Constructed wetlands:

A potential alternative technology for the treatment of wastewaters from institutions in Rwanda

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2017

Abstract

In Rwanda, it is nearly impossible to collect domestic wastewater with centralized systems, due to the lack of financial investments and the sanitation chains; however, on-site systems such as constructed wetlands may be feasible for wastewater treatment in schools and other similar sized institutions. Constructed wetlands are an alternative technology to conventional wastewater treatment to explore due to their operational simplicity and requirements. This project provides technical information and review of two constructed wetland designs (surface flow and subsurface flow constructed wetlands) and proposes a horizontal subsurface flow constructed wetland for Indatwa n'Inkesha school. The treated effluent will meet the regulatory targets of Rwanda Utilities Regulatory Authority for domestic wastewater discharge and could be reused in agriculture. It is expected that the adoption of constructed wetland technologies in Rwanda will depend on the land availability, sanitation chains and safety factors. Further studies are required to understand the viability of this technology, and to provide monitoring data about their long-term performance.

Key words

Constructed wetlands, contaminant, domestic wastewater, institutions, pollutant, Rwanda, treatment.

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List of acronyms

BOD: Biochemical Oxygen Demand.

CW: Constructed Wetland.

GEPD: Georgia Environmental Protection Division.

HFB: Horizontal Flow Bed.

ITRC: Interstate Technology & Regulatory Council.

JMP: Joint Monitoring Program.

MININFRA: Ministry of Infrastructure.

MLWS: Master of Land and Water Systems

N: Nitrogen

P: Phosphorus

REMA: Rwanda Environmental Management Authority.

RURA: Rwanda Utilities Regulatory Authority.

RWFA: Rwanda Water and Forest Authority

SF: Surface Flow.

SSF: Subsurface Flow.

TSS: Total Suspended Solids.

UBC: University of British Columbia.

UN: United Nations.

UK: United Kingdom

USA: United States of America.

USEPA: United States Environmental Protection Agency.

VFB: Vertical Flow Bed.

WASAC: Water and Sanitation Corporation Ltd.

WHO: World Health Organization.

Acknowledgements

I offer my enduring gratitude to the faculty, staff and my fellow students on the Master of Land and Water Systems (MLWS) program at the University of British Columbia (UBC); without their ideas and knowledge transferred to me, the realization of this project could have met insurmountable challenges.

Special thanks are due to my supervisors Dr. Hans Schreier, Ms. Julie Wilson, and my professional co-supervisor Dr. Ken Hall; they opened my mind to a new sphere of knowledge during this long journey with them. There is no doubt that this project could not be successfully completed without their enthusiastic contribution. I also wish to extend my gratitude to Dr. Les Lavkulich, and Dr. Heather MacKay Brown for their endless support throughout this work.

I express my sincere thanks to the UBC MasterCard Foundation (UBC MCF) for giving me the opportunity to be a part of the UBC MCF scholars and for supporting my education. I have no doubt that the knowledge acquired through this program will highly contribute to my work for the community.

Chapter 1. Introduction

The discharge of untreated domestic wastewater can lead to health and ecological problems (Table 1). The Ministry of Infrastructure of Rwanda recognizes that wastewater should be treated prior to surface discharge or reuse, and that Rwanda's priority should be how to control hazardous materials with technologies that the country can afford to pay for and maintain. Unfortunately, it is nearly impossible to treat domestic wastewater with centralized wastewater treatment systems due to the lack of financial investment and the sanitation chains in Rwanda; wastewater is managed on-site mostly with septic tanks, soak pits, and only select hotels and some hospitals have wastewater treatment systems (MININFRA, 2014).

Schools and other similar sized institutions have difficulties managing their wastewater with soak pits or septic tanks due to its high volume; the overflows are reused or discharged untreated, polluting the receiving ecosystems. In Rwanda, wastewaters from schools are mainly greywater (mostly from kitchens, washrooms and clothes washing) due to the use of dry-pit latrines, the production of black water (water from toilets) is limited. An alternative on-site technology such as constructed wetlands is required to treat greywater from schools and other similar sized institutions in Rwanda, in order to align with Rwanda Utilities Regulatory Authority (2009) directive for tolerance levels of contaminants in domestic wastewater discharge and to safely reuse the treated effluents.

Constructed wetlands (CWs) are manmade features developed to mimic the functions of natural wetlands to improve water quality (ITRC, 2003). In CWs, the pollutants are removed through physical, chemical and microbiological processes. Based on the flow regime, constructed wetlands can be classified into surface flow CWs and subsurface flow CWs, each one having its own advantages and disadvantages. For example; surface flow CWs are associated with lower cost but require large surface area and can provide breeding ground for insect vectors, while subsurface flow CWs require smaller surface area and can avoid the problem of insect vectors of surface flow constructed wetlands but require high capital investment.

The use of constructed wetlands for wastewater treatment is not a new idea; by 1994, there were already more than 500 in the USA and 65 in Canada used for municipal, stormwater and agriculture wastewater management (Kirby, 2002). In Tanzania, the use of constructed wetlands has gained popularity for wastewater treatment in schools since 1995 (Kimwaga et al., 2013). Financially, CWs have a significant lower total lifetime cost and often lower capital cost than conventional treatment (ITRC, 2003), due to their simplicity and often due to zero energy and zero chemicals usage (Mara 2003).

This project assesses the feasibility of constructed wetlands technology for wastewater treatment in schools and other similar sized institutions in Rwanda, it proposes a constructed wetland design for Indatwa n'Inkesha school because the untreated greywater is channelized into banana plantation around this school and can increase the risks of humans and ecological contamination. The local topography and the constant climate of Rwanda are ideal for the use of this type of technology; however, land availability and insect vectors such mosquitos could be the restricting factors. Thus, an ideal constructed wetland for Rwanda should require minimum operational costs and maintenance activities with lower risks of human and ecological toxicities, while providing high performance for pollutant removal.

In this document, the words contaminant and pollutant are used interchangeably. However, according to Chapman (2006), contamination means the presence of a substance where it should not be or at concentration higher than background concentration, while pollution is a contamination resulting in adverse biological effects to resident communities.

1.1. Objectives

The general objective of this project is to assess the potential of using constructed wetland technology for the treatment of wastewater from schools and other similar sized institutions in Rwanda. Specifically, this project aims to provide technical information to fill the gap of limited knowledge about this type of technology in Rwanda, to raise awareness about the use of this type of technology for domestic wastewater treatment in schools and other similar sized institutions in Rwanda, to propose a constructed wetland design for Indatwa n'Inkesha school, and to explore options for how outlet water can be reused, or safely discharged.

Chapter 2. Methods

2.1. Scope of the project

This project focuses on the use of constructed wetlands for the treatment of wastewater from institutions in Rwanda, in order to meet the regulatory targets of Rwanda Utilities Regulatory Authority for domestic wastewater discharge. This is not a design manual but can serve as a reference document for further detailed design of constructed wetlands in Rwanda and in other countries with similar conditions. The target audience includes, but is not limited to wastewater engineers, schools and similar sized institutions, and government institutions responsible for water resource management such as Rwanda Utilities Regulatory Authority (RURA), Rwanda Environmental Management Authority(REMA), Rwanda Water and Forest Authority (RWFA), and Water and Sanitation Corporation Ltd (WASC).

