afvalwaterzuivering. Echter, momenteel is er weinig kennis over de implementatie van CWs in ontwikkelingslanden. Dit onderzoek richtte zich daarom op het ontwerpen van een geschikt CW voor de plattelandsgebieden van Noord-Thailand, met specifiek aandacht voor hergebruik van het afvalwater. Een literatuuronderzoek is uitgevoerd met daarnaast k-C* modelberekeningen. Volgens de resultaten van dit onderzoek zijn meerdere aanpassingen in CW onderdelen nodig voor implementatie in Noord-Thailand. Allereerst word geadviseerd om een diverse groep macrofyten te gebruiken. Een opslag module kan gebruikt worden zodat de hydrologie van het CW aangepast kan worden op het klimaat. Daarnaast wordt een apart bodemfiltratie element aangeraden voor optimale verwijdering van fosfor. Het gebruik van een* 'Hybrid CW' *met enkel* 'sub-surface flow´ *elementen zorgt voor optimale verwijdering van afvalstoffen. Dit onderzoek liet zien dat er, gebaseerd op het voorgestelde ontwerp, irrigatie hergebruik mogelijkheden voor het gezuiverde water zijn.*

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LIST OF ABBREVIATIONS

A	Wetland area
BOD	Biological Oxygen Demand
C*	Background concentration
C_0	Outlet Concentration
C_e	Outlet Target Concentration
C_i	Inlet Concentration
COD	Chemical Oxygen Demand
CW	Constructed Wetland
FWS	Free Water Surface Flow Constructed Wetland
HLR	Hydraulic Loading Rate
HRT	Hydraulic Retention Time
HSSF	Horizontal Subsurface Flow Constructed Wetland
k	First order areal rate constant
NH_4-N	Nitrogen present in Ammonium form
NO_3-N	Nitrogen present in nitrate form
Q	Average wastewater flow
q	Hydraulic loading rate
SSF	Subsurface Flow Constructed Wetland
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
VSSF	Vertical Subsurface Flow Constructed Wetland
RE	Removal Efficiency

INTRODUCTION

Freshwater resources are essential to human and ecosystem health. Yet, these resources are becoming increasingly scarce (Kivaisi, 2001). The decrease in quantity of freshwater resources is caused by overexploitation of existing resources (Kivaisi, 2001; United Nations, 2003). Freshwater resources are not only diminishing in quantity but also in quality due to pollution from anthropogenic influences (Prommi & Payakka, 2015; United Nations, 2003). Clean water for drinking, sanitation and irrigation will become hard to obtain if the quantity and quality of water resources are decreasing.

This is especially the case in developing countries where the limited resources are already heavily polluted (Scoccimarro et al., 1999). A major source of pollution is the discharge of untreated domestic, municipal and industrial wastewater directly into surface waters (Kivaisi, 2001; Scoccimarro et al., 1999). Poor wastewater management is the main cause for this discharge. Agriculture is also considered as an important source of pollution due to runoff of applied fertilizers (Kivaisi, 2001; Prommi & Payakka, 2015; Seeboonruang, 2012). The contamination of surface waters can cause the water to become unsuitable for human consumption, irrigation, sanitation, and recreation (Kivaisi, 2001). This is extremely problematic since in developing countries the population often depends on surface waters for these water uses, especially in rural areas (Hutton & Chase, 2016).

For public health it is important that clean, safe water is available for domestic water use, food production, and recreation (Vymazal, Greenway, Tonderski, Brix, & Mander, 2006). Currently billions of people lack safe water for sanitation purposes, especially in rural areas, leading to the spread of diseases like diarrhea and parasitic infections (Massoud, Tarhini, & Nasr, 2009). About 2200 children die daily as result of diarrheal diseases (CDC, 2016). The improvement of water resources is therefore key to better public health, and in addition for economic growth and poverty reduction (Seeboonruang, 2012; WHO Media Centre, 2016). The contamination of water resources should be avoided or remedied. One way to accomplish this is with wastewater treatment before surface water discharge.

However, conventional treatment facilities appear to be unsuitable for developing, rural areas. These facilities require large capital for installation and have high operation and maintenance costs (Massoud et al., 2009; Solano, Soriano, & Ciria, 2004). Lack of expertise for operation of the facilities is also an recurring problem, leading to inadequate operation. A decentralized approach, focused on just one village or community, is generally considered a more cost-effective and simpler approach to wastewater treatment suitable for rural regions (Solano et al., 2004).

One decentralized method for wastewater treatment is with the use of constructed wetlands (CWs). In developed countries CWs are already widely used to treat various types of wastewater (Kivaisi, 2001). Since they are low-cost and not knowledge intensive they are considered as suitable for developing countries (Kengne, Dodane, Akoa, & Koné, 2009; Kivaisi, 2001; Kouki, M'hiri, Saidi, Belaïd, & Hassen, 2009). Even though CWs have a high potential they're currently not widely adopted in developing countries (Kivaisi, 2001). One reason for this is that standard CW designs suitable to the climatic conditions in developing countries do not exist. Current knowledge on CWs is mostly focused on the conditions in the developed world (Kivaisi, 2001). In order for a CW to be effective it is essential that the design is adapted to local conditions and waste problems (Massoud et al., 2009; Stottmeister et al., 2003). To improve water quality it is thus important to determine the necessary adaptions.

One of the regions where implementation of CWs has a high potential is Thailand. In this country most rivers are polluted by municipal and industrial wastewater and agricultural run-off (Chitmanat & Traichaiyaporn, 2010; Prommi & Payakka, 2015; PCD, 2004). In the rural Northern parts of the country this is problematic since villagers in these parts often use surface waters for irrigation, household, and sanitation purposes (Neef et al., 2007). The use of polluted surface water for these purposes could have detrimental health effects, due to the spread of aforementioned diseases. Treatment of wastewater with CWs before surface water discharge could help improve this situation (Kivaisi, 2001). Designing CWs focused on providing water for household purposes could perhaps even reduce health risks associated with using surface waters. Currently there has been limited research into household reuse applicability of CW treated water.

Implementation of CWs in Northern-Thailand might be an important instrument in solving water problems in the region. This research will try to determine to what extent CWs can be implemented Northern-Thailand. The aim of this research is to propose an appropriate CW for the region that brings the possibility for wastewater reuse. The following research question will be used:

> *"To what extent is the use of a constructed wetland system a viable option for the treatment and reuse of water in Northern Thailand?"*

The research can be divided into several sections. The first section is the theoretical background, in this chapter the necessary context and background information to the subject is given. The subsequent section presents the methodology. The aim of the next section, the results, is to achieve four goals. The first goal is to clarify which adaption to CWs need to be made for local conditions. Secondly, the removal efficiency of CWs needs to be determined. The third goal is to give a CW design suitable for Northern-Thailand. The final goal is determine wastewater reuse possibilities. Combined these four goals will be bring the answer to the research question. The paper ends with a short discussion and conclusion.

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CHAPTER 1: THEORETICAL BACKGROUND

In this chapter some key concepts and background information on CWs is discussed.

1.1 TYPES OF CONSTRUCTED WETLANDS

The concept with the central role throughout this research is *constructed wetlands*. These are intentionally created wetlands with water treatment as their main purpose (Brix, 1994b). CWs are designed for the express purposes of utilizing the natural processes within a wetland (Vymazal et al., 2006; Vymazal & Kröpfelová, 2008). Since CWs are engineered systems they bring a controlled environment (Vymazal, 2014). In this controlled environment adaptions can be made to suit the need of the user.

Based on the flow regime and vegetation CWs can be classified into different types (Vymazal & Kröpfelová, 2008). Figure 1 shows a common classification for CWs. The two most common systems are free water surface flow (FWS) and horizontal sub-surface flow (HSSF), although the vertical sub-surface system (VSSF) is gaining popularity (Vymazal et al., 2006). Among the different types there is a difference in removal efficiency for various pollutants. Since wastewater consists of a wide range of pollutants they are often difficult to treat in a single system (Vymazal et al., 2006; Vymazal & Kröpfelová, 2008). Several types of CWs can therefore be combined into a hybrid system. A hybrid system consists of various types of CWs arranged in series to optimize the pollutant removal (Vymazal et al., 2006).

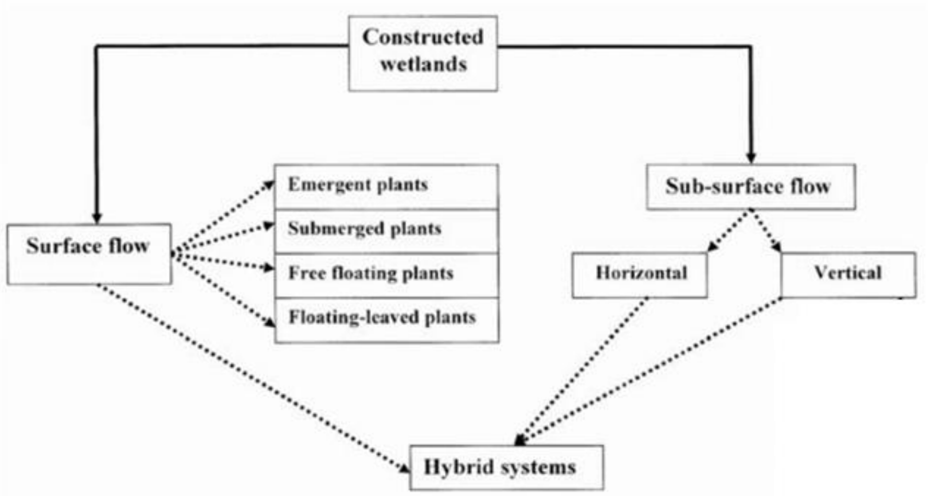

Figure 1: Classification of constructed wetlands for wastewater treatment (Adapted from Vymazal & Kröpfelová, 2008). The solid lines represent the primary division. The dashed lines represent further division based on the two main types of constructed wetlands. Surface flow wetlands can be further subdivided based on used vegetation type. Sub-surface systems are further subdivided according to flow direction.

Figure 2 shows examples of CW systems. FWS systems are characterized by aerobic processes and HSSF systems by anaerobic processes since the soils are waterlogged (Stottmeister et al., 2003). VSSF systems have intermittent wetting and drying, causing the occurrence of anaerobic and aerobic processes.

CWs have three main components: the hydrology of the system, macrophytes, and substrate (Verhoeven & Meuleman, 1999; Vymazal et al., 2006). These components influence the physical, chemical, and biological processes that take place to remove pollutants. Within these components several adaptions can be made to influence pollutant removal. For example the use of different types of substrate.

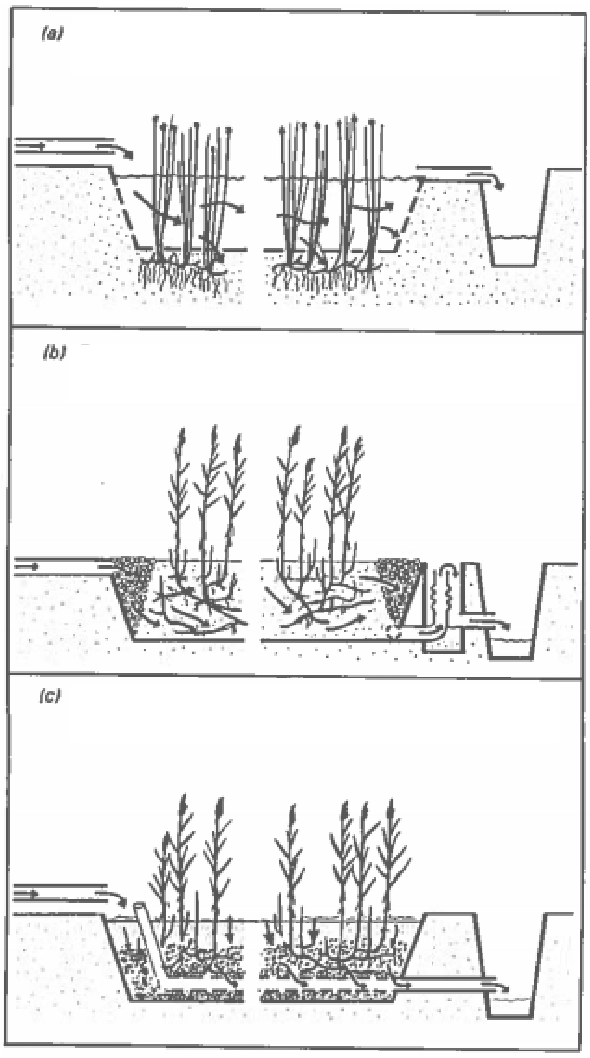

Figure 2: Examples of different constructed wetland systems. a = Free Water Surface System, b = Horizontal Sub-Surface Flow System, and c = Vertical Sub-Surface Flow System (Brix, 1993). The arrows show the general direction of flow.

1.2 PRIMARY POLLUTANTS

CWs have mostly been used to treat domestic wastewater (Vymazal et al., 2006). This is wastewater produced by household activities, like sewage from the kitchen, bathroom, and toilet. Wastewater contains many different pollutants. These pollutants include biodegradable organic matter, inorganic and organic chemicals, toxic substances, nutrients and disease-causing agents (Kouki et al., 2009; Morari & Giardini, 2009). CW's have been proven to reduce or remove these contaminants (Kivaisi, 2001; Kouki et al., 2009; Morari & Giardini, 2009; Verhoeven & Meuleman, 1999). Six parameters are most commonly used to measure wastewater quality, accordingly these will be used as guideline for the removal performance of CWs. The parameters and their removal processes can be found in Table 1.

Table 1: Primary Pollutants in wastewater and associated removal processes.

