PERFORMANCE EVALUATION OF CONSTRUCTED WETLANDS IN A BORDA-DESIGNED DECENTRALISED WASTEWATER TREATMENT SYSTEM

Preyan Arumugam and Chris A. Buckley

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Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

INTRODUCTION AND BACKGROUND

Rapid urbanization is a global issue. In South Africa, eThekwini is one of the fastest growing cities. This has resulted in many densely populated informal settlements forming within the urban edge without basic services such as water and sanitation. The lack of these services has detrimental effects on public health and the environment. The eThekwini Municipality has provided interim solutions in the form of community ablution blocks with washing and toilet facilities. As these communities are within the sewer boundary, the wastewater generated can be diverted directly to sewer. However, this mounts pressure on aging wastewater treatment plants (WWTPs), most of which lack the infrastructure to accommodate the increased loading.

The decentralised approach to sanitation offers an affordable solution without the need for electrical or chemical inputs, minimising the capital and operation costs associated with high-tech conventional WWTPs. Furthermore, it is located near the community serviced, eliminating the need for extended sewer lines and pump stations. Since 2010, eThekwini Water and Sanitation (EWS) has been investigating the approach to decentralised wastewater treatment in partnership with the Bremen Overseas Research and Development Association (BORDA), a German non-profit organisation who has installed many such systems around the world. Decentralised wastewater treatment systems designed by BORDA are constructed on-site and thus, by definition, not regarded as package plants[1].

A demonstration-scale system was constructed in Newlands East at a research site named Newlands Mashu (NM), for a design flow of 41.6 m^3/d. Raw domestic wastewater is gravity fed and primarily treated anaerobically in a two-chambered settler, three-train anaerobic baffled reactor (ABR) and two-chambered anaerobic filter (AF). The ammonium-rich effluent (hereafter referred to as AF effluent) can be reused in agriculture. This is beneficial in terms of promoting subsistence farming in the serviced communities and reducing the potable water demand for irrigation. The AF effluent from Trains 2 and 3 of the ABR is used for agricultural trials on-site to test the growth effects and safety of irrigating with anaerobically treated domestic wastewater.

On the other hand, some informal settlements within the eThekwini Municipality undergo in situ formal housing upgrades and form dense social housing developments. In this case, space is limited, and agriculture is not possible. Therefore, discharge of the effluent is needed, but only after further treatment. At the NM demonstration-scale system, AF effluent from Train 1 of the ABR is treated in a hybrid subsurface flow constructed wetland (CW) system. The first CW is a vertical down-flow CW (VFCW) with a 0.55 m filter layer with unwashed river sand (D_{10} = 0.4 mm) followed by a horizontal flow CW (HFCW) with 50-80 mm gravel media at a depth of 0.9 m. Constructed wetlands mimic the biological, physical, and chemical degradation processes as in natural wetlands, thereby reducing the nutrient, suspended solids, and pathogen content, allowing for safe discharge of the final effluent back to the aquatic environment. To discharge the final effluent, the quality must adhere to the General Authorisations (GA) limits as outlined by the National Water Act.

The primary treatment modules of the demonstration-scale system have been well investigated. However, a monitoring plan to evaluate the final effluent quality (after the HFCW), and thus, the treatment efficiency of the CW system, has not been done on a regular basis. Therefore, a full performance evaluation of the CW system at its current design and operation was needed. Moreover, design reports indicate that the VFCW was constructed at half of the recommended depth to maintain the gravitated flow through the system. It is unclear if this has an impact on its performance.

[1] Refer to NIEKERK, AV, SEETAL, A, DAMA-FAKIR, P, BOYD, L and GAYDON, P 2009. Guideline Report: Package Plants for the treatment of Domestic Wastewater. WRC Project No K5/1869. Water Research Commission, Pretoria.

In terms of the decentralised approach to sanitation for dense social housing schemes, VFCWs, which require a smaller surface area than HFCWs, will be more suitable. Moreover, the undulating landscape in KwaZulu-Natal further supports deeper vertical beds. The European two-stage VFCW system has been designed and employed for higher total nitrogen removal and requires exploration in the South African context.