2.2. Data sources and discussion

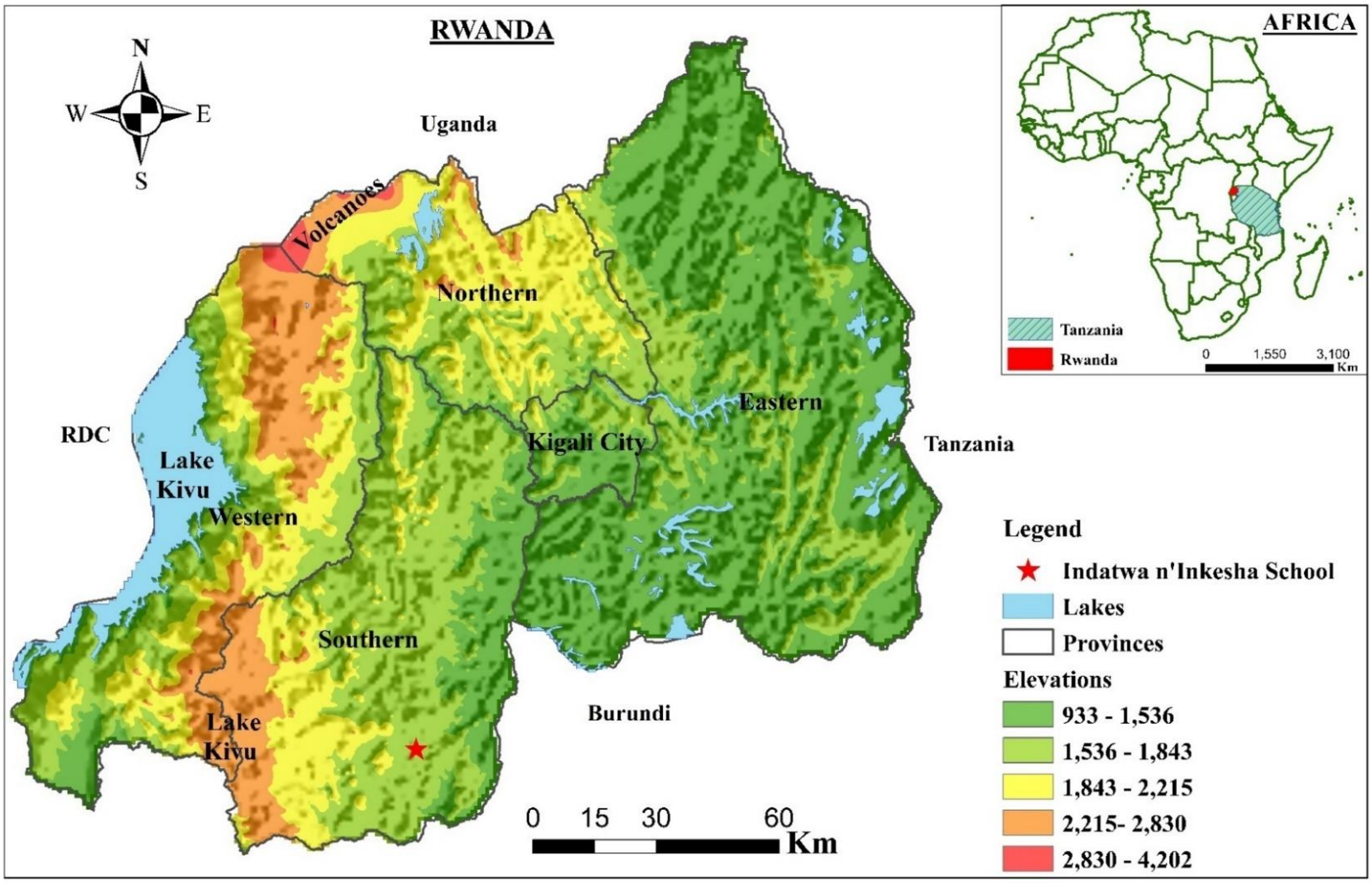
This project used secondary information sources, through a literature review, and best management practice cases (Tanzania and USA). The gathered information is discussed in the context of local challenges and opportunities, and the Rwanda Utilities Regulatory Authority directives (2009) is used as the basis for acceptable levels of contaminants in domestic wastewater. Indatwa n'Inkesha school has be selected as a case study for CW design, due to the amount of wastewater it generates, land availability, and opportunities for wastewater reuse. Given the scarcity of systematic wastewater data in Rwanda, certain assumptions were made about the present contaminants and their concentrations based on the general characteristics of the domestic wastewater.

2.3. Overview of the country's profile

Rwanda is a land-locked country of 26,338 km^2, located in Central-East Africa, and a few degrees south of the Equator, with four administrative provinces and the City of Kigali (Map 1). The population is predominantly rural and pastoral farmers with more than 475 people per square kilometer (REMA, 2011).

Geographically, Rwanda is dominated by mountains (Map 1); the entire country is at a high elevation, characterized by lowlands in the East, a plateau in Centre, and the Congo-Nile watershed ridge in West (REMA, 2011).

Map 1: The topographic map of Rwanda.



The tropical climate of Rwanda is characterized by two rainy and two dry seasons each year, with minor variations in the local microclimate conditions due to the mountainous terrain; these can be classified into the dry and hot lowland zone in East, the urban climate zone in Kigali, the temperate zone of the central highland, the sea climate zone around Kivu lake, and the mountain climate in the high elevations of the Congo-Nile watershed ridge (Henninger, 2013).

With little variation throughout the year, the temperature in high regions varies between 15 °C and 17 °C, and 19 °C to 29 °C in the intermediate elevation. The average annual rainfall exceeds 750 mm (REMA, 2011).

Chapter 3. Literature review

3.1. Domestic wastewater characteristics

Domestic wastewater is the water that has been used by a community and contains waste materials; according to Mara (2003), it is generally composed of 99.9% water and 0.1% solids (Mara, 2003), and it can be classified into greywater (water that have not been in contact with toilet water) and black water (wastewater from toilets or sewage). Table 1 summarize the chemical and microbiological composition of domestic wastewater based on 240-750 L/capita/day water consumption and greywater (from bathtubs, showers, hand basins, washing machines and Kitchen).

Table 1: The composition of untreated domestic wastewater (typical) and greywater (measured in German households).

Major parameters	Greywater (mg/L)	Domestic wastewater (mg/L)	Health and ecological risks
Suspended solids, total (TSS)	30-70	120-400	Can lead to the development of sludge deposits and anaerobic conditions in the aquatic environment.
Biochemical Oxygen Demand (BOD_5)	250-550	110-350	Can lead to the depletion of natural oxygen in aquatic environment.
Chemical Oxygen Demand (COD)	400-700	250-800	
Nitrogen (total as N)	10-17	20-70	Can lead to eutrophication and ground water contamination
Phosphorus (total as P)	3-8	4-12	
Total coliform (No./100ml)	10^2-10^6	10^6-10^{10}	Can lead to transmission of pathogenic diseases
Faecal coliform (No./100ml)	10^2-10^6	10^3-10^8	

Source: Adapted from Srivastava (2014), Nolde (1995)

In Rwanda, 96% of the population uses on-site dry pit latrines, while few people (1.4%) use flush toilets, only 76% of the population have access to improved drinking water sources and the average water consumption is around 20 L/capita/day (WHO/UNICEF JMP, 2015). Wastewater is managed on-site by the property owners, mostly using septic tanks and soak pits, however, schools and other similar sized institutions generate high volume of greywater which is difficult to manage with soak pits and septic tanks, so instead they may reuse it in agriculture because of its fertilizing quality or discharge it untreated, although it may contain contaminant levels exceeding the RURA's tolerant levels for domestic wastewater discharge (Table 2).

Table 2: Rwanda Utilities Regulatory Authority (2009), contaminant tolerance levels for domestic wastewater discharge.