Pollutant	Description	Unit	Removal Mechanism			Reference
			Physical	Chemical	Biological	
Chemical Oxygen Demand (COD)	Measurement of organic matter. The value gives the mass of oxygen needed to chemically breakdown an amount of organic matter.	mg/L	Sedimentation[1]		Mineralization[2]	Environmental Leverage, 2003; Vymazal et al., 2006
Biological Oxygen Demand (BOD)	Amount of organic matter that is biodegradable. It gives the amount of oxygen needed by biological organisms to break down organic matter	mg/L	Sedimentation		Microbial degradation (aerobic & anaerobic)[3]; Assimilation[4]	Brix, 1993; Kadlec & Knight, 1996; Environmental Leverage,2003
Total Suspended Solid (TSS)	Amount of suspended solids in the water. It consist of many different types of particles and is therefore difficult to define exactly.	mg/L	Sedimentation			Brix, 1993 ; Kadlec & Knight, 1996
Total Nitrogen (TN)	The combined amount of organic nitrogen, ammonia (NH_3) and ammonium (NH_4^+).	mg/L		Ammonia volatilization[5]	Microbial processes (ammonification, denitrification); Assimilation	Brix, 1993; Johnston, 1993; Vymazal, 2007
Total Phosphorus (TP)	Total amount of phosphorus in the water.	mg/L	Sedimentation; Adsorption[6]	Precipitation[7]	Assimilation	Brix, 1993; Davies & Cottingham, 1993
Total Pathogens	Total amount of bacteria in a certain amount of water	CFU/100 mL	Sedimentation; Adsorption	Oxidative damage[8]; UV radiation[9]	Natural die-off; Consumption by microorganisms	Brix, 1993; Stottmeister et al., 2003

1: Sedimentation is the process where particles in suspension in water settle out of suspension under the effect of gravity (Collin, 2010).
2: The breakdown of organic waste into inorganic chemical components (Collin, 2010). See Section 1.3 for further explanation.
3: Decomposition of chemical compound into its elements as done by microbes (Collin, 2010).
4: The uptake of substances from food into the body's tissue, done by microorganisms, plants and animals (Collin, 2010).
5: The process whereby ammonia in hydroxyl form becomes volatile, i.e. in gaseous state (Vymazal, 2007).
6: The adhesion of a gas or liquid to the solid surface it touches (Collin, 2010).
7: The formation of solid particulates in a solution (Collin, 2010).
8: Since bacteria, enteric in particular, are facultative or obligate anaerobes the presence of oxygen creates unfavorable conditions for these organisms (Vymazal, 2005b).
9: UV radiation indirectly (photo-oxidative damage) and directly (photo-biological damage) damages pathogens (Maiga, von Sperling, & Mihelcic, 2017).

1.3 MICROBIAL PROCESSES IN CWS

The main role in the removal of pollutants is played by the diverse community of microorganisms (Sipaúba-Tavares & de Souza Braga, 2008; Stottmeister et al., 2003). Specifically for organic matter and nitrogen removal microorganisms are considered essential (Truu, Juhanson, & Truu, 2009; Vymazal, 2007; Kadlec & Knight, 1996).

The reduction of organic matter occurs through microbial metabolism (Hsu et al., 2011; Sipaúba-Tavares & de Souza Braga, 2008; Weerakoon et al., 2016). This degradation can occur aerobically or anaerobically, of which aerobic degradation is more efficient. Generic aerobic respiration works according to the following reaction (Kadlec & Knight, 1996):

$$BOD + O_2 \xrightarrow{bacteria} CO_2 + H_2O$$

This can be considered the dominant reaction for BOD reduction. CWs with higher oxygen availability can be expected to have a higher removal efficiency for BOD (Weerakoon et al., 2016).

The biogeochemical cycle of nitrogen in a wetland is shown in Figure 3. Most of these processes require microbial transformations. The most important removal process is denitrification, this is a permanent sink that accounts for 60-95% of the nitrogen removal in CWs (Lin, Jing, Wang, & Lee, 2002; Lund, Horne, & Williams, 2000; Sipaúba-Tavares & de Souza Braga, 2008; Spieles & Mitsch, 2000). For denitrification to occur nitrate (NO_3^-) needs to be available first. Nitrification is defined as the biological oxidation of ammonium (NH_4^+) to nitrate, with nitrite (NO_2^-) as the intermediate (Vymazal, 2007). The first step of this oxidation, ammonium to nitrate, is done by strictly aerobic bacteria. It can thus only take place under oxic conditions. The removal of ammonium is therefore more efficient in a VSSF, where aeration allows for high oxygen availability (Adyel, Oldham, & Hipsey, 2016; Luederitz, Eckert, Lange-Weber, Lange, & Gersberg, 2001; Vymazal, 2007). The subsequent process for nitrogen removal, denitrification, occurs only under anaerobic conditions (Lin et al., 2002; Stottmeister et al., 2003; Vymazal, 2007). The reaction is irreversible. Denitrification occurs in waterlogged soils, accordingly FWS but especially HSSF CWs are most successful in denitrification (Adyel et al., 2016; Luederitz et al., 2001; Stottmeister et al., 2003).

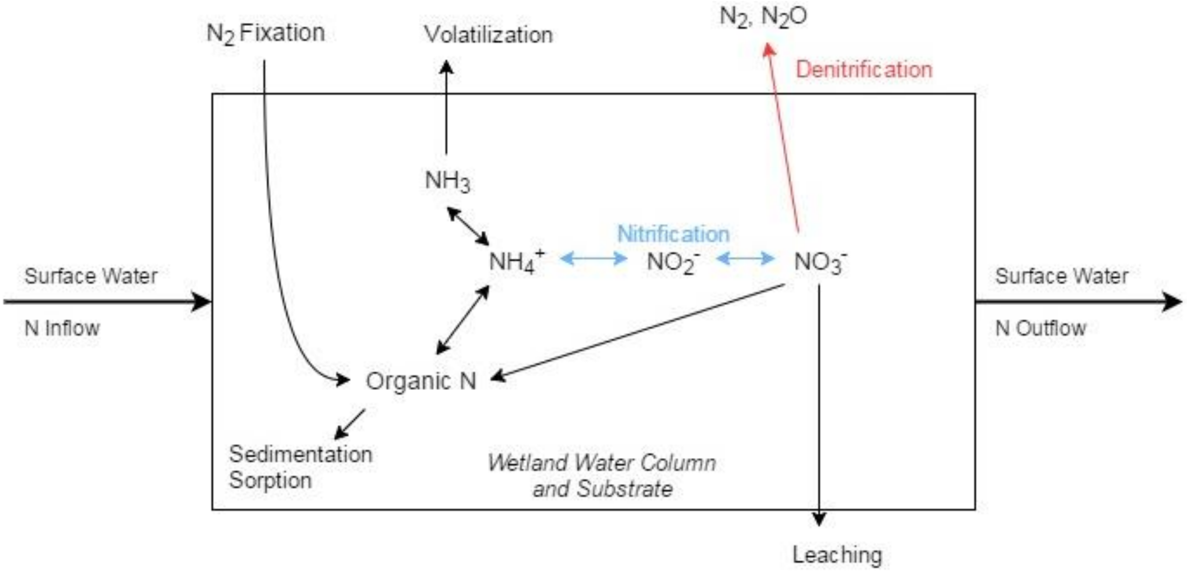

Figure 3: Model of the biogeochemical Nitrogen-cycle in wetland environments (Adapted from Spieles & Mitsch, 2000). Blue arrows represent aerobic nitrification occurs. The red arrow represents anaerobic denitrification. As can be seen the processes of ammonia (NH_3) volatilization, Nitrate (NO_3^-) leaching, and denitrification remove nitrogen from the wetland system. The processes of Organic N sorption and sedimentation lead to nitrogen removal from the water column but the nitrogen remains in the wetland system.

1.4. VIABILITY

The goal of this research is to see if CWs can be considered *viable* for rural communities in Northern-Thailand. Although multiple factors can be considered for viability this research focusses on the factor of sustainability. This factor is important in order to preserve resources in the long-term. Not only current communities but also future communities need to benefit from CW implementation.

In the context of resource management sustainability points towards design of systems that do not lead to diminished quality of life due to either losses in economic opportunity or adverse impacts on social conditions, human health, and the environment (Mihelcic et al., 2003). Three dimensions are of importance for sustainable resource management: economic, social-cultural, and environmental (Balkema, Preisig, Otterpohl, & Lambert, 2002; Massoud et al., 2009). The relation between the dimensions is presented in Figure 4. There are a multitude of different parameters that can be considered for each dimension. For the scope of this research the focus will be on three parameters from the environmental dimension that are generally considered for wastewater treatment systems (Balkema et al., 2002; Massoud et al., 2009; Muga & Mihelcic, 2008).

The first parameter is climatic conditions in Northern-Thailand. This region has a 'Tropical Savannah Climate' according to the *Köppen-Geiger climate classification* (Peel, Finlayson, & McMahon, 2007). This type of climate has noticeable wet and dry periods. The second parameter is pollutant removal. Both of these parameters are considered by looking at how CWs should be adapted for optimal pollutant removal. The last aspect considered is reuse of the treated water, which has mostly been focused on irrigation reuse in literature (Kivaisi, 2001; Morari & Giardini, 2009). For this research household reuse possibilities are also considered.

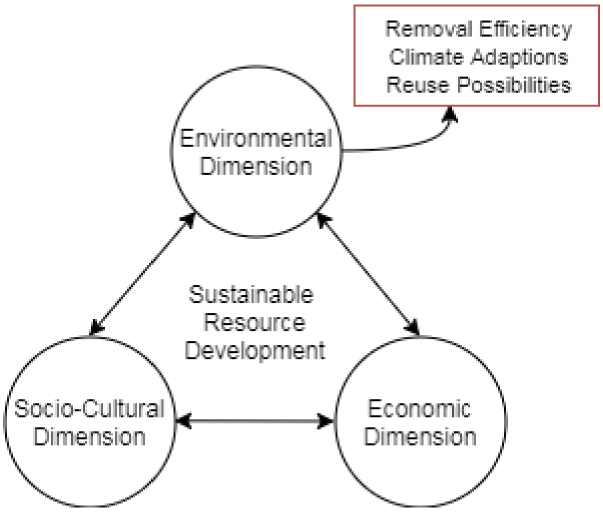

Figure 4: Dimensions associated with Sustainable Resource Management (Adapted from Balkema et al., 2002 and Massoud et al., 2009).

1.5 CONCEPTUAL MODEL

Based on the information discussed in this chapter a conceptual model was created, which is presented in Figure 5.

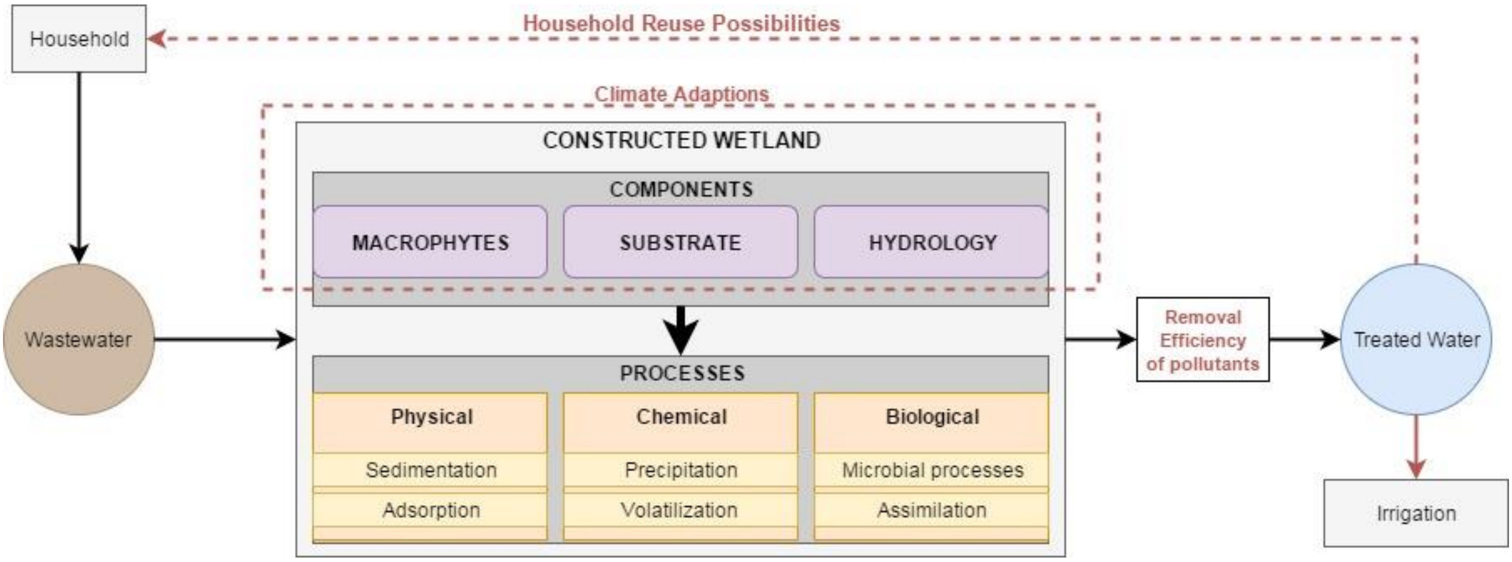

Figure 5: Conceptual Model of a Constructed Wetland. Dashed lines represent relations that are largely unknown in current literature. The lines and text in red represent the focus of this research.. Namely, how the different components need to be adapted to the climate, the removal efficiency of a constructed wetland, and lastly the reuse possibilities of treated water for irrigation or household purposes.