AIMS

The South African design guideline for small wastewater treatment systems is restricted to the use of HFCWs with no specific detail on the installation and implementation of VFCWs for domestic and municipal wastewater treatment. In fact, the literature on the local application of CWs is limited to acid mine drainage and winery effluent. Therefore, this research served as a preliminary evaluation of subsurface flow CWs treating anaerobically treated domestic wastewater.

More specifically, the project aimed to:

1. Monitor the performance of the Newlands Mashu constructed wetlands
2. Compare the performance with generally accepted design approaches
3. Highlight gaps or shortcomings in the design techniques
4. Provide guidance as to the design and operation of constructed wetlands serving dense social housing or informal settlements

In addition, this project aimed to evaluate the application of pilot-scale VFCWs at the NM site to determine the treatment efficiency of two-stage VFCWs compared to deeper single-stage VFCWs for total nitrogen removal.

SITE MODIFICATIONS

Operation of the CW system including modifications (2016-2018):

a) Initial performance assessments of the VFCW in 2016, show concentrations of CODt, NH_4-N and *E. coli* bacterial cell counts above the GA limit for discharge.

b) In February 2017, the mechanical dosing devise (float siphon) which allows for the intermittent feeding operation of the VFCW did not operate on a regular basis becoming non-functional when high hydraulic loading (up to 30 m^3/d) through Train 1 resulted in the siphon losing its ballast weight and floatation ability. The siphon was repaired and reinstalled in late August 2017.

c) This in turn resulted in continuous flow to the VFCW and ultimate clogging of the surface of the bed. Both CWs were shut down in April 2017.

d) Due to dry zones on the surface of the bed after dosing, the distribution system was redesigned and installed in October 2017 to allow for more even distribution.

e) The gravel media on the surface of the bed was removed, the filter media compacted, and a 0.05 m layer of 0.5-2 mm sand was added on the surface to create temporal flooding after dosing to improve the retention time and thus, the treatment efficiency of the bed.

f) Both CWs were planted with *Cyperus sexangularis* and *Typha capensis* in late October 2017. Both CWs were then started-up.

g) Performance assessment through grab sampling showed variable effluent quality from both CWs. Due to inlet load and flow variation, composite sampling was preferred over random grab sampling.

h) Both CWs were shut down again in August 2018 to allow for the construction of the sampling sumps. The below-ground sumps were constructed from manhole rings and installed at the outlet of each CW for batch collection of the drainage. Commissioning occurred in October 2018.

SAMPLING METHODOLOGY

Demonstration-scale constructed wetland system

The CWs operated for three months undisturbed in preparation for the monitoring campaign. A 16-week sampling campaign took place between February and May 2019. Each CW was sampled every alternative week to not affect the inlet flow conditions to the subsequent HFCW, which operates under continuous flow. The final composite sample from each CW was made up of sub-composites of each batch fill of the sump. It must be noted that the final effluent is referred to the effluent after treatment in the VFCW and subsequently in the HFCW (i.e. treatment in the hybrid CW system). The performance of each CW was measured by the removal efficiencies and mass removal rates of the organic, nutrient, and pathogen content from the AF effluent. The final effluent quality (treatment in the VFCW and then the HFCW) was then compared to the GA limits for discharge.

Pilot-scale vertical flow constructed wetlands

The pilot-scale VFCWs were constructed on-site, also using manhole rings, and pulse fed with AF effluent diverted for the agricultural trials. The hydraulic loading rate (HLR), media gradation, and depth of each configuration were adapted from successful two-stage VFCWs implemented in Austria. The start-performance of each configuration was assessed from September to October 2019, six weeks after start-up.