Parameters	Limits
TDS, mg/L	≤1500
TSS, mg/L	≤50
N (total), mg/L	≤30
P (total), mg/L	≤5
BOD, mg/L	≤50
COD, mg/L	≤400
Coli forms, No./100mL	≤400

The discharge of untreated domestic wastewater can lead to various health and environmental problems (Table 1). According to Rwanda's Ministry of Health (2012), water borne and excreta related diseases such as diarrhea, Escherichia histolytica, Escherichia coli and ascariasis accounted for nearly two thirds of all the neglected tropical diseases (≈737,000 cases) in 2012. It is crucial for a highly populated country like Rwanda with economic water scarcity, to treat the domestic wastewater before its discharge or reuse in order to reduce human and ecological contamination, while reducing the stress on the available freshwater.

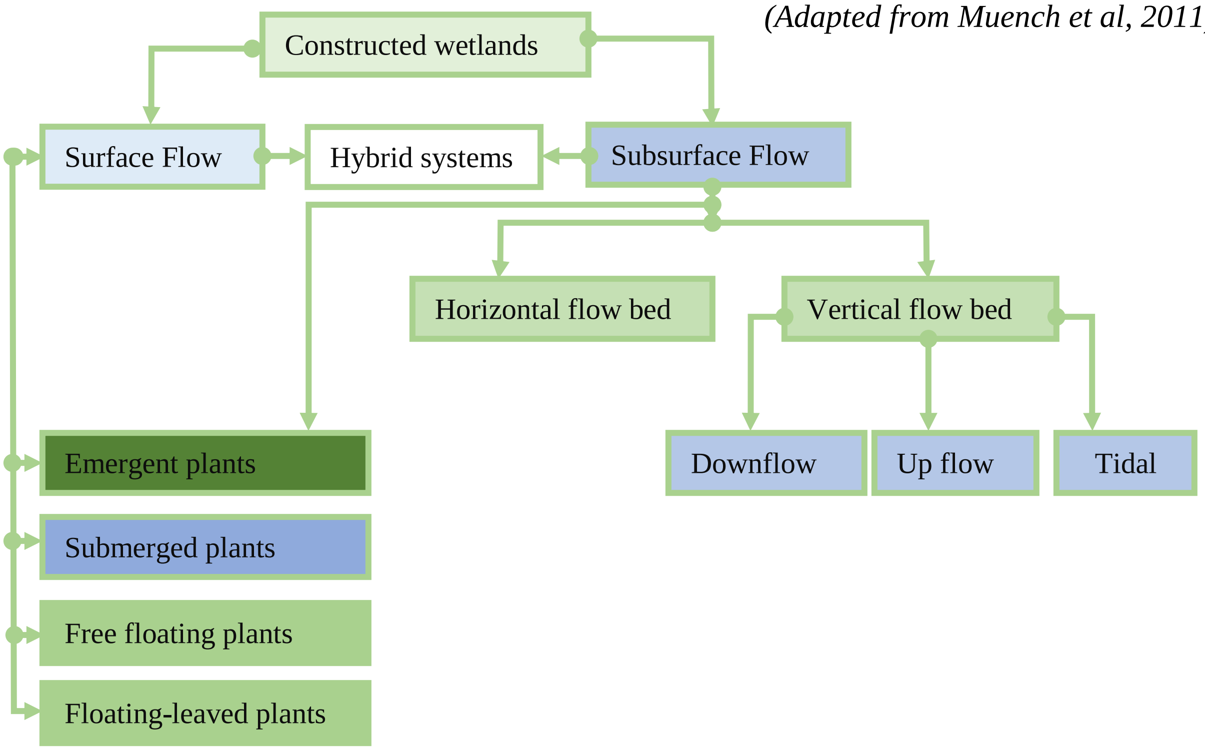
3.2. Constructed wetlands

3.2.1. Introduction

Constructed wetlands are manmade features developed to utilize the natural functions of wetland vegetation, soils and their microbial population in a controlled manner to treat wastewater (ITRC, 2003). Constructed wetlands can provide additional benefits including habitants for wildlife and plants, recreational and aesthetic benefits (IRTC, 2003). According to UN-HABITAT (2008), constructed wetlands are the alternative technology for wastewater treatment in developing countries, but their adoption rates are slow due to the limited technical capacity and awareness.

Constructed wetlands can be classified based on the flow regime or the type of the plants as shown in Figure 1. The flow regime can be classified into Surface Flow (SF) and Subsurface Flow (SSF) constructed wetlands discussed in the following sections.

Figure 1: Classification of constructed wetlands
(Adapted from Muench et al, 2011)



3.2.1.1. Surface flow constructed wetlands

Surface flow constructed wetlands consist of surface water exposed to the atmosphere (20-40 cm deep), containing often 20-30 cm of rooting soils, and the intended flow path through the system is horizontal (Figure. 4) (Vymazal, 2010). Surface flow CWs provide greater water flow control, and their water budget can be estimated using the Equation 1 (USEPA, 2000).

$$\frac{dV}{dt} = Qi - Qo + Qc - Qb + Qsm + (P - ET - I)\,A \qquad \text{Equation 1}$$

$\frac{dV}{dt}$ (rate of change in water volume)

Qi (input wastewater flow rate)

Qo (output water flow rate)

Qc (catchment runoff rate)

Qb (bank loss rate)

Qsm (snowmelt)

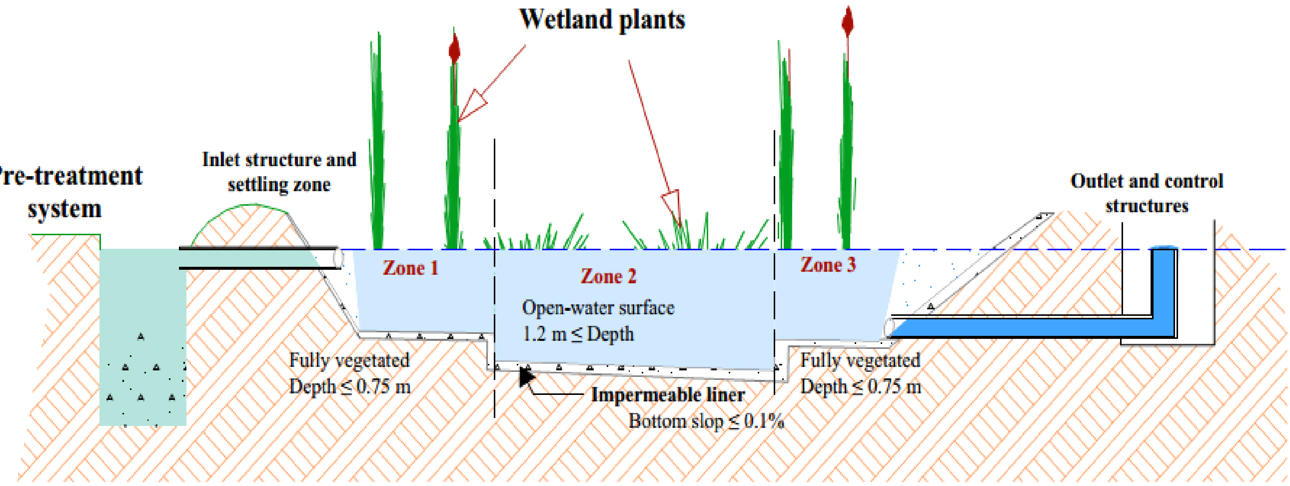
P (precipitation)

ET (evapotranspiration)

I (infiltration to ground)

A (wetland top surface area)

Figure 2: A typical section of a surface flow constructed wetland (adapted from USEP, 2000)



3.2.1.2. Subsurface flow constructed wetlands

Subsurface flow constructed wetlands consist of a substrate of porous media to keep the water level totally below the surface: they can even be walked on and they avoid the mosquito problems of surface flow CWs (USEPA, 2000). Depending on the flow direction, subsurface constructed wetland can be classified into vertical flow bed CWs and horizontal flow bed or vegetated submerged bed CWs (Figure 3&4) (Wallace, 2005).