CHAPTER 2: METHODS

To answer the research question a literature review was undertaken. First information about the role the three CW components play in pollutant removal was collected. Information on the necessary adaptions to the local condition in Northern-Thailand was also gathered.

Furthermore a quantitative data collection was created. This data collection consists of data on the removal efficiency and other parameters of CWs in tropical regions (see appendix). The collection was based mostly on two sources. The first is a recent research done by Zhang et al. (2014). This research was done to determine the efficiency of different types of CWs in tropical regions. The second research was done by Vymazal (2013). This research collected data about hybrid CWs published after 2003. From this research only the tropical hybrid CWs were selected and included in the data collection.

Data on removal efficiencies in CWs are often not directly comparable due to multiple known and unknown factors playing a role. The comparison approach is however justified by the fact that it is often applied in literature to determine the success of CWs, for example Kadlec and Knight (1996) and Vymazal (2005a; 2013). Based on the data collection the removal efficiency of different types of CW could be determined. In this way the data can show the optimal CW type for pollutant removal.

Based on the determined necessary adaptions in the CW components and removal efficiencies a CW design optimized for the Thai conditions will be proposed. In order to subsequently determine the reuse possibilities of the treated water from the proposed design two calculations will be done. Firstly a preliminary size of the CW will be determined using the following formula, also known as the k-C* model:

$$A = \left(\frac{0.0365 \cdot Q}{k}\right) \cdot ln\left(\frac{C_i - C^*}{C_e - C^*}\right)$$

The units and derivation of the formula can be found in the appendix. This model is used since it is currently considered the best available design tool for CWs (Rousseau, Vanrolleghem, & De Pauw, 2004). Accordingly it is often used in literature (Kumar & Zhao, 2011; Noorvee, Repp, Mander, & Elar, 2005). The k-C* model is a first order rate model and can be considered a black box model since it does not describe internal processes (Kumar & Zhao, 2011).

Based on the area calculations possible effluent concentrations will be determined using the following formula:

$$C_0 = C^* + (C_i - C^*) \cdot e^{\left(-\frac{k \cdot A}{0.0365 \cdot Q}\right)}$$

The units and derivation of this formula can be found in the appendix. The found effluent concentrations can be compared to guidelines to see if there are reuse possibilities. The guidelines used for reuse possibilities are presented in the appendix. It should be mentioned that the target effluent concentrations, i.e. the guidelines, are used in the formula to determine area. The CW is thus designed to fit with at least one of the guidelines.

CHAPTER 3: COMPONENTS

This chapter discussed the influence of CW components on removal processes and design implication for a CW in Northern-Thailand.

3.1 MACROPHYTES

Vegetation in CWs consist mostly of macrophytes, these are large aquatic plants that have made morphological adaptions to sustain oxygen deficits. (Rehman, Pervez, Khattak, & Ahmad, 2017). Macrophytes help with the reduction of pollutants in multiple ways. The presence of plants increases filtration effects and reduces water velocity, causing solids to settle out on the substrate (Brisson & Chazarenc, 2009; Brix, 1994a; Rehman et al., 2017). Rooting of macrophytes in the sediment helps prevent erosion (Brix & Schierup, 1989; Brix, 1994a; Rehman et al., 2017). The hydraulic quality of soils is also affected by rooting (Rehman et al., 2017; Stottmeister et al., 2003). Both degradation of dead roots and the growth of new roots create new secondary pores, which increases the ease of water flow.

Plants also assimilate nutrients for their growth (Stottmeister et al., 2003). Unless biomass is harvested this uptake forms a temporary storage. In tropical regions harvesting could have significant effects on pollutant removal since it can be done multiple times a year (Vymazal, 2011). The presence of plants also helps sustain the microorganism community.

3.1.1 SUSTAINING MICROORGANISMS

Sustaining microorganism can be considered the most important role of macrophytes (Brix, 1994a). By supporting microorganism macrophytes play a huge role in the removal of nutrients and organic matter. Macrophytes sustain microorganisms by providing a habitat in the form of surface area for microbial growth (Brisson & Chazarenc, 2009; Gagnon, Chazarenc, Comeau, & Brisson, 2007; Rehman et al., 2017). However, most crucially the plant rhizosphere, i.e. root zone, stimulates microbial processes (Gagnon et al., 2007).

Since plants need to survive in waterlogged soils they have made anatomical adaptions to provide their roots with oxygen from the atmosphere. For example by diffusion of gasses through their roots (Stottmeister et al., 2003). They do not only use this oxygen for respiration but also release some in the rhizosphere, causing the formation of an oxidative protective film on roots (Rehman et al., 2017; Stottmeister et al., 2003). In this oxidative area the microbial degradation of nutrients and organic matter is enhanced (Brix, 1994a; Gagnon et al., 2007; Maltais-Landry, Maranger, & Brisson, 2009; Rehman et al., 2017). Oxidative damage on pathogens also increases (Weber & Legge, 2008).

Furthermore macrophytes act as carbon source for microbial metabolism (Gagnon et al., 2007; Stottmeister et al., 2003). Carbon is necessary as energy source for microbial transformations (Lin et al., 2002; Vymazal, 2007). For a nearly complete nitrogen removal a critical C:N ratio of 5:1 needs to be reached. Since planted wetlands generally exhibit greater nitrogen removal it is suggested that plants bring enough carbon for the critical ratio to be reached (Lin et al., 2002). However, this plant release of carbon is probably only significant if the carbon load in the wastewater is low (Stottmeister et al., 2003).

3.1.2 PLANT SPECIES

There is a great diversity in macrophyte species used in CWs. A study by Brisson and Chazarenc (2009) found 51 different species across 25 research papers. They concluded that an overall ranking in performance by species was not possible. Even with the most common species the relative performance seemed highly depended on other variables, like pollutants, design, and type of wastewater. The two most common species used were *Phragmites australis* and *Typha latifolia,* but even between these two species the relative efficiencies differed per study. For Northern-Thailand an optimal species is thus not likely to be pinpointed. However, there are some species that are commonly used under tropical conditions, as presented in Table 2.

Table 2: Macrophyte species suitable for tropical regions

Species	Common Name	Remarks	Source
***Typha* spp.**	Cattails	Perennial; More resistant to warm climates than Phragmites ssp.; Extensive horizontal rhizome system; up to 3m high; productive species; aggressive; susceptible to predation by worms and insects	Hoffmann et al., 2011; Tanaka & Weragoda, 2011; Vymazal, 2011
- *latifolia*		Cosmopolitan (except Africa)	
- *orientalis*		Found between East Asia (China, Japan) and Australia	
- *angustifolia*		Considered as suitable for tropic regions, although sometimes replaced by *domingensis.*	
***Phragmites* spp.**	Common Reed	Perennial; Highly aggressive; Extensive rhizome system; Widespread species	Hoffmann et al., 2011; Tanaka & Weragoda, 2011; Vymazal, 2011
- *australis*		Most used	
- *karka*		Used in India and Nepal	
***Scirpus (Schoenoplectus)* spp.**	Bulrush	Perennial; Grows in colonies; up to 3m tall; Roots can penetrate up to 70-80 cm deep	Tanaka & Weragoda, 2011; Vymazal, 2011
- *lacustris*			
- *grossus*			
***Cyperus* spp.**	Sedge		Hoffmann et al., 2011; Tanaka & Weragoda, 2011; Vymazal, 2011
- *papyrus*		Decorative; Limited rooting; 3m high	
- *flabelliformis*		Successfully applied in Thailand	
Canna	Canna lily	-	Konnerup, Koottatep, & Brix, 2009
Heliconia	Lobster-claws	-	Konnerup et al. 2009

For a developing country it might be best to use locally available plants, this is more cost efficient and makes use of plants that are adapted to the local conditions (DuPoldt et al., 2000; Hoffmann et al., 2011; UN-HABITAT, 2008). Plants that stimulate microbial communities optimally by efficient oxygen transport and maximum surface area are also more preferable (UN-HABITAT, 2008).

The species might be considered as of lesser importance compared to species density (DuPoldt et al., 2000). Dense vegetation optimally stimulates pollutant removal. Additionally high species richness has been found to have a positive effect on pollutant removal (Means, Ahn, & Noe, 2017; Engelhardt & Ritchie, 2001). A more diverse group of macrophytes enhances nutrient cycling, increases productivity and carbon storage, and improves the protection of the wetland from disturbances. For the implementation of a CW in Thailand it is therefore advised to choose a combination of different locally available species.

3.2 HYDROLOGY

The hydrological regime is responsible for the transport of the pollutants through the CW system (Fennessy, Cronk, & Mitsch, 1994). The hydraulic loading rate (HLR), and the associated hydraulic retention time (HRT), can be considered as the main hydrological variables (Fennessy et al., 1994; Spieles & Mitsch, 2000; Wu et al., 2015). HLR is the amount of water going into the system and HRT is the period of time the water stays within the system.

The HLR determines the speed with which the pollutants in the water go through the system (Adyel et al., 2016; Trang et al., 2010; Weerakoon et al., 2016). This influences the contact time the pollutants have with the different CW elements. Generally a lower HLR brings optimum removal of pollutants (Sehar et al., 2015; Weerakoon et al., 2016). Especially the removal of nutrients from wastewater is affected by HLR (Trang et al., 2010). Longer HRT times would cause all forms of nitrogen and phosphorus to be removed more efficiently (Lu, Huang, Liu, Shang, & Liu, 2015; Sipaúba-Tavares & de Souza Braga, 2008; Weerakoon et al., 2016).

That optimal nitrogen removal requires longer HRT is reasonably accepted within the scientific field, however for other pollutants this is less so. The removal efficiency of BOD and COD have been considered as lower with higher HLR, due to less contact time between the wastewater and the CW (Weerakoon et al., 2016). TSS removal efficiency is also lower due to higher HLR, since the physical processes of sedimentation and filtration are hindered. However, from research by Trang et al. (2010) it became apparent that TSS, BOD, and COD are still removed efficiently until really high values of HLR are reached. Accordingly extremely high HLR should be avoided.

The HLR is dependent on multiple factors of which climate is an important one (Lu et al., 2015). During rainy conditions the nutrients in the wastewater become diluted due to the influx of water, which can have an positive effect on removal (Travaini-Lima, Milstein, & Sipaúba-Tavares, 2016). TSS and BOD concentrations however increase due to increased surface run-off. Due to the influx of water into the system the HLR increases as well, this lessens the time that removal processes can take place. Overall removal efficiency is considered lower during periods of high precipitation.

During dry periods there is a low current, which causes natural sedimentation and increases the HRT (Sipaúba-Tavares & de Souza Braga, 2008; Travaini-Lima et al., 2016). CWs are generally considered more efficient during dry periods. Although extremely dry periods are regarded as troublesome since very low HLR limits the extent of possible removal reactions (Adyel et al., 2016). For CWs it could be considered optimal to limit water input during high precipitation, by for example storage, and use the stored water during periods of extreme drought (Adyel et al., 2016; Sipaúba-Tavares & de Souza Braga, 2008). For Northern-Thailand this approach is advised.

3.3 SUBSTRATE

The substrate in CWs consists of the materials filling the wetland and the soil. The soil matrix has decisive influences on hydraulic processes (Lu et al., 2015; Stottmeister et al., 2003). The hydraulic state of the soil influences the flow of wastewater through the CW and in turn the removal of pollutants (Stottmeister et al., 2003). Poor hydraulic conductivity can result in clogging of the system, which causes overflow and short circuiting (Brix, Arias, & Del Bubba, 2001; Wu et al., 2015). A permeable soil allows water flow and can store nutrients (Sipaúba-Tavares & de Souza Braga, 2008). Grain size distribution is a main factor deciding hydraulic conductivity and therefore a main parameter when selecting substrate (Stottmeister et al., 2003). The optimal grain size can be found in Figure 6.

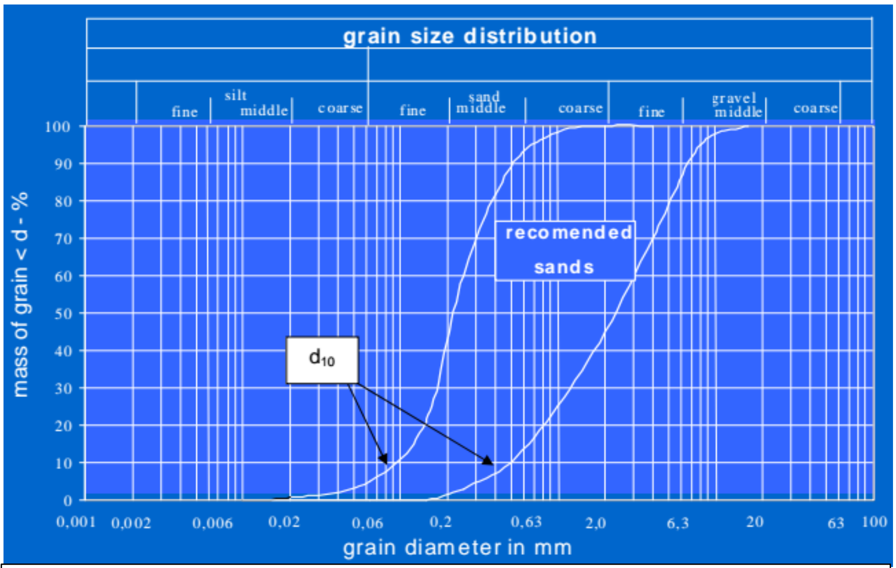

Figure 6: Recommended grain size distribution for the substrates in constructed wetlands (Hoffman et al., 2011). The d10 represents the grain size where 10% of grains are smaller than that grain size. Optimally the d10 should be between 0,1 mm and 0,4 mm.