SUMMARY OF MAIN FINDINGS

Demonstration-scale constructed wetland system

a) Loading

Over the entire monitoring period (February-May 2019), daily flow to the CW system ranged from 12-750% of the design flow resulting from blockages upstream and suspected higher social activity, respectively. Rainfall did not affect the flow rate. For the first half of the monitoring campaign, the CW system operated above the design flow of 13.9 m^3/d. After a scheduled desludging event of the settler upstream of the CWs in mid-March 2019, the flow to the CW system stabilised around the design flow. The organic loading to the VFCW was 58.3 g COD m^{-2} d^{-1} of which 76.3% was biodegradable (inclusive of the soluble and particulate fractions). Nutrient loading, measured only by nitrogen, was 9.9 g N m^{-2} d^{-1}. Average inlet faecal coliforms (quantified by *E. coli* bacterial cell count) in the feed to the VFCW was 3.2 x 10^5 CFU/100 mL.

b) Performance

Organic (CODt) and nutrient (NH_4-N and PO_4-P) removal efficiencies were 83.8, 92.4, and 22.1% after the VFCW. The overall removal (after the VFCW and then HFCW) was 88.2, 97.8 and 55% for CODt, NH_4-N and PO_4-P, respectively. Mass removal rates of CODt and total N were 48.7 g COD m^{-2} d^{-1} and 1.2 g N m^{-2} d^{-1} after the VFCW with overall mass removal being 51.2 g COD m^{-2} d^{-1} and 3.7 g N m^{-2} d^{-1}, respectively. Low (12.5%) nitrate-N removal was observed in the HFCW. This was due to the lack of biodegradable COD in the VFCW effluent as a carbon source for denitrification. Overall, pathogen removal was higher after the HFCW.

When comparing the final effluent quality (after the HFCW) to the GA Limits, ≥ 85% of the samples (n = 8) were compliant for organics (CODt), ammonium (NH_4-N), orthophosphate (PO_4-P), pH and electrical conductivity (EC). The number of samples compliant for faecal coliforms (*E. coli*) and TSS was 83.3 and 75%, respectively.

c) Limitations

The action of the pump in the sampling sumps resulted in suspended matter from the walls of the sump to interfere with actual TSS concentration in the drainage from each CW. Therefore, the actual TSS in the CW effluent is suspected to be much lower in the actual samples.

Pilot-scale unplanted vertical flow constructed wetlands

a) Loading

Each column operated continuously at an HLR of 19 m/d. The organic and nitrogen loading rate was 45.3 g COD m^{-2} d^{-1} of which 88.8% was biodegradable (inclusive of the soluble and particulate fractions) and 14.2 N m^{-2} d^{-1}, respectively.

b) Performance

Nitrification, indicated by nitrate-N in the effluent, was evident after six weeks in all configurations. The two-stage VFCWs demonstrated higher ammonium removal and thus, nitrate-N concentration was higher in the effluent compared to the single-stage VFCWs. Overall, the final effluent quality from each configuration was compliant for TSS, PO_4-P, pH, EC, and faecal coliforms but not for CODt, NH_4-N, and NO_3-N.

CONCLUSIONS

In terms of performance, the demonstration-scale CWs must be operated in series for higher effluent quality. However, based on the low nitrate-N removal, the final effluent cannot be safely discharged to a natural water source like a river. Therefore, the hybrid design (VFCW followed by a HFCW) is not appropriate for dense social housing schemes. Further monitoring (at least 12 months) will be helpful to determine any changes in treatment efficiency over time. In addition, suitable plant-based carbon sources (e.g. decaying or fermented CW biomass) must be investigated as a cheap, natural source of biodegradable COD to improve denitrification in the CW system.

The start-up performance of the pilot-scale VFCWs indicates that the two-stage systems showed higher nitrification rates compared to the single VFCWs, even those with greater filter depth. However, total nitrogen removal was poor across all configurations. Modifications to the media porosity and changes in the flow configuration need to be investigated to improve operating performance. Long-term performance evaluation is necessary, especially responses to load variation including recovery from rest when applied in parallel bed design and operating under a feed/rest cycle.

RECOMMENDATIONS FOR FUTURE RESEARCH

The monitoring data from the demonstration-scale CW sampling campaign was used in a successful water use licence application for an in situ formal housing development in eThekwini. The dense social housing scheme will have urine diversion (UD) flushing toilets at the household level and a demonstration-scale decentralised wastewater treatment system with two-stage VFCWs for secondary treatment. It is calculated that because urine is the major contributor to the nitrogen loading, source separation of urine will reduce the overall nitrogen loading to the CWs producing fully compliant effluent for discharge. This requires a full performance evaluation of the demonstration-scale two-stage VFCWs.