In general, the subsurface flow constructed wetlands have little oxygen transfer, though, the vertical flow bed CWs are far more aerobic and require less land than horizontal flow CWs (Vymazal, 2010). The use of vertical flow bed CWs did not gain much popularity like other types of CWs due to the higher operational requirements and the necessity to pump the wastewater on the wetland surface (Vymazal, 2010).

Figure 3: A typical section of a vertical flow bed constructed wetland

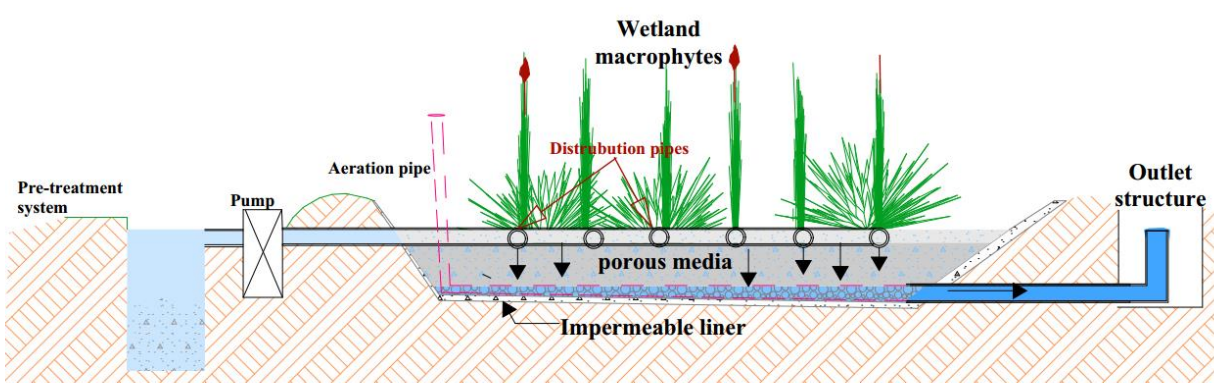
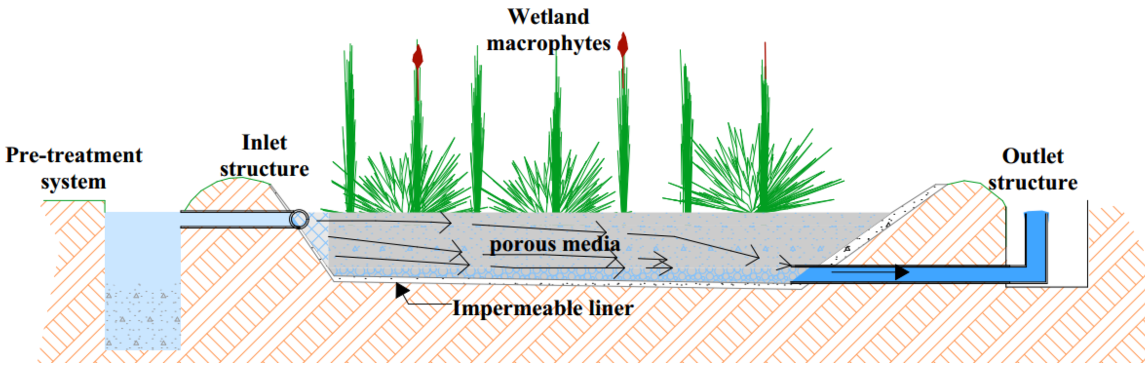


Figure 4: A typical section of a horizontal flow bed constructed wetland



As a secondary treatment technology, constructed wetland treatment requires the pre-treatment of wastewater (primary treatment) to increase the performance and to reduce the required surface area, regardless of the type of CW used (Kirby, 2002). The pre-treatment requirements defer depending on the wastewater sources; black water may require high pre-treatment than greywater. In addition, one or more types of constructed wetlands can be combined to form a hybrid system in order to exploit the specific advantages of each system (Table 3) (Muench et al, 2011).

Table 3: Summary of advantages and disadvantages of different constructed wetland types.

CW types	Advantages	Disadvantages
Surface flow	High removal rates of pathogens, Aesthetics, and wildlife habitat.	Large area, breeding ground for vectors, odor problems, high water loss, exposure to surface wastewater
Horizontal flow bed	High denitrification, low costs, small area, low odor and vectors.	Clogging problems, lower pathogenic and nutrient removal rate.
Vertical flow bed	High nitrification, smaller area, low odor and vectors.	Expertise and pumps requirement, high capital cost and maintainance. Low pathogenic and nutrient removal rate.

3.2.2. Contaminant removal processes in constructed wetlands

In general, the processes that contribute to pollutant removal in a constructed wetland are physical filtration and sedimentation; biological uptake and transformation of nutrients by bacteria and plant roots, and chemical precipitation, absorption and decomposition (Table 4).

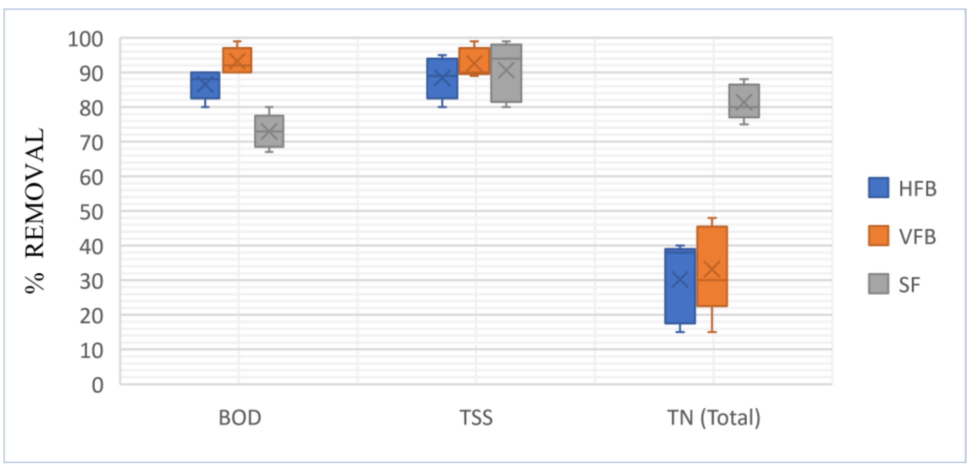
Table 4: Pollutant removal mechanisms in constructed wetlands.

Parameter	Removal processes
Suspended solids	Sedimentation and filtration.
Soluble organics	Aerobic and anaerobic microbial degradation
Nutrients	Volatilization, absorption, denitrification, matrix sorption, plant uptake, ammonification and nitrification
Pathogens	Sedimentation and filtration, natural die-off, predation, Ultraviolet radiations and antibiotics of macrophytes roots.

Source: Adapted from UN-HABITAT (2008)

Wastewater is treated by supplying it with oxygen, so that bacteria can utilize the wastewater contents as food (Mara, 2003). The microbiological activities involved in constructed wetland processes are typically temperature dependent; therefore, constructed wetland efficiencies may vary seasonally, but the average performance over the year is acceptable (Figure 5) (Kedlec, 2001). If the effluent has to meet stringent discharge standards at all times, tertiary treatment will be required (Kirby, 2002).

Figure 5: Typical contaminant removal ratios (%) for different types of CWs.