A considerable role of substrate is in the removal of phosphorus. The processes of adsorption and precipitation are essential for the removal of phosphorus (Hill, Duxbury, Geohring, & Peck, 2000; Westholm, 2006). Adsorption of phosphorus can be considered as the main sink of phosphorus in the long term (Sakadevan & Bavor, 1998; Tang, Huang, & Scholz, 2009). The adsorption is controlled by the redox potential, pH, and the occurrence of iron, aluminum, organic matter or clay in the substrate (Drizo, Frost, Grace, & Smith, 1999; Kurniadie, 2011; Sakadevan & Bavor, 1998; Vohla, Koiv, Bavor, Chazarenc, & Mander, 2011). The effectiveness of a substrate to remove phosphorus is a function of water-substrate contact (Westholm, 2006). More contact means an higher adsorption potential. Important parameters are thus porosity, particle size distribution, and specific surface area (Drizo et al., 1999; Ren, Zhang, Liu, & Wang, 2007; Vohla et al., 2011). Fine grained soils have large surface area, enhancing phosphorus adsorption (Drizo et al., 1999). However, they also have lower hydraulic conductivity.

Phosphorus adsorption and precipitation is a finite process (Adyel et al., 2016; Drizo et al., 1999; Westholm, 2006). In time the sites on which phosphorus adsorbs or precipitates become saturated and unavailable. Generally CW substrates have a life cycle of 2-5 years before they become saturated with phosphorus (Drizo et al., 1999; Hill et al., 2000; Vohla et al., 2011). The soil then needs to be replaced in order for phosphorus removal to occur in the system.

3.3.1 SUBSTRATE SELECTION

A single best substrate has not been identified since it is hard to compare and generalize data from different CWs and substrates (Ren et al., 2007; Vohla et al., 2011). Each CW has very different circumstances. For developing countries it is therefore advised to use suitable, locally available and relatively cheap materials (Drizo et al., 1999). By using a pretreatment unit solids can be preliminary removed from the wastewater, this prevents clogging in the substrate (Vohla et al., 2011). Finer materials can then be used in the CW.

Since the substrate becomes saturated, limiting phosphorus removal, it is advised to use a separate soil filtration unit with easily replaceable materials (Vohla et al., 2011). This unit could be filled with soils optimized for phosphorus removal, like shales and zeolites. Shales, due to their small particles size, have a high adsorptive capacity (Drizo et al., 1999; Hill et al., 2000; Tang et al., 2009). Zeolites have a good oxygen environment which is preferable for microorganisms (Lu et al., 2015).

CHAPTER 4: DESIGN

In this chapter a design for a CW in Thailand will be proposed together with an analysis of reuse possibilities for water retrieved from this system.

4.1 ELEMENTS

A short summary of the removal efficiency of CWs in tropical regions is given in Table 3. Based on the data collected it is apparent that a hybrid system is the most successful in overall pollutant removal since the removal efficiencies for all pollutants are higher with hybrid systems than the other systems. In Northern-Thailand a hybrid system should therefore be implemented. The hybrid system can consist of one or multiple SSF or FWS elements.

However, the stagnant water of FWS elements are considered breeding spots for mosquitos (Rousseau, Lesage, Story, Vanrolleghem, & De Pauw, 2008). SSF systems limit mosquito breeding due to belowground water flow. The use of only these elements is therefore encouraged. Additionally it is recommended to combine both horizontal and vertical SSF elements, since these are more appropriate for denitrification and nitrification respectively.

Table 3: Removal Efficiency of constructed wetlands in tropical regions. Based on data collection.

CW Type	Removal Efficiency (%)								n
	COD	BOD	TSS	TN	NH_4-N	NO_3-N	TP	Pathogens	
FWS	73,93	77,01	79,22	59,93	40,73	75,25	43,08	26,78	27
HSSF	72,19	70,67	83,61	50,03	62,57	42,46	69,75	99,9	21
VSSF	65,41	85,91	77,55	54,99	71,75	60,10	65,70	3,02	15
Hybrid	82,05	81,80	85,71	62,18	71,22	80,76	52,53	99	35

4.2 CW DESIGN

Based on the information given in Chapter 3 and the removal efficiencies of CW elements a CW design has been created, as presented in Figure 7. For this design a preliminary size was calculated. The calculations show that the two VSSF elements should encompass a total area of 2101 m^2 and the HSSF element should encompass 132 m^2. Peripherals, like dikes and buffers, will occupy about 25% of a CW (Kadlec & Knight, 1996). This means a total area of 2745 m^2 will be necessary for this CW design.

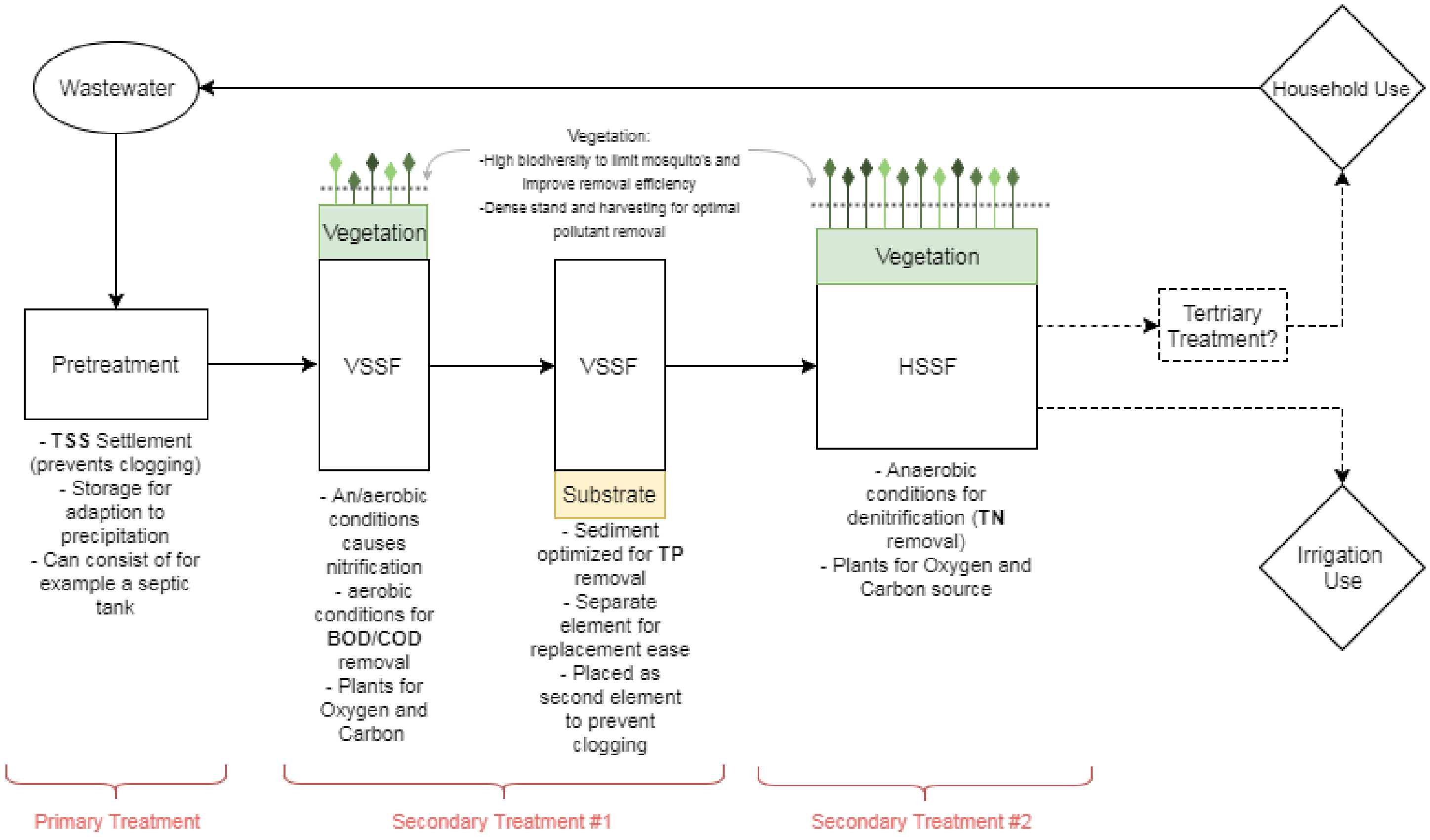

Figure 7: Proposed constructed wetland design for Northern-Thailand. The reasoning behind the addition of elements is stated in the figure. Dashed lines represent uncertain relations that will be determined in section 4.3. Only the two secondary treatment elements are considered as the constructed wetland.

4.3. REUSE

By using the calculated area for the CW elements effluent values were calculated, these and three guidelines can be found in Table 4. From the table it can be deduced that the Thai Guidelines for 'Class 2' and the EPA guidelines for 'Processed Food Crops' can be reached. The treated water can thus likely be used for irrigation of crops that will not be eaten raw. For household reuse and food crop irrigation the pathogen concentration remains problematic. For both these uses pathogen concentration needs to be not detectable. A tertiary treatment unit for disinfection, e.g. chlorination, might make household reuse possible but this requires more technological advanced systems (EPA, 1999).

Table 4: Effluent Concentrations and Water Quality Guidelines

Pollutant	Effluent Concentration Based on Design	Thai Guidelines Class 2*	EPA Guidelines Food Crops**	EPA Guidelines Processed Food crops**
BOD	1,5 mg/L	1,5 mg/L	≤10 mg/L	≤30 mg/L
TSS	8,53 mg/L	Not given	-	≤30 mg/L
TN	2,27 mg/L	5,5 mg/L	-	-
TP	0,87 mg/L	Not given	Not given	Not given
Pathogens	10 CFU/100mL	6 MPU/100 mL	Not detectable	≤30 CFU/100mL

*: Class 2 Water represent very clean fresh surface water that can be used for consumption after ordinary water treatment process, recreation, agriculture, conservation of aquatic organisms, and fisheries. Further information on the Thai classification system can be found in the appendix.

**: Food crops can be eaten without cooking whereas processed food crops require cooking before consumption.

DISCUSSION

This research took a focus on designing a CW for rural, tropical regions of Northern-Thailand, this was done based on an overview of the influences of different CW components on removal efficiency. In taking this focus the research can help in addressing current limitations and give possible directions for future research.

Current literature has mainly focused on CWs for developed regions. For North-America and Europe extensive guidelines for the implementation of CWs already exist, e.g. Davis (1995) and Tousignant et al. (1999). Formulation of similar guidelines for developing regions could facilitate easier implementation of CWs. However, this research showed that there is still much uncertainty for the formulation of exact design criteria, for example the best suitable macrophyte. Further research to specify adaptions is therefore advised. Since the thesis could formulate limited concrete design criteria the proposed design should be taken as imperative for further research rather than as guideline for implementation.

This research is in accordance with similar research on the agricultural reuse possibilities of the treated water (Kivaisi, 2001; Morari & Giardini, 2009). For the improvement of sustainable resource management it might be interesting to focus future research on how CW systems, in developing countries, could achieve human reuse guidelines by for example optimizing simple tertiary treatment units for pathogenic destruction.

This thesis focused on just five pollutants. This decision is supported by the fact that these five are considered the most important wastewater pollutants. However, other pollutants like trace metals, pesticides, organic carbons, and hygiene products can also occur in wastewater (Kadlec & Knight, 1994). It is important to determine which pollutants are present in site specific wastewater to adapt CW components accordingly for optimal pollutant removal. *Typhia spp.* are, for example, efficient at oil and grease removal (Haberl et al., 2003).

Several biological, ecological, physical, chemical processes have not been considered due to time limitations. Examples of these processes are plant competition, microorganism species, predation, the effects of slopes, and the effect of the pH and temperature on removal processes. The exact effect of precipitation on dilution factors have also not been considered. Before actual implementation of a CW these processes should be taken into account to prevent unknown effects caused by these processes to influence CW operation.

This research has not considered several site specific factors that are important for successful implementation. These are natural factors like geography, topography, and CW shape. Social factors like organization within society and social stability (Balkema et al., 2002). And Technical aspects like water containment and transport. All these different factors, and more, should be taken into account in order to formulate a proper design for a specific site. This is necessary since CWs that have not been properly designed, or constructed, generally show bad performance (Haberl et al., 2003).

Not only the effect of site specific factors on the CW but also the large scale effects of CWs in the landscape should be taken into account. The redirection of water could have unknown impacts on the water basin. CWs bring an influx of wetland birds, reptiles, and mammals (Kadlec & Knight, 1996), this could perhaps have an impact on the local ecosystem structure. Before implementation these impacts should be considered.

In the data collection no difference is made between a microcosm, mesocosm or field-scale CWs. This scale could affect the reliability of the removal efficiencies, since high removal at microcosm scale is not directly related to high removal at field scale. The relatively small amount of data in the collection also causes the conclusions and approximate percentages to have a questionable reliability. However, for the purposes of this research the data collection is considered useful since it brings a quick overview for possible removal efficiency in tropical regions.

In the collection the countries considered as tropical include countries from Asia, Africa, and Oceania. The research done by Zhang et al. (2015) was taken as guideline to determine which countries were considered as tropical. The decision to include data of different tropical regions was made to be able to acquire more data, however it might hinder the applicability of the data to Northern-Thailand.