In the meantime, the pilot-scale VFCWs may be used to test if impounding the drainage layer in the first stage will improve the total nitrogen removal as well as determine the response to load variation and recovery from rest. This is important if parallel bed design is employed in which case each bed undergoes a loading/rest cycle at different times. This acts as a fail-safe during higher loading which may cause clogging that is a notable problem in VFCWs. The performance data of the pilot-scale two-stage VFCWs will aid in the design process of the demonstration-scale two-stage VFCWs for the new housing upgrade.

The lessons learned from this study, and that of the future demonstration-scale two-stage VFCWs, will aid in policymaking and guiding the rollout of decentralised wastewater treatment on a national scale, filling the gap in urban sanitation.

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The following full-time registered students were funded or employed by this project.

Student	Degree, Institution & Role
Mrs Preyan Arumugam	PhDEng Civil Engineering candidate, School of Engineering, UKZN, Principal Investigator
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ACRONYMS & ABBREVIATIONS

ABR	anaerobic baffled reactor
AF	anaerobic filter
bCOD	biodegradable chemical oxygen demand
BORDA	Bremen Overseas Research and Development Association
CODt	total chemical oxygen demand
CW	constructed wetland
DWS	Department of Water and Sanitation
EWS	eThekwini Water and Sanitation
GA	General Authorisations
HFCW	horizontal flow constructed wetland
HLR	hydraulic loading rate
HRT	hydraulic retention time
KZN	KwaZulu-Natal
NM	Newlands Mashu research site
O&M	operation and maintenance
OM	organic matter
SSF	subsurface flow
TN	total nitrogen
TSS	total suspended solids
UD	urine diversion
VFCW	vertical flow constructed wetland
WWTP	wastewater treatment plant

UNITS OF MEASUREMENT

m	distance / height
m^2	area
mg/L	concentration
L	volumes less than 1000 L
m^3	volumes ≥ 1000 L

GLOSSARY

Constructed wetland: an artificial wetland designed to mimic the natural biodegradation processes present in natural wetlands but in a controlled manner, also termed *treatment wetlands*.

Decentralised wastewater treatment: collection and treatment of wastewater at or near the source without the need for electrical or chemical inputs.

Gap housing refers to the gap in residential properties own by individuals who earn between ZAR3 000 to ZAR15 000 therefore, unable to qualify for state-subsidised housing or personal home loans.

Package plant: any onsite, waterborne, domestic wastewater treatment system; either consisting of one or many modules; with a total capacity less than 2000 m^3/day. It typically includes equipment largely constructed and packaged off site and brought onsite for installation.

Subsurface flow: the flow is beneath the surface.

CHAPTER 1:BACKGROUND

1.1 INTRODUCTION

The application of decentralised wastewater treatment systems has gained global acceptance for its low-tech, economical approach to producing high quality effluent that can be reused or safely discharged near the source of generation (BORDA, 2009). This is especially beneficial in countries where the lack of capital funding and technical expertise limits the use of conventional wastewater treatment technologies. It essentially fills the gap for urban sanitation where waterborne sanitation is still desired, and the effluent can be reused in agriculture, especially in water scarce areas.

In the eThekwini Municipality (Durban), rapid urbanisation has proliferated the number of densely populated informal settlements within the sewer boundary, many of which are without basic water and sanitation services. The lack of these services leads to poor living conditions with adverse health and environmental impacts. As a counteractive measure to address these issues, the eThekwini Municipality has made interim provision of these services in the form of community ablution blocks (CABs)[2]. The CABs with installed washing, bathing, and toilet facilities can be connected to the central sewer for wastewater disposal and treatment.