Source: Adapted from Muench, et al. 2011

Today, various methods have been proposed to compute the pollutant removal and to predict different reactions (BOD, TSS, TN, …), each method having its own strengths, weaknesses and assumptions because some parameters are difficult to measure (USEPA, 1999). The volumetric equation (Equation 2) by Reed et al. (1995), and the areal equation (Equation 4) by Kadlec & Knight (1996) are among the fundamentally methods commonly used (USEPA, 1990).

$$\frac{Co}{Ci} = \exp(-K_{vt}t) \qquad \textit{Equation 2}$$

Where

Co = effluent target concentration (mg/L)

Ci = influent pollutant concentration (mg/L)

t = theoretical hydraulic detention time (day)

K_{vt} = temperature dependent first-order rate volumetric reaction rate constant (day^{-1})

The wastewater detention time can be estimated using the Equation 3, with wetland porosity representing the ratio of the actual volume available for water and the theoretical basin volume.

$$t = \frac{Ve}{Q} \qquad \textit{Equation 3}$$

Where t= hydraulic detention time (days),

V= volume of the wetland basin (m^3),

e= wetland porosity,

Q= average flow rate (m^3/day).

The Kadlec & Knight (1996) method introduced the concept of background concentration of pollutants (Equation 4), when the pollutant concentration is less than the background concentration; wastewater is not in the treatability range of constructed wetlands, therefore, an alternative treatment technology is required.

$$\frac{Co-C*}{Ci-C*} = \exp\left(-\frac{Kta}{q}\right) \qquad \textit{Equation 4}$$

Where:

Ci = influent pollutant concentration (mg/L)

Co = effluent target concentration (mg/L)

K_{ta} = temperature dependent first-order areal rate constant (m/day)

C* = pollutant background concentration (mg/L)

q = hydraulic loading rate (m/day)

$$K_{ta} = K_{20} * \Theta^{(T-20)} \qquad \textit{Equation 5}$$

Where K_{20} = first-order areal rate constant at 20 ºC (m/day)

T = operational temperature of the system (ºC)

Θ = temperature coefficient for rate constant

$$q = \frac{Q}{A} \qquad \textit{Equation 6}$$

Where A= surface area (m^2)

Q = average flow rate (m^3/day)

Table 5 summarizes different model parameters for the Kadlec & Knight (1996) method.

Table 5: Constants for Kadlec and Knight method (1996).

Parameters	K_{20} (m/day)		Θ		C* (mg/L)	
	SF	HFB	SF	HFB	SF	HFB
BOD	0.1753	0.3205	1.00	1.057	3.5+0.053Ci	3.0
TSS	2.7397	0.1189	1.00	1.00	5.1+0.16Ci	6.0
N (total)	0.0673	0.0274	1.05	1.05	1.5	1.5
P (total)	0.0328	0.0249	1.00	1.097	00.2	0.0
Fecal Coliform	0.2055	0.274	1.00	1.003	300 (cfu/100ml)	200 (cfu/100ml)

Source: Adapted from Wallace (2005).

SF= Surface Flow, and HFB = Horizontal Flow Bed

3.2.3. Constructed wetland configuration

3.2.3.1. Constructed wetlands dimensioning

The design of constructed wetlands is governed by wastewater characteristics and treatment targets; however, constructed wetlands should be designed for minimal maintenance, fostering the pollutant removal processes, and keeping the design simple because complex designs are more prone to failure (ITRC, 2003).

While the dimensions and hydraulic parameters (surface area, volume, detention time, loading rate, …) can be estimated using mathematical equations, the shape of a surface flow constructed wetland is often a function of the site characteristics (USEPA, 2000). The length and the width of a subsurface constructed wetland are often determined using Darcy’s law (Equation 7) (USEPA, 2000).

$$Q = K_s A_c S \qquad \textit{Equation 7}$$

Where Q= average flow rate (m^3/d),

Ks = hydraulic conductivity of a unit area of the medium perpendicular to the flow direction (m^3/m^2/d),

A_c =Total cross-sectional area perpendicular to the flow (m^2), S= hydraulic gradient of the water surface.

The water depth can be estimated based on the need to keep the wastewater in contact with the plant roots depending on the design guidelines. In the UK, a water depth of 50-80 cm is recommended while a water depth of 95 cm is recommended in Australia (Wallace, 2005).

The surface area of a constructed wetland required for the removal of a given pollutant can be obtained from rearranging the pollutant removal equations, the “rule of thumb” method or from the areal loading rate method where a maximum loading rate per unit area is specified, for example:

- ✓ After rearranging Equation 4 and substituting the hydraulic loading rate with Equation 6, the required surface area for the removal of a particular contaminant using the Kadlec & Knight (1996) method can be obtained using Equation 8:

$$A=\frac{Q*[ln(Ci-C*)-ln(Co-C*)]}{Kta} \qquad \textit{Equation 8}$$

- ✓ The “rule of thumb” has been used for long time, setting the horizontal flow bed CWs between 3-10 m^2 PE^{-1} (population equivalent) (Wallace, 2005), the vertical flow bed CWs between 2-5 m^2 PE^{-1}, and the surface flow CWs between 10-20 m^2 PE^{-1} (Deun, et al., 2016).
- ✓ The USEPA (2000) method suggests the area loading rates (Table 6) that can be used to determine the required surface area (Equation 9). Unfortunately, no criteria are provided for the required area for the removal of pathogens.

$$A=\frac{QCi}{ALR} \qquad \textit{Equation 9}$$

Where A= surface area (m^2)

Ci = influent pollutant concentration (mg/L)

ALR= area loading rate (mg/m^2.day)

Table 6: Area Loading rates for USEPA method

Parameters	**Area loading (mg/m^2. day)**		**Effluent concentration (mg/L)**	
	HFB	**SF**	**HFB**	**SF**
BOD	6000	4500	30	<20
		6000		<30
TSS	20000	3000	30	<20
		5000		<30

Source: USEPA (2000)

According to the USEPA (2000) guideline, the design of surface flow CWs with the USEPA method is ideally based on a 3-zone model (Figure 2), while the surface area of a vegetated flow bed CW is divided into a primary treatment zone (30%) and secondary treatment zone (70%). It also recommends using 1% of the clean hydraulic conductivity of the bed in the primary treatment zone, 10% in the secondary treatment zone, and keeping water depth at least at 5 cm below the ground level.

3.2.4.1. Constructed wetland substrates

Constructed wetland substrates filter and trap particles, they serve as a medium for plant and microbial growth, and facilitate the distribution of wastewater through the depth of the bed (Buckley & Arumugam, 2016). The substrates are typically sand, gravel, or crushed stone (Table 7), due to their availability and lower cost in most places. According to Vohla et al., (2009), these substrates are not particularly effective at removing Phosphorous due to their coarseness, other substrates such as clay aggregates and steel slag have been found to be effective for its removal. To reduce the potential clogging risks over the years, safety factors should be applied to the media hydraulic conductivity (Wallace, 2005) and the substrates in inlet zone should be checked regularly or changed accordingly.

Table 7: Hydraulic conductivity values of substrate materials commonly available in Rwanda.

Substrate	Hydraulic conductivity (clean), m/d
5-10 mm gravel	34 000
14 mm fine gravel	15 0000
22 mm coarse gravel	64 000
19 mm rock	120 000

Adapted from USEPA (2000)

3.2.4.2. Constructed wetland vegetation

Constructed wetland vegetation can be classified into emergent, submerged, and floating plants, usually 4-6 plants per square meter are planted (Vymazal, 2010). The vegetations must be able to withstand waterlogged conditions, loading entering the system, the substrate type used, and the climate of the area; native species are typically recommended (Muench et al, 2011). In addition to nutrient uptake, wetland plants stabilize substrate materials, provide roots surface area for bacteria to grow on, and provide oxygen to the area around the roots. Increasing the diversity of plant communities can improve the efficiency of the constructed wetland (Buckley & Arumugam, 2016), although, it is difficult to keep the polyculture unless there is a physical barrier, so the plants do not overgrow each other (USEPA, 2000). Table 8 highlights potential plants for constructed wetlands commonly used in the East African region.