The used k-C* model has some associated drawbacks. The model considers an idealized situation that in reality does not exist. The model assumes a state of steady flow while in reality water in a CW is rarely in a steady state (Kadlec, 2000; Rousseau et al., 2004). Additionally k and C* are assumed constant (Kadlec, 2000). In reality these parameters are functions of the wetland characteristics and operation (Kumar & Zhao, 2011). Even though the k-C* model can be considered as inadequate (Kadlec, 2000), it has been stated that the model can be used if one is aware of the pitfalls and all assumptions are fulfilled (Rousseau et al., 2004). In order to work with the model the assumptions that CWs have plug flow and overall stable climatic conditions were therefore accepted. The model is also used as preliminary sizing method, as it was proposed by Kadlec and Knight (1996), instead of exact sizing method to limit the impact of probable model miscalculations

CONCLUSION

This research aimed to determine to what extent CWs can be considered a viable option for wastewater treatment and reuse in Northern-Thailand. The research found that CWs can be considered viable options for wastewater treatment in Northern-Thailand if the CW components are adapted to local conditions. For macrophytes used a diverse selection of locally available species is advised. The use of a replaceable soil filtration unit for optimal phosphorus removal is recommended. For hydrologic adaptions it is advised use a storage unit to limit climate influences. Additionally the use of a hybrid system with vertical and horizontal SSF elements is advised for optimal pollutant removal. Although this research could not formulate exact design specifications the provided adaptions could be used as base for further research for site specific CWs in Northern-Thailand.

The extent of reuse possibilities is found to be limited to agricultural purposes. Since household reuse is not possible CWs can currently not help solve sanitation problems. However, it could be argued that the achievable water quality from the CW design can be considered an improvement of the current situation.

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APPENDIX

APPENDIX I: FORMULAS AND PARAMETERS USED

The calculation method used is based on the method given in Kadlec and Knight (1996). The formula used is derived from two formulas. The general form of the k-C* model is:

$$ln\left(\frac{C_e - C^*}{C_i - C^*}\right) = -\frac{k}{q}$$

Where: C_e = Outlet Target Concentration (mg/L)
C_i = Inlet Concentration (mg/L)
C^* = Background concentration (mg/L)
k = First order areal rate constant (m/yr)
q = hydraulic loading rate (m/d)

The hydraulic loading rate can be expressed as:

$$q = \frac{Q}{A}$$

Where: Q = Average wastewater flow (m^3/d)
A = Wetland area (m^2)

From these two formulas the area can be calculated. Rearrangement and unit conversion produces the following formula, which is used in this research:

$$A = \left(\frac{0.0365 \cdot Q}{k}\right) \cdot ln\left(\frac{C_i - C^*}{C_e - C^*}\right)$$

This formula can be rearranged to form a formula that can be used to calculate the effluent concentration:

$$C_0 = C^* + (C_i - C^*) \cdot e^{\left(-\frac{k \cdot A}{0.0365 \cdot Q}\right)}$$

Where: C_0 = Outlet Concentration (mg/L)

The area calculation should be done for the different pollutants found in wastewater. The different pollutants will probably lead to different necessary areas. For the calculation of the effluent concentrations the largest area found should be used, in this way the CW is designed to optimally remove most pollutants.

For the value of k and C* value estimates have been made, as can be seen in table below. The same values are used for an HSSF and VSSF element. This decision has been made since the literature either presents no difference or no specification is made. COD is not included, this is done since the area calculation method from Kadlec & Knight (1996) doesn't include this parameter either.

Table I: C* an k values

Pollutant		FWS		SSF		Source
		C*	k	C*	k	
BOD	*Tertiary (0-30 mg/L)*	2	33	1	86	(Kadlec, 2009)
	Secondary (30-100 mg/L)	5	41	5	37	(Kadlec, 2009)
	Primary (100-200 mg/L)	10	36	10	25	(Kadlec, 2009)
	Super (200+ mg/L)	20	189	15	66	(Kadlec, 2009)
TSS		$5.1 + 0.16C_i$ mg/L	1000	$7.8 + 0.063C_i$ mg/L	3000	(Kadlec & Knight, 1996)
TN		1,5	6	1	8,4	(Kadlec, 2009)
TP		0,0003	6	0	6	(Kadlec, 2009)
Pathogens		300	75	10	95	(Kadlec & Knight, 1996)

WASTEWATER CHARACTERISTICS

For the calculations it is necessary to determine the inlet concentrations for the pollutants. Wastewater consists for 99,9% of water (FAO, n.d.). The amount of different types of pollutants in the wastewater is depended on multiple factors, including country and region. General values for wastewater constituents can be found in Table II. Wastewater is generally lower in strength in developing regions (Mara, 2004; FAO, n.d.). However, the wastewater is considered as stronger in tropical regions due to lower water use which limits dilution of pollutants (Mara, 2004). Water consumption in tropical regions is 40-100 L/day in tropical regions as compared to 350-400 L/day in the United States. An exact reason for this lower water use is not given. It could be that more natural precipitation is used, which is perhaps not counted toward water use.

Since there is no clear data about wastewater characteristics for the developing, rural areas in Northern-Thailand this research uses medium strength wastewater characteristics. Medium is taken as the middle way between the conflicting information presented above. Where developing areas have low strength wastewater while tropical regions have high strength wastewater.

Table II: General wastewater characteristics.

Pollutant	Wastewater characteristic (mg/L)			Source
	High	Medium	Low	
COD (dissolved and suspended)	1200	750	500	Henze & Comeau, 2008
BOD	300	200	100	FAO, n.d.
TSS	350	200	100	FAO, n.d.
TN	85	40	20	FAO, n.d.
TP	20	10	6	FAO, n.d.
Pathogens	10^8		10^6	Henze & Comeau, 2008

APPENDIX II: REUSE GUIDELINES

Both the Thai water Quality Standards and the Environmental Protection Agency water quality for reuse will be used, since neither have determined values for all pollutants. Household reuse will be considered as 'Class 1' or 'Class 2' according to the Thai guidelines, but with no occurring pathogens. This since both these classes only require ordinary treatment for pathogenic destruction before use, if this can be achieved in the CW then ordinary treatment will not be necessary.

THAI WATER QUALITY GUIDELINES FOR SURFACE WATER

Table III: Surface Water Quality Standards of the Pollution Control Department in Thailand (PCD, 2004)

Parameter	Units	Statistics	Standard Value for Class				
			Class1	Class2	Class3	Class4	Class5
1. Colour,Odour and Taste	-	-	n	n'	n'	n'	-
2. Temperature	C°	-	n	n'	n'	n'	-
3. pH	-	-	n	5-sep	5-sep	5-sep	-
4. Dissolved Oxygen (DO)	mg/l	P20	n	6.0	4.0	2.0	-
5. BOD (5 days, 20°C)	mg/l	P80	n	1.5	2.0	4.0	-
6. Total Coliform Bacteria	MPN/100 ml	P80	n	5	20	-	-
7. Fecal Coliform Bateria	MPN/100 ml	P80	n	1	4	-	-
8. NO_3 -N	mg/l	-	n	5.0			-
9. NH_3 -N	mg/l	-	n	0.5			-

n = naturally occuring

Table IV: Water Classification System for Thailand (PCD, 2004)

Classification	Objectives/Condition and Beneficial Usage
Class 1	Extra clean fresh surface water resources used for :
	(1) conservation not necessary pass through water treatment process require only ordinary process for pathogenic destruction
	(2) ecosystem conservation where basic organisms can breed naturally
Class 2	Very clean fresh surface water resources used for :
	(1) consumption which requires ordinary water treatment process before use
	(2) aquatic organism of conservation
	(3) fisheries
	(4) recreation
Class 3	Medium clean fresh surface water resources used for :
	(1) consumption, but passing through an ordinary treatment process before using
	(2) agriculture
Class 4	Fairly clean fresh surface water resources used for :
	(1) consumption, but requires special water treatment process before using
	(2) industry
Class 5	The sources which are not classification in class 1-4 and used for navigation.

EPA WATER QUALITY STANDARDS FOR WASTEWATER REUSE

Only irrigation reuse purposes were taken from the EPA guidelines were considered. Processes food crops are crops that are first cooked or otherwise prepared whereas food crops can be eaten raw. The guidelines have been taken from Jeong, Kim, & Jang (2016).

Table V: EPA Agricultural Reuse Guidlines (Jeong et al., 2016)

Type of Reuse	Pollutant		
	Coliform	TSS	BOD
Food Crops	Not detectable	-	≤10
Processed Food Crops	≤200	≤30	≤30

APPENDIX III: REMOVAL EFFICIENCY DATA

The data collected about the Removal Efficiencies of CWs in tropical areas is presented here, divided per CW type. Numbers presented in red were calculated by the researcher of this paper. The data is presented in the following order:

1. FWS CWs Removal Efficiency
2. HSSF CWs Removal Efficiency
3. VSSF CWs Removal Efficiency
4. Hybrid CWs Removal Efficiency

Notes:

- When only inflow and outflow concentrations were given and no removal efficiency the removal efficiency was calculated using the following formula:

$$RE = \frac{Inflow\ Concentration - Outflow\ Concentration}{Inflow\ Concentration} \times 100$$

- The average removal efficiencies were calculated by taking the average of all removal efficiencies of the selected type.

1. FWS CWs Removal Efficiency

Country	Removal efficiency																							
	COD (mg/L)			BOD (mg/L)			TSS (mg/L)			TN (mg/L)			NH4-N (mg/L)			NO3-N (mg/L)			TP (mg/L)			Pathogens		
	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)
Sri Lanka, Peradeniya	-	-	-	-	19,2	68	-	45,8	71,9	-	-	-	-	3,4	74,4	-	0,9	50	-	1,36	19	-	-	-
Greece, Pompia	-	18	96,1	-	7,7	94,4	-	5,6	95,5	-	18	52,5	-	-	-	-	-	-	-	6,2	53,1	-	-	-
Southern Spain	-	50	90,72	-	7	98,22	-	6	97,9	-	7,9	85,53	-	2,3	94,54	-			-	5,3	34,57	-	-	-
Taiwan, Hsin-Hai	-	-	-	-	20	-	-	-	-	-	-	-	-	6,9	46	-			-	1,9	44	-	-	-
Australia, Cairns	-	-	-	-	-	-	-	-	-	-	1,5	75	-	0,2	33,3	-	0,1	99	-	7	12,5	-	-	-
Australia, Blackall	-	-	-	-	-	-	-	-	-	-	6	76	-	1	92,3	-	1	87,5	-	<0,05	75	-	-	-
Taiwan	-	67	61	-	9	89	-	17	81	-	16	16	-	-	-	-	6	85	-	45	35	-	-	-
El Salvador	-	72,8	65,18	-	20,08	80,78	-	-	-	-	6,08	58,59	-	0,54	95,75	-	-	-	-	186	66,5	-	-	-
Taiwan, Tapei	-	28,24	64,48	-	10,89	59,85	-	19,6	-	-	8,4	56,66	-	0,533	-	-	-	-	-	0,47	63,85	-	-	-
Thailand, Petchaburi	-	-	-	-	12,7	74,3	-	40,4	46,5	-	-	-	-	5,18	75,4	-	0,35	-	-	2,2	44,9	-	-	-
Argentina, Santo Torne	-	37	68	-	13	64	-	-	-	-	-	-	-	2	28	-	3,1	72	-	0,155	43	-	-	-
Spain, Valencia	-	33,2	-	-	-	-	-	13,2	75	-	1,6	52	-	0,116	78,07	-	0,59	58	-	0,143	65	-	-	-
USA, Florida	-	0,54	95,75	-	72,8	65,18	-	20,08	80,78	-	6,08	58,59	-	-	-	-	-	-	-	1,86	66,5	-	-	-
Kenya, Nyanza	-	-	-	-	-	-	-	11	76	-	-	-	-	2,9	36	-	-	-	-	4,1	29	-	-	-
Vietnam 1	-	-	84	-	-	83	-	-	93	-	-	84	-	-	91	-	-	-	-	99	-	-	-	-
Vietnam 2	-	-	68	-	-	65	-	-	94	-	-	61	-	-	69	-	-	-	-	98	-	-	-	-
Vietnam 3	-	-	57	-	-	81	-	-	95	-	-	62	-	-	65	-	-	-	-	85	-	-	-	-
Vietnam 4	-	-	63	-	-	76	-	-	86	-	-	16	-	-	-1,4	-	-	-	-	72	-	-	-	-
China, Beijing	-	-	-	125	17,8	85,76	275	17	93,82	14,4	5,1	64,58	-	-	-	-	-	-	0,94	0,42	55,32	-	-	-
Australia, South Lismore	-	-	-	9,4	0,7	92,55	74	1,8	97,57	5,4	1	81,48	0,7	0,02	97,14	-	-	-	2,8	0,5	82,14	3,1	2,7	12,90
Greece, Pompia	-	-	-	165	7,8	95,27	208	6,2	97,02	34,2	17,9	47,66	-	-	-	-	-	-	14,8	7,45	49,66	4,4	2,8	36,36
Australia, Cairns	-	-	-	9	4	55,56	5	4	20,00	6,1	1,5	75,41	0,3	0,2	33,33	-	-	-	7,8	6,9	11,54	4,9	3	38,78
India, Warangal	-	-	-	152	19,5	87,17	165	16	90,30	36	3,9	89,17	20	3,6	82,00	-	-	-	7,4	1,7	77,03	-	-	-
New Zealand, Kohukoku	-	-	-	48	7	85,42	107	16	85,05	58	27,3	52,93	46,9	19,9	57,57	-	-	-	14,9	10,4	30,20	4,4	2,9	34,09
New Zealand, Portland	-	-	-	32	10	68,75	111	15	86,49	10,4	5,9	43,27	0,7	3,3	-371,43	-	-	-	3,5	3,2	8,57	3,4	3	11,76
Australia, Ingham	-	-	-	22	11	50,00	24	16	33,33	19,5	9,7	50,26	8	5,4	32,50	-	-	-	6,8	5,4	20,59	-	-	-
New Zealand, Camrbidge	-	-	-	52	13	75,00	40	13	67,50	-	-	-	47	25	46,81	-	-	-	12,6	12,1	3,97	-	-	-
Average			**73,93**			**77,01**			**79,22**			**59,93**			**40,73**			**75,25**			**43,08**			**26,78**