There are also in situ formal housing upgrades for some informal communities within the urban edge forming dense social housing schemes. Recent funding from the Department of Human Settlements has permitted 560 informal communities within the municipality to be upgraded[3]. However, in most instances, the closest centralised wastewater treatment plant (WWTP) does not have the infrastructure to manage the increased hydraulic loading, forcing municipalities to look at other solutions. It must be noted that housing upgrades cannot proceed before alternate, adequate, safe sanitation measures are put in place.

Decentralised wastewater treatment is a feasible sanitation option. Its modular design can be modified to suit the needs of the community served (i.e., reuse of the primary anaerobically treated effluent for agriculture or further treatment of the final effluent for safe discharge). Usually constructed near the source, the gravitational flow limits the need for extended sewer lines and pump stations, therefore appropriate in KwaZulu-Natal with mostly undulating landscapes. Furthermore, the treatment of the raw wastewater is by physical, biological, and microbiological means without any chemical inputs resulting in an affordable solution to wastewater management on an interim to permanent time-frame (BORDA, 2009). Since 2010, the eThekwini Municipality, in partnership with the Pollution Research Group at the University of KwaZulu-Natal, has been investigating the application of decentralised wastewater treatment at the Newlands Mashu Research Site.

1.1.1 Description of the Newlands Mashu decentralised wastewater treatment system

The first demonstration-scale decentralised wastewater treatment system in eThekwini was commissioned in 2010. Located in Newlands East (29° 46' 25. 648" S, 30° 58' 28. 329" E), north of central eThekwini, the system was designed according to the Bremen Overseas Research and Development Association (BORDA) guidelines (Sasse, 1998). Raw wastewater generated from 84 gap households averaging 5 persons/household is diverted from the municipal sewer line to the system with a design capacity of 41.6 m^3/d.

Primary treatment consists of sedimentation followed by anaerobic digestion. The influent flows into a two-chamber settler that later distributes the flow into three parallel anaerobic baffled reactor (ABR) trains. The purpose of the three-train ABR was to test the performance of the ABR under different hydraulic loading rates (Pillay et al. 2013). Trains 1 and 2 are identical consisting of seven equal-sized chambers. Train 3 was

[2] https://use.metropolis.org/case-studies/ethekwini-communal-ablution-blocks-for-informal-settlements (Date accessed 25 July 2017)

[3] https://www.iol.co.za/mercury/news/city-reveals-plan-to-upgrade-informal-settlements-35513239 (Date accessed 17 November 2019)

constructed with four chambers; the first three double in size compared to a single chamber from Trains 1 and 2 to determine the effect of higher retention time on ABR performance (Foxon KM et al., 2006). A two-chamber anaerobic filter (AF) with gravel media treats the ABR effluent (Appendix 1).

Electromagnetic flow meters (SAFMAG) were installed in the sump following the AF of each train, which records the flow rate to produce the cumulative daily flow. At this stage, the nutrient-rich AF effluent, low in organic matter compared to the influent, can be reused for irrigation. Alternatively, the AF effluent can be further treated in a hybrid subsurface flow constructed wetland (CW) system consisting of a vertical down-flow CW (VFCW) with sand media and a horizontal flow CW (HFCW) with gravel media (Figure 1) for producing effluent safe for discharge. Constructed wetlands are a common treatment option in decentralised wastewater treatment systems due to its buffering capacity to filter suspended solids and biologically reduce the nutrient content (especially nitrogen) through microbial degradation (nitrification/denitrification) and plant assimilation (Kadlec and Wallace, 2009; Stefanakis et al., 2014; Vymazal, 2010). The CW system was designed for a flow of 13.9 m^3/d on the assumption that each train will receive a third of the daily flow. However, based on the design of the outlet pipes of the settler, the bulk of the flow is diverted into Trains 1 and 3 [refer to Appendix 1 and Pillay et al. (2013)].