Table 8: Potential plants for subsurface flow CWs, commonly used in East African region

Plant names	**Common names**	**Uptake capacity (kg/ ha. Year)**	
		Nitrogen	Phosphorous
Cyperus papyrus	Papyrus	1100	50
Phragmites mauritianus	Reed	2500	120
Typha sp.	Cattail	1000	180
Scirpus sp.	Bulrush	-	-
Vetiveria zizanoides	Vetiver	-	-

Source: Adapted from Kimwaga et al. (2013); Kivaisi (2001).

3.2.5. Constructed wetland operation and maintenance

Constructed wetlands require simple but regular maintenance; the hydraulic and organic load should be checked regularly and should not exceed the design values, and proper management of organic loadings can also help to control the mosquito population (IRTC, 2003). While single unit constructed wetlands can achieve the desired treatment level, incorporating multiple cells facilitates maintenance activities (GEPD, 2002). Whether CW Plants should be harvested or not is still a debate, but according to Wallace (2005), plants need to be harvested if they affect operational and maintenance activities. According to Kimwaga (2013), the common problems related to constructed wetlands in sanitation chains in Tanzania included the failure to address clogging and flooding, leakage, overloading and stormwater runoff; they can all be addressed through proper planning by incorporating safety factors and regular monitoring.

3.2.6. Treated effluent management

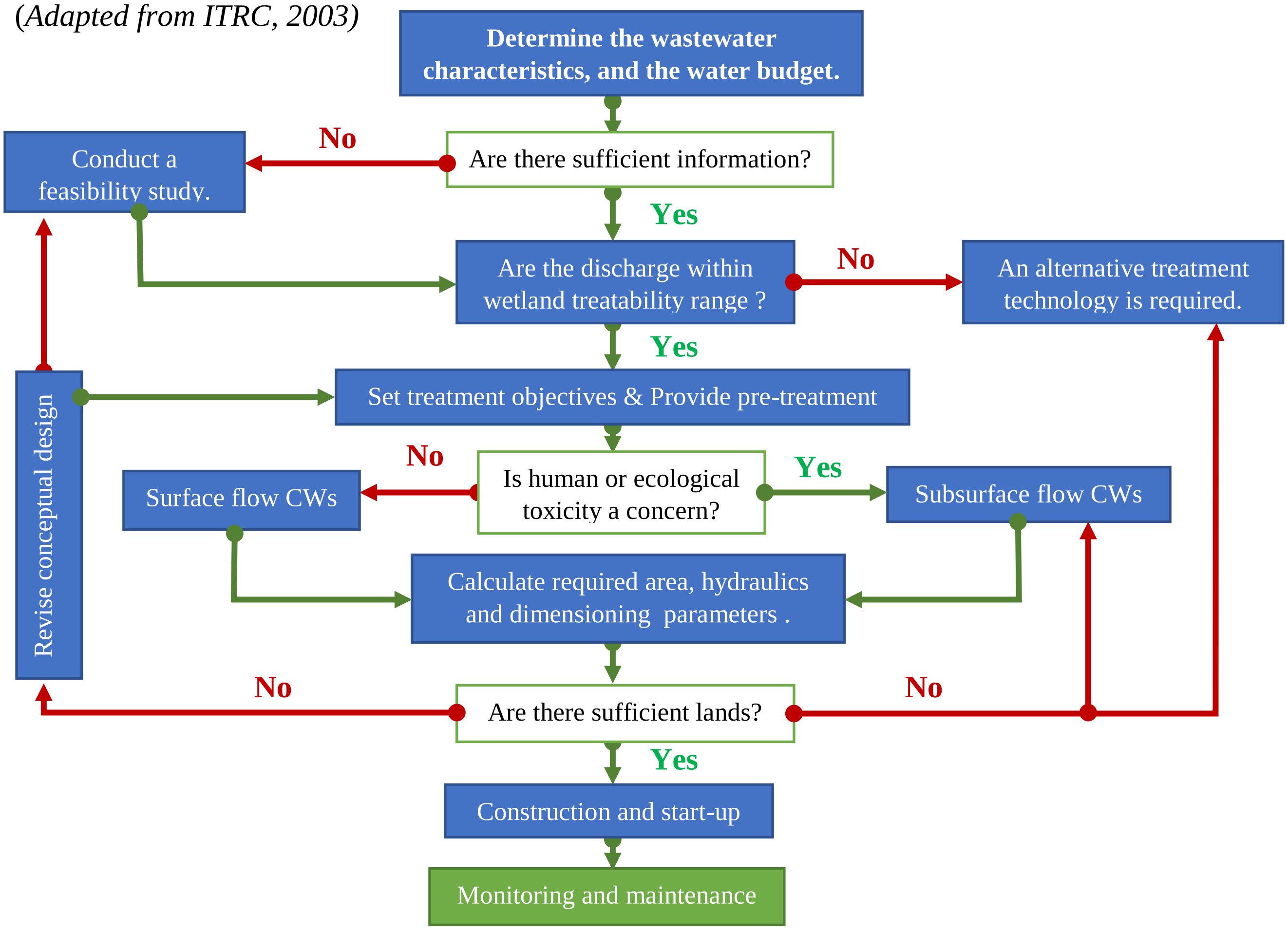
Constructed wetlands can be designed to meet regulatory targets so that water can be reused or safely discharged into the receiving water bodies. According to USEPA (2012), treated effluent has the potential for agricultural reuse, recreational reuse, environmental reuse, industrial reuse, and groundwater recharge. The reuse of treated domestic wastewater is a great opportunity to reduce the demand on municipal drinking water used in garden watering and other activities that require lower water quality. In Tanzania, the effluent of a constructed wetland at Ruaha secondary school is used to grow elephant grass for their cows, while the wetland is used in student education (Kimwaga, et al, 2013).

Chapter 4. Discussion: constructed wetlands in Rwanda.

4.1. Introduction

In 1990, Rwanda was categorized among countries experiencing water scarcity based on the available renewable water per person per year (<1000 m^3); therefore, there is a need to protect and properly manage the available water resource through saving, recycling and pollution control (Kivaisi, 2001). Unfortunately, it is nearly impossible to control pollutants in domestic wastewater with centralized wastewater treatment systems due to the lack of financial investment. Only on-site systems such as constructed wetlands can be used to treat wastewater from schools and other similar sized institutions based on the wastewater production. As there are not yet the guidelines governing the use of constructed wetlands in Rwanda, the adoption of this type of technology may follow the decision tree in Figure 6.

Figure 6: Adoption of constructed wetlands decision tree
(Adapted from ITRC, 2003)



4.2. Case study: Designing a constructed wetland for Indatwa n'Inkesha school

Indatwa n'Inkesha school is a secondary boarding school, located in the Southern province of Rwanda (Map 1), with around 1200 students and staff. They generate 12 m^3/day of wastewater during weekdays and 24 m^3/day during weekends (due to clothes washing); the lower water consumption can be associated with the use of dry pit latrines and clothes hand washing. The wastewater in Indatwa n'Inkesha school is mainly greywater (from kitchens, washrooms and clothes washing), and it is directly channelized into agricultural fields (banana plantations) around the school, as it is considered to have fertilizer quality.