Country				HLR (m3/day)	HRT (day)	Dimensions	Plant Species	Type of wastewater	stage of treatment	Reference	
	Pathogens										Remarks
	ıflow	outflow	removal (%)								
Sri Lanka, Peradeniya		-	-	13	18hr	25,0 x 1,0 x 0,6	Scirpus grossus, Typha angustifolia	municipal	secondary	Zhang et al., 2014	
Greece, Pompia		-	-	144	-	4300m2 ; 1200m2	Phragmites Australis Arundo Donas	Municipal	secondary	Zhang et al., 2014	
Southern Spain		-	-	44 mm/day	-	23,5 x 13,5 x 0,8; 26 x 8,8 x 0,4	Phragmites australis; Typha spp.	municipal	stormwater	Zhang et al., 2014	
Taiwan, Hsin-Hai		-	-	4000	7	1,07 ha x 0,5 m	Typha orientalis; Phragmites communis	domestic	stormwater	Zhang et al., 2014	
Australia, Cairns		-	-	500 m3/(ha-day)	10	-	-	municipal	tertriary	Zhang et al., 2014	
Australia, Blackall		-	-	-	20	-	-	municipal	tertriary	Zhang et al., 2014	
Taiwan		-	-	0,4	5	4,0 x 1,0 x1,0	Pistia stratiotes; Phragmites comunis	municipal	tertriary	Zhang et al., 2014	
El Salvador		-	-	151,4	9,8	48,9 x 15,0 x 0,6	Typha angustfolia	municipal	secondary	Zhang et al., 2014	
Taiwan, Tapei		-	-	-	-	-	Phragmites australis; Typha orientalis	municipal	tertriary	Zhang et al., 2014	
Thailand, Petchaburi		-	-	6-150 mm/day	2	4,0 x 1,0 x1,5	Typha angustifolia	municipal	saline condition	Zhang et al., 2014	
Argentina, Santo Torne		-	-	100	43076	50 x 40 x 0,5	Typha domingensis; Eichornia crassipes	industrial	sewage	Zhang et al., 2014	
Spain, Valencia		-	-	11232	-	715-9791 m2	Cattails; Rushes	lake water	-	Zhang et al., 2014	
USA, Florida		-	-	151,4	9,8	15 x 49 x 1,2	Typha angustifolia; Cyperus alternifolius	-	-	Zhang et al., 2014	
Kenya, Nyanza		-	-	75 mm/day	-	3,0 x 20,0 x 0,4	Cyperus papyrus; Echinochloa; Pyramidalis	Sugar Factory	-	Zhang et al., 2014	
Vietnam 1		-	-	31 mm/day	-	-	Phragmites Vallatoria	-	-	Trang et al., 2010	
Vietnam 2		-	-	62 mm/day	-	-	Phragmites Vallatoria	-	-	Trang et al., 2010	
Vietnam 3		-	-	104 mm/day	-	-	Phragmites Vallatoria	-	-	Trang et al., 2010	
Vietnam 4		-	-	146 mm/day	-	-	Phragmites Vallatoria	-	-	Trang et al., 2010	
China, Beijing		-	-	500	-	10638 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	
Australia, South Lismore	3,1	2,7	12,90	3500-20000	-	3600 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	Fecal Coliform
Greece, Pompia	4,4	2,8	36,36	144	-	5500 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	Fecal Coliform
Australia, Cairns	4,9	3	38,78	84,2	-	1683 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	Fecal Coliform
India, Warangal		-	-	5	-	118 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	
New Zealand, Kohukoku	4,4	2,9	34,09	30	-	1200 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	Fecal Coliform
New Zealand, Portland	3,4	3	11,76	68	-	1300 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	Fecal Coliform
Australia, Ingham		-	-	317	-	7920 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	
New Zealand, Camrbidge		-	-	3234	-	66000 m2	Emergent	municipal	-	Vymazal & Kröpfelová, 2008	
Average			**26,78**								

2. HSSF CWs Removal Efficiency

Country	Removal efficiency																							
	COD (mg/L)			BOD (mg/L)			TSS (mg/L)			TN (mg/L)			NH4-N (mg/L)			NO3-N (mg/L)			TP (mg/L)			Pathogens		
	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)
Egypt	-	58	65,9	-	29,1	70,3	-	8,9	82,2	-	4,6	36	-	-	-	-	-	-	-	1,7	32,4	-	-	-
Egypt	-	67	83,5	-	25	86,4	-	9	89	-	39,6	69,3	-	-	-	-	-	-	-	9,3	56,2	-	-	-
Kenya, Nairobi City CW1	-	91	42,76	-	28,9	60,73	-	25,5	75,27	-	-	-	-	19	26,36	-	1,1	-	-	0,8	42,86	-	-	-
Kenya, Nairobi City CW2	-	89,5	43,89	-	34,6	52,98	-	27,9	72,91	-	-	-	-	18,8	17,13	-	0,9	22	-	0,6	57,14	-	-	-
India, Mother Dairy Pilot Plants	-	55	72	-	4	90	-	12	81	-	7,5	67	-	-	-	-	-	-	-	1,5	75	-	-	-
Singapore	-	12,4	95,8	-	-	-	-	-	-	-	-	-	-	1,3	95,2	-	0,2	-	-	6,7	69,6	-	-	-
Costa Rica	-	1	99,4	-	-	-	-	-	-	-	11	31,25	-	-	-	-	-	-	-	-	-	-	-	-
China, Shenzhen	-	25,31	70	-	8,37	90	-	-	-	-	8,27	46	-	6,28	50	-	-	-	-	0,65	60	-	-	-
Taiwan, Pingtung	-	190	84	-	39	91	-	21	96	-	156	24	-	1,44	22	-	1,7	54	-	21	47	-	-	-
Bangladesh, Dhaka	-	0,2	98	-	0,08	98	-	12,1	55	-	-	-	-	15	86	-	33	50	-	3	87	-	-	-
Sri Lanka, Peadeniya	-	105,9	40,8	-	18,6	65,7	-	47,33	65,8	-	-	-	-	4,08	74,8	-	0,71	38,8	-	8,03	61,2	-	-	-
China, Shenzhen	-	33,9	76,72	-	7,68	86,4	-	7,92	86,78	-	9,11	44,93	-	-	-	-	-	-	-	0,56	81,7	-	-	-
El Salvador	-	147,13	56,2	-	62,8	-	-	32,13	84,15	-	12,04	39,3	-	-	-	-	-	-	-	2,61	-	-	-	-
Hong Kong	-	-	-	-	-	-	-	-	-	-	16,23	69,63	-	1,71	91,83	-	0,14	47,5	-	0,09	91,83	-	-	-
Vietnam, Can Tho University 1	-	-	84	-	-	83	-	-	93	-	-	84	-	-	91	-	-	-	-	-	99	-	-	-
Vietnam, Can Tho University 2	-	-	68	-	-	65	-	-	94	-	-	61	-	-	69	-	-	-	-	-	98	-	-	-
Vietnam, Can Tho University 3	-	-	57	-	-	81	-	-	95	-	-	62	-	-	65	-	-	-	-	-	85	-	-	-
Vietnam, Can Tho University 4	-	-	63	-	-	76	-	-	86	-	-	16	-	-	-	-	-	-	-	-	72	-	-	-
Indonesia	-	-	98,46	-	-	98,55	-	-	98,06	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thailand	-	-	42-83	-	-	-	-	-	88-96	-	-	"4-37"	-	-	-	-	-	-	-	-	"6-35"	-	-	-
Costa Rica	-	-	-	-	-	94-99,4	-	-	91,7-97,9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	99,9
Average			**72,19**			**79,67**			**83,61**			**50,03**			**62,57**			**42,46**			**69,75**			**99,90**

Country	HLR (m3/day)	HRT (day)	Dimensions	Plant Species	Type of wastewater	stage of treatment	Substrates	Reference	Remarks
Egypt	-	5	1,1 x 1,0 x 0,4	Phragmites australis	Greywater	Secondary	-	Zhang et al., 2014	
Egypt	-	10	1,1 x 1,0 x 0,4	Phragmites australis	Black water	Secondary	-	Zhang et al., 2014	
Kenya, Nairobi City CW1	-	-	7,5 x 3,0 x 0,6	Cyperus papyrus	municipal	Secondary	-	Zhang et al., 2014	
Kenya, Nairobi City CW2	-	-	7,5 x 3,0 x 0,6	Cyperus papyrus	municipal	Secondary	-	Zhang et al., 2014	
India, Mother Dairy Pilot Plants	43,05 L/(mxday)	5,15	69 x 46 x0,3	Phragmites australis	municipal sludge	tertiary	-	Zhang et al., 2014	
Singapore	5,6 cm/day	4	1,2 x 0,6 x 0,6	Thpha angustifolia	municipal	Secondary	-	Zhang et al., 2014	
Costa Rica	2500 L/day	24	14,0 x 1,2 x 0,6	Cois lacryma-jobi	Greywater	Secondary	-	Zhang et al., 2014	
China, Shenzhen	5	3	33 x 3 x 0,5	Kandelia candel; Aegiceras corniculatum	municipal	Secondary	-	Zhang et al., 2014	
Taiwan, Pingtung	-	8,5	9,5 x 2,6 x 0,7	Eichhornia crassipes	Swine effluent	Secondary	-	Zhang et al., 2014	
Bangladesh, Dhaka	6 cm/day	12,5	1,3 x 1,0 x 0,8	Phragmites australis	Tannery WW	Secondary	-	Zhang et al., 2014	
Sri Lanka, Peadeniya	-	18	1 x 25 x 0,6	Scirpus grossus; Hydrilla verticillata	municipal	Secondary	-	Zhang et al., 2014	
China, Shenzhen	-	11,5h; 8h	80 x 30 x 1,5 ; 58 x 20 x 1,6	Cana indica; Thalia dealbata	Municipal	Secondary	-	Zhang et al., 2014	
El Salvador	151,4	-	18,3 x 7,3 x 0,6	Phragmites australis	Municipal	Secondary	-	Zhang et al., 2014	
Hong Kong	-	10	0,67 x 0,54 x 0,38	Kandelia candel; Aegiceras corniculatum	Municipal	Secondary	-	Zhang et al., 2014	
Vietnam, Can Tho University 1	31 mm/day	-	12 x 1,6 x 1,1	Phragmites vallatoria	Municipal	Secondary	-	Zhang et al., 2014	
Vietnam, Can Tho University 2	62 mm.day	-	12 x 1,6 x 1,1	Phragmites vallatoria	Municipal	Secondary	-	Zhang et al., 2014	
Vietnam, Can Tho University 3	104 mm/day	-	12 x 1,6 x 1,1	-	Muncipal	Secondary	-	Zhang et al., 2014	
Vietnam, Can Tho University 4	146 mm/day	-	12 x 1,6 x 1,1	-	Municipal	Secondary	-	Zhang et al., 2014	
Indonesia	-	-	1,7 x 7,0 x 0,7	Cyperus papyrus	-	-	Sand, gravel	Qomariyah al., 2017	
Thailand	-	-	2 x 1 x 1	Canna; Helicona	-	-	Gravel	Qomariyah al., 2017	
Costa Rica	-	-	14 x 1,2 x 0,6	Coix lacrymajodi	-	-	crush rock	Qomariyah al., 2017	Fecal coli
Average									

3. VSSF CWs Removal Efficiency

Country	Removal efficiency																							
	COD (mg/L)			BOD (mg/L)			TSS (mg/L)			TN (mg/L)			NH4-N (mg/L)			NO3-N (mg/L)			TP (mg/L)			Pathogens		
	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)
Greece, Chalkidiki	-	62	89	-	39	92	-	9	95	-	14	77	-	-	-	-	-	-	-	5,6	62	-	-	-
Mexico, Jalisco	-	49,5	80,32	-	20,8	81,94	-	21,9	61,56	-	14,6	49,38	-	-	-	-	-	-	-	4,2	50,14	-	-	-
Uganda, Kampala	-	-	-	-	-	-	-	-	-	-	16,1	72,48	-	7,1	75,43	-	0,09	60,87	-	2,6	83,23	-	-	-
China, Wuxi	-	-	-	-	61,8	81,3	-	96	77,1	-	-	48,9	-	32,9	61,7	-	41,3	66,6	-	-	-	-	-	-
Thailand, Chiang Mai	-	92	91	-	15	96	-	4	98	-	97	76	-	51	84	-	-	-	-	0,6	97	-	-	-
China, Wuhan 1	-	115,5	59,9	-	-	-	-	-	-	-	25,6	15	-	22,59	-	-	0,34	79,52	-	1,418	52	-	-	-
China, Wuhan 2	-	130,1	62,8	-	-	-	-	-	-	-	26,4	12,8	-	22,56	-	-	0,37	-	-	1,51	51,1	-	-	-
India	-	15,11	89,28	-	10,09	84,41	-	-	92,91	-	3,41	83,99	-	0,41	99,96	-	0,14	96,78	-	2,46	43,36	-	-	-
China, Guangzhou	-	25,31	70	-	8,37	90	-	-	-	-	8,27	46	-	6,28	50	-	-	-	-	0,65	60	-	-	-
Turkey, Ankara 1	-	-	27,3	-	-	-	-	-	-	-	-	-	-	-	62,3	-	-	-	-	-	52,6	-	-	-
Turkey, Ankara 2	-	-	30,6	-	-	-	-	-	-	-	-	-	-	-	48,9	-	-	-	-	-	57,9	-	-	-
China, Taihu	-	4,25	40,4	-	-	-	-	-	-	-	2,37	51,6	-	0,89	45,9	-	0,5	62,9	-	0,05	51,6	-	-	-
Sri Lanka, Peradeniya 1	-	-	-	28,8	2,9	89,93	160,3	56,5	64,75	-	-	-	16,2	2,1	87,04	3,7	2,5	32,43	2,8	0,5	82,14	910000	22000	97,58
Sri Lanka, Peradeniya 3	-	-	-	28,8	5,3	81,60	160,3	74,5	53,52	-	-	-	16,2	2,3	85,80	3,7	2,9	21,62	2,8	0,4	85,71	910000	33000	96,37
Indonesia	-	-	78,89		-	76,03	-	-	-	-	-	71,70	-	-	88,18	-	-	-	-	-	91,06	-	-	-
Average			65,41			85,91			77,55			54,99			71,75			60,10			65,70			96,98