Figure 1: Aerial view of the Newlands Mashu decentralised wastewater treatment system, eThekwini (taken September 2019)

Photo credit Jodache Naidoo, Pulse Control Systems

ABR = anaerobic baffled reactor; AF = anaerobic filter; CR = control room; FM = flow meter; HFCW = horizontal flow constructed wetland; SC = siphon chamber; SDB = sludge drying bed; SS1 = vertical flow constructed wetland sampling chamber; SS2 = horizontal flow constructed wetland sampling sump; TS = trunk sewer; VFCW = vertical flow constructed wetland

1.1.2 Problem statement

Initially, the objective of EWS was to engage with the served community and promote subsistence farming of crops for commercial use through reuse of the anaerobically treated effluent for irrigation. This improves the livelihoods of the community as well as reduces the demand for potable water for agriculture. Moreover, it reduces the need for additional treatment of the AF effluent, decreasing capital costs and space requirements. The growth effects of irrigating with AF effluent has been studied on-site using swiss chard (Musazura et al., 2015), banana and taro (Musazura et al., 2019). Further research into the safety of irrigating crops for consumption is ongoing onsite.

In areas where agriculture is not possible, especially in dense social housing schemes, discharge of the final effluent is required provided that the quality meets the Revised General Authorisation (GA) limits (DWS, 2013) (Appendix 2). This requires regular monitoring of the final effluent as well as the entire system performance. The treatment efficiency of the primary modules of the demonstration-scale decentralised wastewater treatment system has been extensively investigated, indicating high solids and organic matter removal. At the same time, the concentration of nutrients, particularly ammonium, remains high (Foxon KM et al., 2006; Pillay et al., 2013; Schoebitz, 2013). However, little emphasis was placed on the performance of the demonstration-scale CW system.

Pillay et al. (2013) reported that to maintain the hydraulic head for gravitational flow through the system, the VFCW was constructed at half of the recommended depth of 1.5 m. Furthermore, the mechanical dosing device (siphon), required for intermittent loading, was modified to increase the distribution of the AF effluent on the surface of the VFCW after notably dry zones were observed post-loading. When comparing effluent quality from both CWs operated individually, Pillay et al. (2013) found higher removal efficiencies of organic (COD) and nutrient (ammonium and orthophosphate) concentrations in the VFCW compared to the HFCW. It was stated that the HFCW would be preferred as it prevents human contact with the wastewater as the flow in completely subsurface. Although, the overall recommendation for the NM system was to operate both CWs in series for higher treatment efficiency. Since March 2014, both CWs were connected in series as a hybrid system.

Monitoring of the final effluent via random grab sampling of the HFCW effluent from May 2014 to July 2015 by EWS indicated high variability in organic (CODt), ammonium, and pathogen (*E. coli* bacterial cells) concentrations, often above the GA limit for discharge (Appendix 3). Based on the EWS monitoring data and the design challenges of the CW system, a full performance evaluation of the CW system was needed.

Due to space limitations in dense social housing schemes, VFCWs will be more appropriate because of the smaller surface area demand compared to HFCWs. Furthermore, HFCWs require a pre-nitrification step for denitrification to reduce the total nitrogen load in the final effluent. Single-stage VFCWs produce nitrate-rich effluent that limits the discharge of the final effluent although successful two-stage VFCWs have been implemented in Austria for higher total nitrogen removal. This European design needs to be investigated in the South Africa context including the application of single-stage VFCWs with increased filter depth as the landscape in KwaZulu-Natal is mostly undulating.

1.2 AIMS AND OBJECTIVES

The South African design guideline for small wastewater treatment works[4] only provides minor guidance towards the use of notably horizontal flow CWs / reedbeds. Little is known on the performance and design of constructed wetlands for the treatment of pre-treated domestic wastewater in the South African context. Thus, this research had modest aims based on the design and lessons learned from the demonstration-scale decentralised wastewater treatment system in eThekwini.

In general, the project aimed to:

1. Monitor the performance of the Newlands Mashu constructed wetlands
2. Compare the performance with generally accepted design approaches
3. Highlight gaps or shortcomings in the design techniques

[4] Refer to DPW 2012. Small waste water treatment works DPW design guidelines PW 2011/1 (Department of Public Works now Department of Public Works and Infrastructure).

4. Provide guidance as to the design and operation of constructed wetlands serving dense social housing or informal settlements

Lastly, the research extended to the pilot-scale application of VFCWs under different design configurations to determine which type of VFCW will produce fully compliant effluent for discharge.