4.3. Design considerations

4.3.1. Selection of the constructed wetland type and designing parameters

The treatment targets for the CW for Indatwa n'Inkesha school are to meet RURA (2009) targets for domestic wastewater discharge, and to reuse the treated effluent in agriculture based on USEPA (2012) guidelines (Table 9), as there is not yet a national guideline for domestic wastewater reuse in agriculture. In addition, the constructed wetland will serve as an instructional tool to teach wetland processes, wastewater treatment and water conservation practices. Considering the treatment targets, safety factors (due to the proximity of the site to the school and potential mosquito problems from stagnant water), and the need to develop a system with little operational and minimum maintenance activities (using gravitational flow and zero energy), a decision was made to design a horizontal flow bed CW for this school. Wastewater discharge is assumed to be the main contributor to the system due to the lack of required data to determine the water budget. In addition, wastewater is assumed to have greywater characteristics based on its main sources (kitchen, washrooms and clothes washing), however, there is uncertainty about the contaminants levels.

Table 9: Design objectives for selected contaminants

Pollutants	Discharge	RURA (2009)	USEPA (2012)
TSS (mg/L)	85	≤50	≤30
BOD (mg/L)	110	≤50	≤30
N (total) (mg/L)	20	≤30	≤25

Additional design parameters are assumed as follows:

Maximum discharge flow (Q): 24 m^3/day Substrate: 20 mm gravel bed.

The bottom gradient: 1%,

Hydraulic conductivity: 340,00 m/day,

Safety factors: 1% (primary treatment zone), and 10% (secondary treatment zone)

Depth: 80 cm.

Water level: 5 cm below the ground

Plant: Cyperus papyrus (5-6 plants/ m^2)

4.3.2. Horizontal flow bed configuration using USEPA (2000) method.

The first step to determine the dimensions of a horizontal flow constructed wetland is to determine the surface area (Table 10) required to meet the design targets (Table 9). The USEPA (2000) method was used due to its simplicity using the proposed area loading rates (Table 6), and due to limited data (such as water temperature).

Table 10: Sizing of the horizontal flow bed for Indatwa n'Inkesha school

Parameters	Wastewater (mg/L)	Area (m^2)	Width (m)	Length(m)
TSS	85	102	10	10.2
BOD	110	440		44.0

The surface area required for BOD removal is enough to remove suspended solids as well, and the nitrogen level is already below the allowable limit. Therefore, the surface area required for BOD removal (440 m^2) is considered as the design surface area. Other dimensions (width, and length) were determined using Darcy's law (Equation 7). The USEPA method suggests 2 m of inlet zone and 1 m of outlet zone, and the ground water will be protected with an impervious stone pavement due to its local availability. Cyperus papyrus was chosen as a suitable plant type due to its local availability and the difficulties associated with maintaining polyculture, high capacity for nutrient uptake, and the ability to regrow and replenish quickly after harvesting (Vymazal, 2015). Detailed design plans are presented in appendix A, one cell unit was proposed but for maintenance purpose, this can be divided into two identical units.

4.3.3. Operational and maintenance

To increase the performance and to reduce the potential risk of clogging, pre-treatment system such as a standard septic tank is required to reduce the amount of sediments and solids entering the system. As discussed in the previous sections, the wetland vegetation should be harvested if it affects maintenance activities and to facilitate visual checking of the system. The hydraulic loading, the inlet and outlet zones as well as influent and effluent water quality should be monitored regularly, the hydraulic loading should not exceed the design values. The school should take advantage of these monitoring activities to teach students about constructed wetlands technology and to involve them into maintenance activities, this will help to develop their capacity and to reduce the gap of limit knowledge about this type of technology.

4.4. Uncertainties and limitations

The lack of a common design method is a challenge for the use of this type of technology, given the assumptions made in the development of different methods, translocating them may not always be feasible. Therefore, the constructed wetland designed for Indatwa n'Inkesha school should be revised based on primary data to reduce uncertainties. In addition, pathogens removal and viability of CW in Rwanda were not assessed due to limited data. Land availability and wastewater discharge disruption during holidays (or dry seasons) may be a restricting factor for the use of constructed wetlands in some schools in Rwanda; further studies should look at how long constructed wetlands could survive without inflow water.

Chapter 5. Conclusion and recommendations

5.1. Conclusion

Constructed wetlands are a potential technology for wastewater treatment in schools and other similar sized institutions in Rwanda. Their operations are possible with locally available resources and their effluents meet RURA's regulatory targets. While the overall performance of the horizontal flow bed CW designed for Indatwa n'Inkesha school is acceptable, the reclaimed water should only be used where there is no direct contact with human or livestock preferably for drip irrigation of food crops, otherwise a tertiary treatment is required to remove pathogens that are not removed through the wetland processes. The land availability and safety factors are expected to govern the use of constructed wetlands in Rwanda; however, further research is required to collect systematic data about CW governing factors in Rwanda. A constructed wetland at Indatwa n'Inkesha school will contribute to improved water quality, and it could be used as an instructional tool for students.

5.2. Recommendations

Further research should be conducted to understand the long-term performance of CWs in Rwanda, their economic viability, and the social-cultural acceptance of this new type of technology. In addition, there is a need to understand how long a constructed wetland would survive without inflow wastewater given that wastewater discharge in schools depends on the academic year. The Rwanda Water and Forest Authority, the Rwanda Environmental Management Authority, and the Water and Sanitation Corporation Ltd should promote the use constructed wetlands through the development of national guideline to provide systematic data and design parameters to facilitate the use of this type of technology. In addition, they should promote the use of constructed wetlands not only for domestic wastewater treatment but also to reduce pollutants entering freshwater from point and non-point sources.

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Appendices

Appendix A: Detailed plans for horizontal flow bed CW for Indatwa n'Inkesha school