Country	HLR (m3/day)	HRT (day)	Dimensions	Area	Plant Species	Type of wastewater	stage of treatment	Substrate	Reference	Remarks
Greece, Chalkidiki	180	-	640 m2 x 1m; 360 m2 x 1m		Phragmites australis	municipal	secondary	-	Zhang et al., 2014	
Mexico, Jalisco	128 L/day	-	1,8 x 1,8 x 0,7		Strelitzia reginae; Anthurium and	municipal	secondary	-	Zhang et al., 2014	
Uganda, Kampala	0,064	5	0,58m2 x 0,82m		Cyperus papyrus	municipal	tertiary	-	Zhang et al., 2014	
China, Wuxi	0,4	-	2,0 x 2,0 x 1,0		Phragmites communis; Phragimit	livestock	secondary	-	Zhang et al., 2014	
Thailand, Chiang Mai	-	-	2,0 x 2,0 x 1,0		Scirpus grossus Linn.	UASB effluent	secondary	-	Zhang et al., 2014	
China, Wuhan 1	250 mm/day	1,2	1,0 x 1,0 x 1,0		Typha orientalis, Arundo Donax, Canna indica, Arundo donax	municipal	secondary	-	Zhang et al., 2014	
China, Wuhan 2	250 mm/day	1,2	1,0 x 1,0 x 1,0		Typha orientalis, Arundo Donax, Canna indica, Arundo donax	municipal	secondary	-	Zhang et al., 2014	
India	236 mm/day	4	2,1 x 0,8 x 0,6		Typha angustifolia	municipal	tertiary	-	Zhang et al., 2014	
China, Guangzhou	0,45	18	5,0 x 3,0 x 1,8		Cyperus alternifolius	municipal	secondary	-	Zhang et al., 2014	
Turkey, Ankara 1	10 L/day	11	1,0 x 0,5 x 0,4		Typha latifolia	Landfill	-	-	Zhang et al., 2014	
Turkey, Ankara 2	10 L/day	8	1,0 x 0,5 x 0,4		Typha latifolia	Leachate	-	-	Zhang et al., 2014	
China, Taihu	0,64 m/day	-	20 x 1,5 x 1,0		Typha angustifolia	Lake Water	-	-	Zhang et al., 2014	
Sri Lanka, Peradeniya 1	13,3 cm/day	-	1,4 x 0,5 x 0, 6		Typha angustifolia	-	-	-	Weerakoon et al., 2016	
Sri Lanka, Peradeniya 3	13, 3 cm/day	-	1,4 x 0,5 x 0, 8		-	-	-	-	Weerakoon et al., 2016	
Indonesia	-	-	6 x 5 x 1,2		Phragmites Karka	-	-	sand, gravel	Qomariyah al., 2017	
Average										

4. Hybrid CWs Removal Efficiency Part 1

Country	Removal efficiency																							
	COD (mg/L)			BOD (mg/L)			TSS (mg/L)			TN (mg/L)			NH4-N (mg/L)			NO3-N (mg/L)			TP (mg/L)			Pathogens		
	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)	inflow	outflow	removal (%)
Nepal, Kathmandu Valley	-	20,2	93,8	-	3,29	97,01	-	2,83	97,25	-	-	-	-	1,61	95,18	-	-	-	-	4,22	46,6	-	-	-
Mexico, Texcoco	-	223,3	85,83	-	-	-	-	56,6	85,98	-	44,6	72,62	-	22,9	65,46	-	5,2	81,7	-	-	-	-	-	-
Nepal	-	318,6	89,07	-	173,3	89,12	-	37,8	97,49	-	-	-	-	45	68,3	-	-	-	-	17,1	29,91	-	-	-
Turkey	-	-	-	-	-	-	-	-	-	-	4,59	91,33	-	3,24	91,2	-	0,26	88,79	-	-	-	-	-	-
Columbia, Bogota Savannah	-	-	-	-	28	92,26	-	10	96,9	-	15	63,41	-	9	62,5	-	-	-	-	3	40	-	-	-
Indonesia, Jakarta	-	1,23	97,72	-	-	-	-	-	-	-	3,04	65,66	-	0,06	97,21	-	0,65	85,96	-	0,6	37,33	-	-	-
Mexico, Sante Fe de la Laguna	-	100	68	-	33	52	-	20	79	-	31	82	-	-	-	-	-	-	-	15	14	-	-	-
Thailand, Koh Phi Phi	-	-	-	-	25	91,58	-	16	90	-	33	68,89	-	-	-	-	0,1	50	-	4,5	46,43	-	-	-
Taiwan	-	-	-	-	-	-	-	-	-	-	0,18	95,36	-	0,11	86,25	-	0,07	97,37	-	3,53	31,98	-	-	-
Spain, Pontevedra	-	448	71,66	-	279	67,52	-	17	87,02	-	25,2	64,04	-	12,5	-	-	-	-	-	1,9	57,59	-	-	-
China, Chongqing	-	21	84,1	-	-	-	-	3,2	96,6	-	-	-	-	2,2	79,6	-	-	-	-	0,45	84,5	-	-	-
Brazil, Videira	387	-	93	-	-	-		-		-	-	-	51		89	-	-	-	12,9		69	-	-	-
China, Pugu Lake	132	-	84	-	-	-	93	-	97	-	-	-	10,8		80	-	-	-	-	-	-	-	-	-
China Baishiyi	246	-	90	-	-	-	143	-	85	-	-	-	34		84	-	-	-	-	-	-	-	-	-
China, Fairy Mountain	167	-	84	-	-	-	155	-	99	39	-	65	22		72	-	-	-	-	-	-	-	-	-
Mexico, Santa Maria	643	206	-	-	-	-	64	16,4	-	70	57	-	44	21,6	-	-	-	-				-	-	-
Nepal, Thimi Municipality	1422	319	78	774	173	78	322	38	88	-	-	-	209	45	78	-	-	-	28,4	17,1	40	-	-	-
China, Shenzhen	145	34	77	56	7,7	86	60	7,9	87	16,5	9,1	45	-	-	-	-	-	-	3,1	0,56	82	-	-	-
Turkey, Gebze	284	36	86	84	8	90	62	8	81	66	25	62	-	-	-	-	-	-				-	-	-
Japan, Embetsu, Hokkaido	4425	323	93	1574	138	91	770	17	98	183	32	83	77	22	71	-	-	-	29	5	83	-	-	-
Japan, Bekkai, Hokaido 1	2385	142	94	-	-	-	-	-	-	101	97	63	35	13	62	-	-	-	21,7	6,6	70	-	-	-
Japan, Bekkai, Hokaido 2	5002	211	96	-	-	-	-	-	-	198	22	89	38	7	82	-	-	-	37,6	4,5	88	-	-	-
Japan, Kiyosato, Hokkaido	24017	2000	92	-	-	-	-	-	-	1425	260	82	1030	267	74	-	-	-	99	20	80	-	-	-
Japan, Hokkaido	10112	3059	70	-	-	-	-	-	-	1866	1134	39	1798	1157	36	-	-	-	115	26	77	-	-	-
Bangladesh, Dhaka	11500	200	98	4200	80	98	27600	12400	55	-	-	-	87	11,7	87	-	-	-	10	1	90	-	-	-
New Zealand, Hamilton	-	-	-	114	2,2	98	72	3,3	95	42	11,4	73	33	0,3	99	-	-	-	5,2	2,9	45	-	-	-
China	36,5	27,2	26	4,3	1,9	56	12,4	5,2	58	1,2	0,63	48	0,62	0,41	34	-	-	-	0,09	0,08	17	-	-	-
China, Wuhan	289	107	63	-	-	-	-	-	-	30,7	26	15	19,4	22,6	-16	-	-	-	3,05	1,5	51	-	-	-
Taiwan, Tainan County	-	-	-	6,2	2,5	60	20,6	9,1	56		0,18	0,06	67			-	-	-	3,6	3,8	-6	-	-	-
Taiwan	-	-	-	-	-	-	11	1,65	85	7,4	3,6	51	3	0,94	69	-	-	-	1,56	1,17	25	-	-	-
Thailand, Phayao Province	539	198	63	253	108	57	310	83	73	257	162	37	222	144	35	-	-	-	-	-	-	-	-	-
China Northern Ningbo	320	47/49	85	-	-	-	124	16/14	87/89	-	-	-	45,6	8,5/7,7	81/83	-	-	-	-	-	-	-	-	-
China, Hangzhou City	-	-	-	-	-	-	-	-	-	21,2	1,7	92	4,1	0,08	98	-	-	-	-	-	-	-	-	-
Thailand, Koh Phi Phi	-	-	-	295	25	92	160	16	90	54	33	39	-	-	-	-	-	-	8,4	4,5	46	-	-	-
Mexico, Santa fe de la Laguna	911	97	89	768	37	95	403	26	94	85	27	68	69	19	72	-	-	-	85	27	68	-	-	-
Average			**82,05**			**81,79**			**85,71**			**62,17**			**71,22**			**80,76**			**52,53**			**99**