1.3 SCOPE AND LIMITATIONS

The Newlands Mashu (NM) research site is situated in Newlands East, north of the eThekwini central business district (CBD). The topography in KwaZulu-Natal is undulating with NM situated in a valley. The city of eThekwini has a warm sub-tropical climate with the average minimum and maximum temperatures at 7.9°C and 30.5°C, respectively[5]. The decentralised wastewater treatment system was designed for a low to middle income-earning historically disadvantaged community with gap housing. Historically, the scum accumulation (composed of fats, oil, and grease (FOG) as well as sanitary and plastic material) at the inlet of the system is notably higher than other BORDA-designed systems worldwide. This is suspected to be due to the diet of the community and possible home industries. Disposal of sanitary waste materials through the sewer is still a problem despite community awareness. Regular maintenance activities include the descumming of the settler and the first ABR chamber twice a week. Checks for blockages upstream of the decentralised wastewater treatment system are done daily on-site.

1.4 TARGET AUDIENCE

This report serves as a performance assessment of the secondary treatment modules in the first demonstration-scale BORDA-designed decentralised wastewater treatment system in South Africa and thus, targeted at South African municipalities and local practitioners intending to employ an on-site/decentralised approach to sanitation for dense social housing schemes where safe discharge of the final effluent is required. The system design could also be adapted for commercialisation by the private sector for single households where the CWs will provide an aesthetic value as well as reuse of the final effluent for gardening and car washing in drought-prone and water-scarce areas.

[5] Data sourced from ODINDO, A, BAME, I, MUSAZURA, W, HUGHES, J and BUCKLEY, C 2016. Integrating agriculture in designing on-site, low cost sanitation technologies in social housing schemes. Technical Report No. TT 700/16, Water Research Commission. Pretoria, South Africa.

CHAPTER 2:LITERATURE REVIEW

The purpose of this mini review is to briefly discuss the role of decentralised wastewater treatment in the South African context focusing on the use of constructed wetlands (CWs). For dense social housing schemes, subsurface flow CWs are more appropriate as the wastewater flows below the surface preventing human contact and pest breeding. Therefore, the design and operational parameters which affect these type of CWs are highlighted with particular attention to nitrogen removal, which is generally variable in CWs.

2.1 INTRODUCTION

In the bid to close the gap between inequality amongst its nation, South Africa has committed to basic service delivery of which housing, water, and sanitation are core components. According to the latest General Household Survey, 83% of the country's population has access to improved sanitation defined by either a flush toilet or a ventilated pit latrine (Statistics South Africa, 2018). Rapid urbanisation has resulted in populous informal communities forming within the urban edge demanding the much-desired "western" waterborne sanitation. As a result, flush toilets remain the most common form of sanitation even in water-scarce times and continue to be rolled out in these communities served with community ablution blocks (CABs).

Within the eThekwini Municipality, 13% of the households are informal, and in situ formal housing upgrades are part of basic service delivery. However, the development of these dense social housing schemes is haltered if there is no adequate wastewater disposal and treatment system. Connections to the central sewer network are not always possible since many wastewater treatment plants (WWTPs) are near capacity and lack the infrastructure to withstand the higher hydraulic loading.

In this case, small decentralised wastewater treatment systems are an appropriate option. Its modular design (which includes basic technologies) can be modified to suit the treatment goals reducing capital costs otherwise associated with conventional WWTPs. It can be constructed onsite or near a community disregarding the need for sewer networks and is applicable for waterborne sanitation, filling the gap in urban sanitation. Furthermore, it requires no electrical or chemical inputs and can be operated off-grid, provided there is gravitation flow through the system. This lowers operating costs making decentralised systems cost-effective (BORDA, 2009).