Figure 7: Plan view

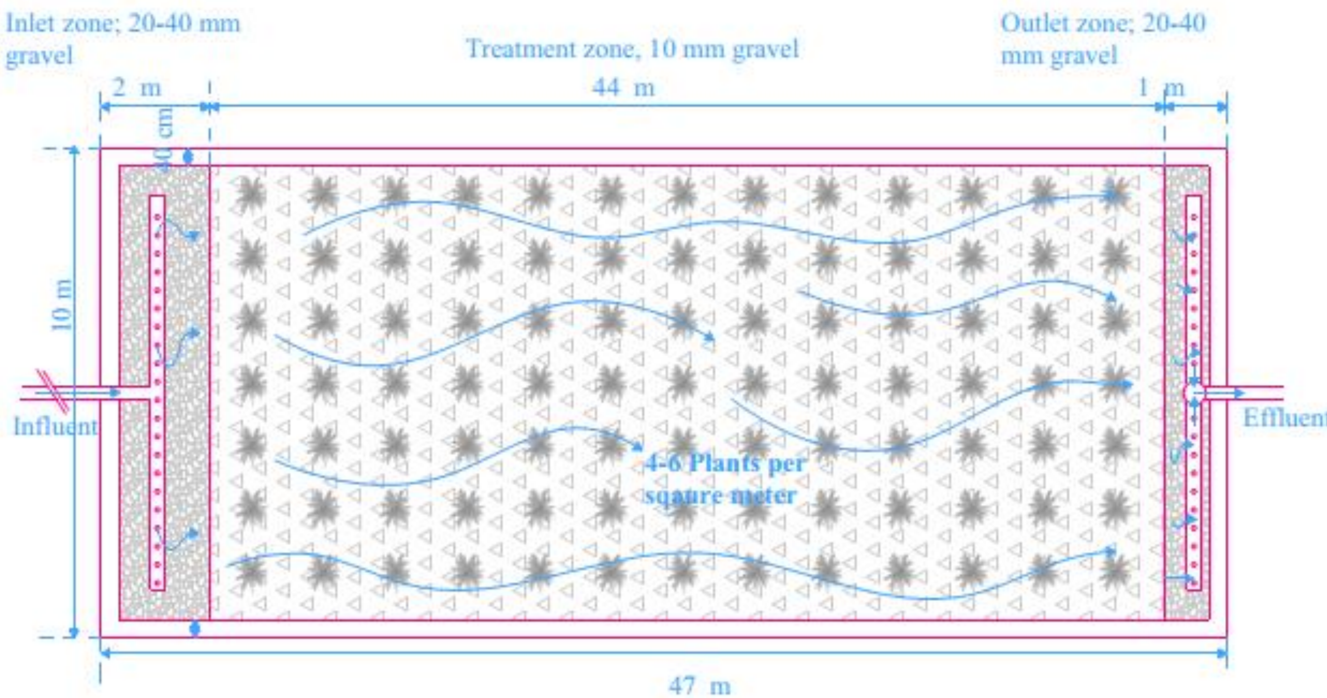
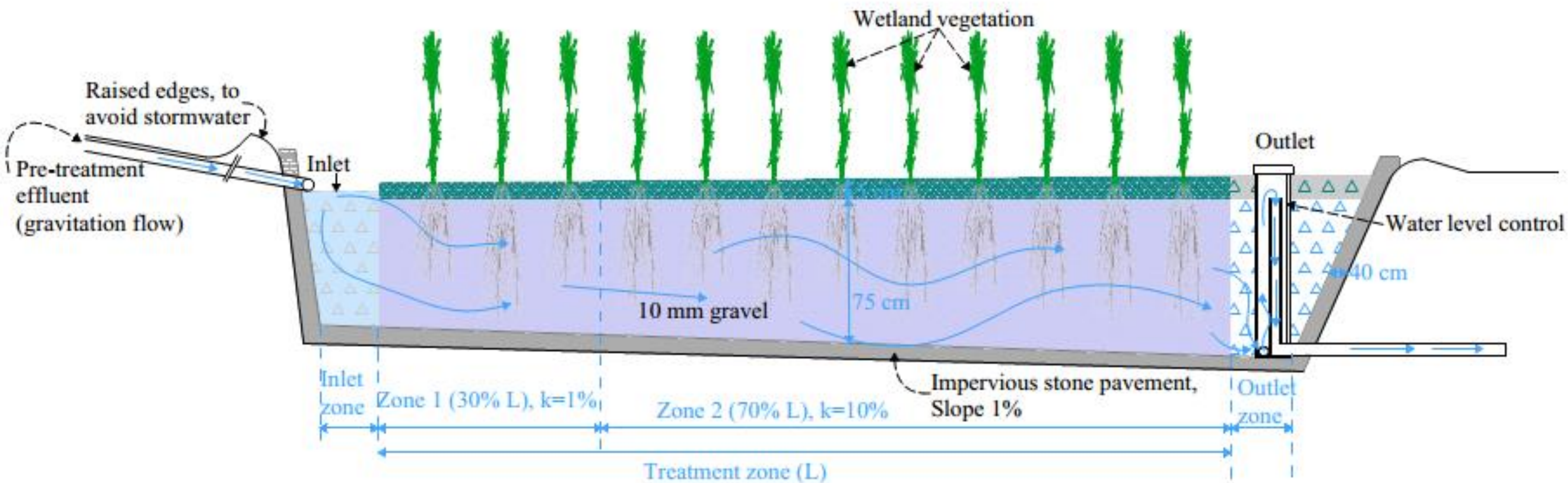
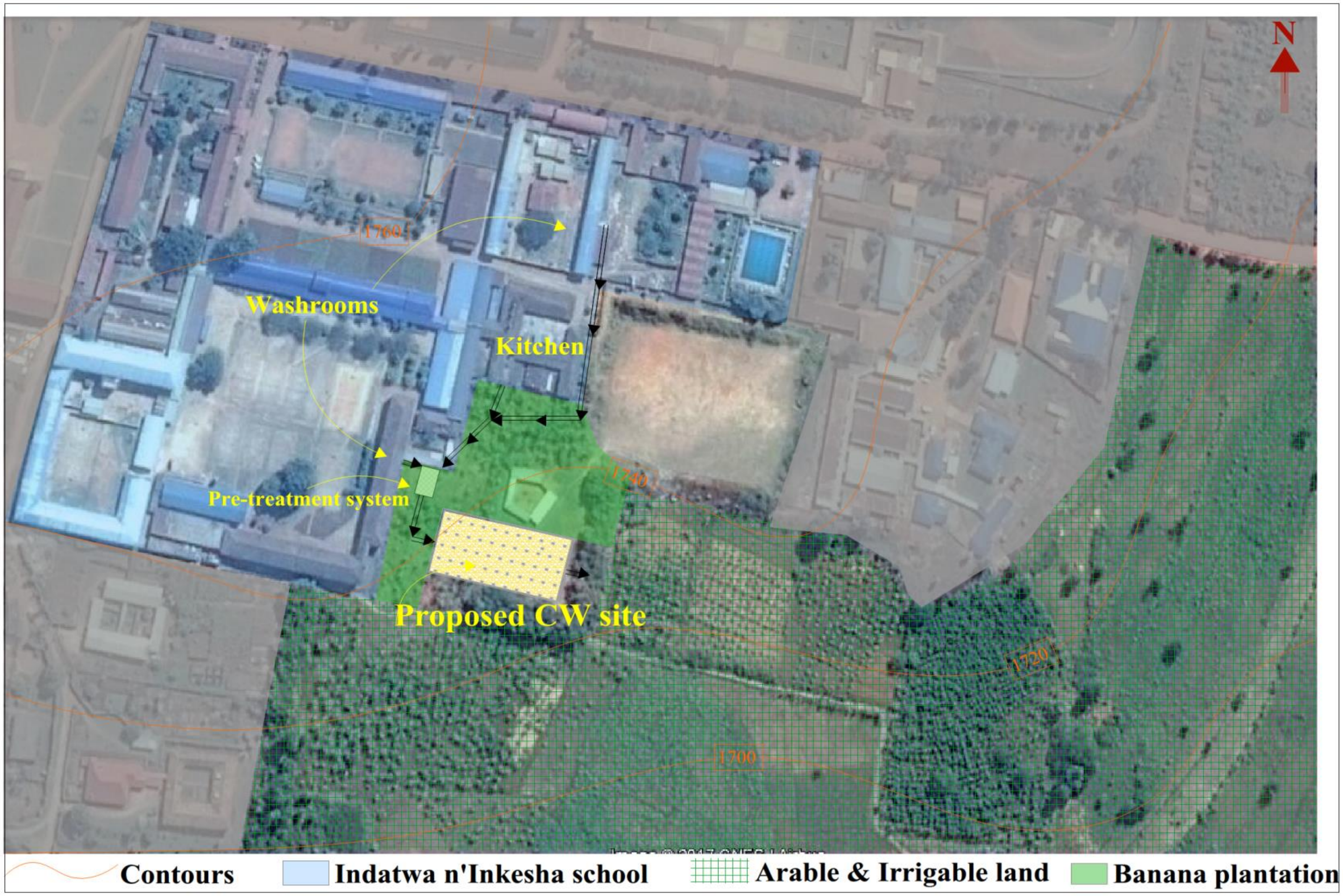


Figure 8: Section view



Appendix B: Proposed site plan for CW at Indatwa n'Inkesha school

Figure 9: Indatwa n'Inkesha school and its neighborhood



Adapted from Google Maps, 2017