5. Hybrid CWs Removal Efficiency Part 2

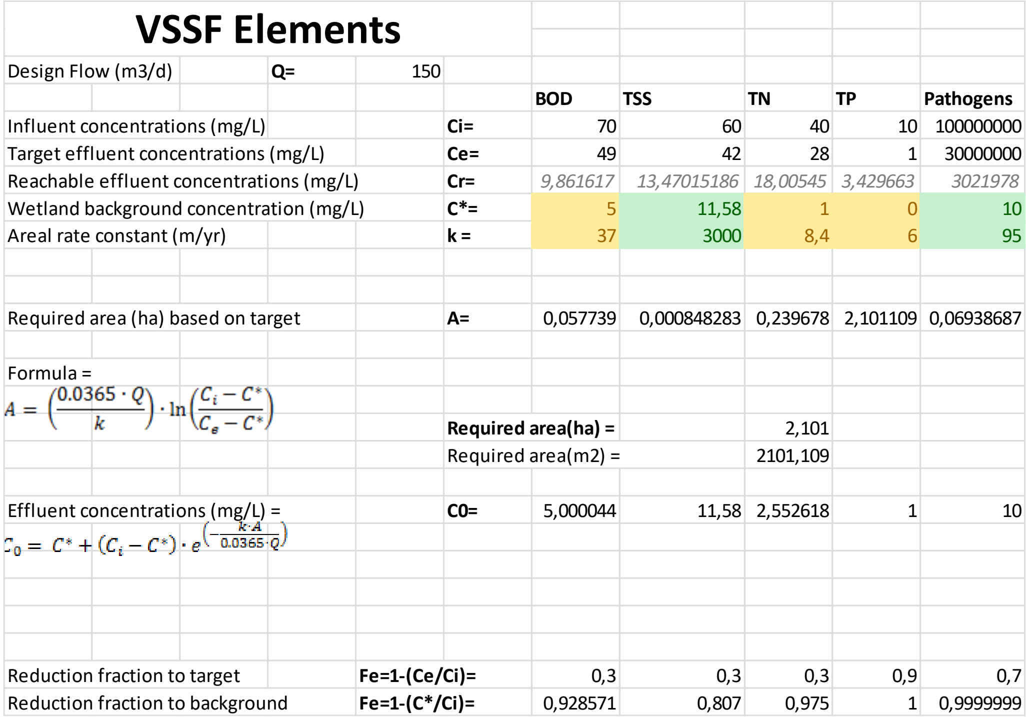
Country	HLR (m3/day)	HRT (day)	Dimensions	Plant Species	Type of wastewater	stage of treatment	Type of Hybrid	Reference
Nepal, Kathmandu Valley	20	-	7 x 20; 11 x 11	Phragmites Karka	Hospital	secondary		Zhang et al., 2014
Mexico, Texcoco	2,8	2,3	8,8 x 1,8 x 0,6; 2,8 x 4,0	Phragmites communis	municipal	secondary		Zhang et al., 2014
Nepal	0,13 m/day	-	8,0 x 9,5 x 0,5; 10,0 x 7,5 x 0,6	Phargmites Karka; Canna latifolia	municipal	secondary	-	Zhang et al., 2014
Turkey	60 L/(m2xday)	-	1,5 x 3,5 x 0,4; 1,5 x 3,5 x 0,32	Iris australis; Phragmites australis	municipal	secondary	-	Zhang et al., 2014
Columbia, Bogota Savannah	40 cm/day; 10 cm/day	4,5	4354m2 x 0,6m; 17416 m2 x 0,5m	-	municipal	secondary	-	Zhang et al., 2014
Indonesia, Jakarta	250 L/day	1	3,0 m2 x 0,4m	Typha sp.; Lemna sp.	laboratory	secondary	-	Zhang et al., 2014
Mexico, Sante Fe de la Laguna	-	0,5	1,5 x 1,5 x 0,6	Typha latifolia; Phragmites australis	municipal	secondary	-	Zhang et al., 2014
Thailand, Koh Phi Phi	400	-	2300 m2 x 0,7m; 750m2 x 0,6m	Canna, Heliconia; Papyrus	municipal	secondary	-	Zhang et al., 2014
Taiwan	1,35 cm/day	-	5,0 x 1,0 x 0,8	Phragmites australis	agricultural	secondary	-	Zhang et al., 2014
Spain, Pontevedra	17,6	-	8,3 x 6,0 x 1,4; 10 x 10 x 0,35	Phragmites australis; Juncus effusus	Winery	secondary	-	Zhang et al., 2014
China, Chongqing	26,9	-	433-3283 m2	Phragmites australis	municipal	-	-	Zhang et al., 2014
Brazil, Videira	-	-	60-50 m2	Typha sp - Zizaniopsis bonariensis	Sewage	-	VF-HF	Vymazal, 2013
China, Pugu Lake	-	-	433-3283 m2	Phragmites australis	Sewage	-	VF-HF	Vymazal, 2013
China Baishiyi	-	-	280-1120 m2	Cyperus alternifolius	Sewage	-	VF-HF	Vymazal, 2013
China, Fairy Mountain	-	-	1280-3179 m2	Cyperus alternifolius	Sewage	-	VF-HF	Vymazal, 2013
Mexico, Santa Maria	-	-	31,2-11,1 m2	Typha sp. - Phragmites australis	Sewage	-	HF-VF	Vymazal, 2013
Nepal, Thimi Municipality	-	-	150-150 m2	Phragmites karka, Canna latifolia - Phragmites karka	Sewage	-	HF-VF	Vymazal, 2013
China, Shenzhen	-	-	4800-4640 m2	7 species	Sewage	-	HF-VF	Vymazal, 2013
Turkey, Gebze	-	-	18-13,7 m2	-	Sewage	-	HF-VF	Vymazal, 2013
Japan, Embetsu, Hokkaido	-	-	160-160-336 m2	Phragmites australis	Milking parlor	-	VF-VF-HF	Vymazal, 2013
Japan, Bekkai, Hokaido 1	-	-	256-256-512-150 m2	not provided	Milking parlor	-	VF-VF-HF-VF	Vymazal, 2013
Japan, Bekkai, Hokaido 2	-	-	645-484-484-176 m2	not provided	Milking parlor	-	VF-VF-HF-VF	Vymazal, 2013
Japan, Kiyosato, Hokkaido	-	-	990-510-294-210-147 m2	not provided	Potato starch	-	VF-VF-VF-HF-VF	Vymazal, 2013
Japan, Hokkaido	-	-	572-446-187-195-75 m2	not provided	Pig urine	-	VF-VF-VF-HF-VF	Vymazal, 2013
Bangladesh, Dhaka	-	-	0,65-1,3-0,65 m2	Phragmites australis	Tannery	-	VF-HF-VF	Vymazal, 2013
New Zealand, Hamilton	-	-	3 m2 (total)	Baumeau articulata - Carex virgata	Sewage	-	HF-HF-VF	Vymazal, 2013
China	-	-	320 m2 (total)	Canna indica - Typha latifolia, Acorus calamus	Aquaculture	-	VFd-VFup	Vymazal, 2013
China, Wuhan	-	-	1,0-1,0 m2	Various	Sewage	-	VFd-VFup	Vymazal, 2013
Taiwan, Tainan County	-	-	16-16 m2	Typha angustifolia - Phragmites australis	Shrimp aquaculture	-	FWS-HF	Vymazal, 2013
Taiwan	-	-	200 m2 (total)	Typha latifolia, Phragmites australis	Sewage	-	FWS-FWS-HF	Vymazal, 2013
Thailand, Phayao Province	-	-	180-140 m2	Cyperus flabelliformis - Canna hybrida	Fish industry	-	HF-FWS	Vymazal, 2013
China Northern Ningbo	-	-	96-38,5 m2	Various	Sewage	-	HF-FWS-HF	Vymazal, 2013
China, Hangzhou City	-	-	1-2-2 m2	Vetiver zizanoides- Coix lacryma jobi - Vetiver zizanoides, coix lacryma jobi	Sewage	-	VFup-FWS-VF	Vymazal, 2013
Thailand, Koh Phi Phi	-	-	2300-750-750 m2	Cana sp., Heliconia sp. - Canna sp. - Cyperus papyrus	Sewage	-	VF-HF-FWS-Pond	Vymazal, 2013
Mexico, Santa fe de la Laguna	-	-	5080-2399-589 m2	Typha latifolia	Sewage	-	HF-Pond-HF	Vymazal, 2013
Average								

APPENDIX IV: CALCULATIONS

The calculations were based on the template used by Kadlec and Knight (1996). The system designed is separated into two for the calculations, the VSSF element (two beds in the proposed design) and the HSSF element. This was done because during the calculation of the pollutant removal when taking all elements as one system the change in BOD concentration during the removal process is not taken into account. This change in concentration is important since the C* and k values for both BOD and TSS change depend on the inflow concentration. In the VSSF element the inflow concentration of BOD can be considered as needing secondary treatment (Kadlec, 2009). However, after this element the concentration is reduced and in the HSSF element the BOD concentrations is considered as tertiary. In the design it is called secondary since pathogenic destruction is still necessary, which happens during tertiary treatment.

The sections of the calculations, and their values, will be shortly explained here:

- *Design Flow (m^3/d):* This is the amount of water entering the CW. The value of is based on the fact that one person produces about 0,2 m^3/d of wastewater per day (Henze & Comeau, 2008) with a population of 500 persons in one village this would bring a wastewater of 100 m^3/d. The extra 50 m^3/d is added as buffer. The population assumption of 500 was made based on a field study done by Scoccimarro et al., (1999) where a population of about 2600 was found spread over six different villages in Northern Thailand.
- *The influent concentrations (mg/L):* This value was based on the general values for wastewater pollutant concentrations. The values of Bod and TSS were reduced 65% and 70% respectively. This was done since those percentages form the removal efficiency of a pre-treatment unit (EPA, 2000).
- *Target effluent concentrations (mg/L):* The target effluent concentrations are based on the Thai Water Quality guidelines for class 2 water purification in the case of the HSSF element. The exception is BOD, the target concentration was taken as ‘1,5’ because the target needs to be higher than the background concentration. For the VSSF element a removal of 70% of the influent concentration for BOD, TSS, TN and Pathogens were since this element account for 2/3 of the CW. taken. For TP the target effluent was set to the Water Quality Guidelines since the phosphorus removal is expected to mostly take place in the VSSF element.
- *Reachable effluent concentrations (mg/L):* This concentration is an estimation of the possible effluent concentration based on the removal efficiency determined from the data collection. To calculate this concentration the following formula was used: $C_e = C_i \cdot \left(\frac{C_i \cdot RE}{100}\right)$
- *Wetland background concentration (mg/L) & Areal rate constant (m/yr):* The background concentrations/areal rate constant was retrieved from the literature, as explained in Appendix I.
- *The required area based on target (ha):* This calculation was based on the formula given in Appendix I and stated on the template.
- *Required area (ha)/(m^2):* This value is the largest value of the calculated values.
- *Effluent concentrations (mg/L):* The possible concentrations for the effluent of the CW element based on the required area using the formula stated.
- *Target reached:* The effluent concentration subtracted from the effluent concentration. A negative number indicates that the target could not be reached.
- *Reduction fraction to target/background:* The reduction in influent concentration necessary to reach the target/background concentration.



VSSF Elements

Design Flow (m3/d) Q= 150

		BOD	TSS	TN	TP	Pathogens
Influent concentrations (mg/L)	**Ci=**	70	60	40	10	100000000
Target effluent concentrations (mg/L)	**Ce=**	49	42	28	1	30000000
Reachable effluent concentrations (mg/L)	**Cr=**	*9,861617*	*13,47015186*	*18,00545*	*3,429663*	*3021978*
Wetland background concentration (mg/L)	**C*=**	5	11,58	1	0	10
Areal rate constant (m/yr)	**k =**	37	3000	8,4	6	95
Required area (ha) based on target	**A=**	0,057739	0,000848283	0,239678	2,101109	0,06938687

Formula =

$$A = \left(\frac{0.0365 \cdot Q}{k}\right) \cdot \ln\left(\frac{C_i - C^*}{C_e - C^*}\right)$$

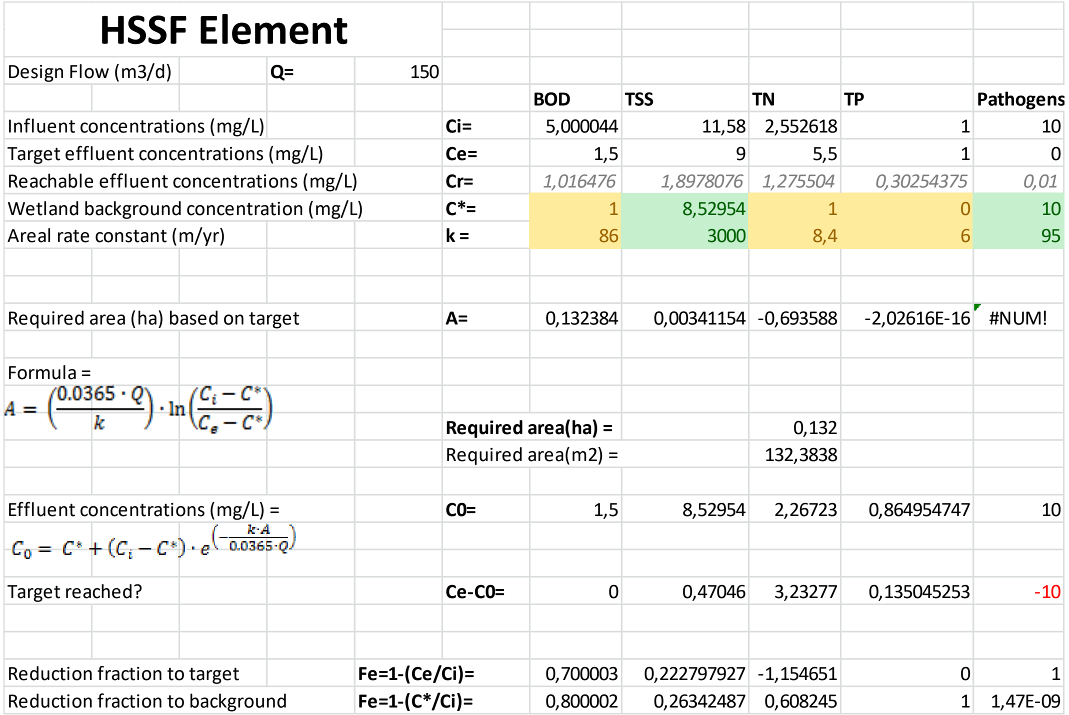
Required area(ha) = 2,101

Required area(m2) = 2101,109

		BOD	TSS	TN	TP	Pathogens
Effluent concentrations (mg/L) =	**C0=**	5,000044	11,58	2,552618	1	10

$$C_0 = C^* + (C_i - C^*) \cdot e^{\left(-\frac{k \cdot A}{0.0365 \cdot Q}\right)}$$

		BOD	TSS	TN	TP	Pathogens
Reduction fraction to target	**Fe=1-(Ce/Ci)=**	0,3	0,3	0,3	0,9	0,7
Reduction fraction to background	**Fe=1-(C*/Ci)=**	0,928571	0,807	0,975	1	0,9999999



HSSF Element

Design Flow (m3/d) Q= 150

		BOD	TSS	TN	TP	Pathogens
Influent concentrations (mg/L)	**Ci=**	5,000044	11,58	2,552618	1	10
Target effluent concentrations (mg/L)	**Ce=**	1,5	9	5,5	1	0
Reachable effluent concentrations (mg/L)	**Cr=**	*1,016476*	*1,8978076*	*1,275504*	*0,30254375*	*0,01*
Wetland background concentration (mg/L)	**C*=**	1	8,52954	1	0	10
Areal rate constant (m/yr)	**k =**	86	3000	8,4	6	95
Required area (ha) based on target	**A=**	0,132384	0,00341154	-0,693588	-2,02616E-16	#NUM!

Formula =

$$A = \left(\frac{0.0365 \cdot Q}{k}\right) \cdot \ln\left(\frac{C_i - C^*}{C_e - C^*}\right)$$

Required area(ha) = 0,132

Required area(m2) = 132,3838

		BOD	TSS	TN	TP	Pathogens
Effluent concentrations (mg/L) =	**C0=**	1,5	8,52954	2,26723	0,864954747	10

$$C_0 = C^* + (C_i - C^*) \cdot e^{\left(-\frac{k \cdot A}{0.0365 \cdot Q}\right)}$$

		BOD	TSS	TN	TP	Pathogens
Target reached?	**Ce-C0=**	0	0,47046	3,23277	0,135045253	-10
Reduction fraction to target	**Fe=1-(Ce/Ci)=**	0,700003	0,222797927	-1,154651	0	1
Reduction fraction to background	**Fe=1-(C*/Ci)=**	0,800002	0,26342487	0,608245	1	1,47E-09