2.2 BORDA-DESIGNED DECENTRALISED WASTEWATER TREATMENT SOLUTIONS

The Bremen Overseas Research and Development Association (BORDA), a German non-profit organization, has been one of the front runners at supplying innovative, environmentally friendly solutions to urban sanitation over the last four decades. Their main approach to tackling the increasing demand for safe sanitation, especially in cities riddled by rapid urbanisation, is decentralised wastewater treatment. Instead of a technology, BORDA has characterised it as an approach that incorporates the technical aspects as well as the socio-economic conditions of the local community involved (BORDA 2009). This allows for community participation and responsibility for simple maintenance activities. This may not meet municipal or government service delivery model however, the work associated with community participation could result in paid work opportunities for these residents. In South Africa, their local partner is eThekwini Water and Sanitation (EWS) supported by the University of KwaZulu-Natal.

The typical design of a BORDA decentralised wastewater treatment system includes a settler for sedimentation of solid matter from the raw wastewater. This allows for sludge to accumulate at the bottom while the scum layer (composed of fats, oil, and grease) to form at the top. The settled sludge is stabilised by anaerobic digestion, and the biogas produced can be collected for reuse. The intermediate wastewater layer flows into an anaerobic baffled reactor (ABR) and allows for anaerobic degradation of the suspended and dissolved solids. Further anaerobic reduction of the organic matter occurs in the anaerobic filter (AF), which contains microorganisms attached to gravel media (Figure 2). At this stage, there is an increase of ammonium through the metabolism of proteins (BORDA, 2009).

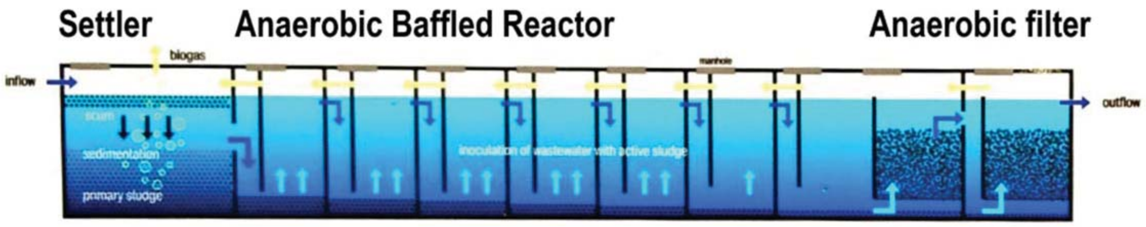

Figure 2: Schematic side elevation of the primary treatment modules at the Newlands Mashu Research site, eThekwini

In most cases, agriculture is incorporated into the design of the system, and the nutrient-rich anaerobically treated effluent is reused for irrigation. Further treatment is therefore, not necessary. However, when agriculture is not possible, as in the case where space is limited, secondary treatment is needed. One such technology to apply is constructed wetlands.

2.3 CONSTRUCTED WETLANDS

A constructed wetland or artificial wetland is engineered from an ecological perspective to mimic natural wetlands by promoting natural processes facilitated by vegetation, sediment, and microbial assemblages in a controlled manner (Lee et al., 2009; Vymazal, 2010).

2.3.1 History and treatment capacity

Wetlands have historically been used for the disposal of waste and wastewater which has led to the irreversible degradation and pollution of these natural systems (Vymazal, 2011). To alleviate the damaging long-term effects of untreated waste to these water bodies, treatment was the solution. In so doing, constructed wetlands (CWs) became a preferred option for the treatment of wastewater.

German scientist, Dr Käthe Seidel, documented the first experimental application of CWs in the 1950s (Seidel, 1953). Since then, the treatment potential of this “green” technology is reflected by the escalation of research documenting application and performance data of CWs over the last four decades (Cooper, 2009) with widespread application in Europe and North America (Kadlec and Wallace, 2009; Vymazal, 2011).

The removal of the pollutants from the receiving wastewater is complex and robust, involving a variety of physicochemical and biological processes that are either directly or indirectly influenced by the loading rate, season, sediment or media type, operating conditions and the redox potential within the CW (Wu et al., 2014). With the addition of macrophytes tolerant to nutrient and organic overload, CWs are successful in removing organics, nutrients, pathogens, suspended solids by microbial degradation and, to a lesser extent, plant uptake of nutrients (Kadlec and Wallace, 2009). The outcome is a substantial reduction in operation and maintenance costs associated with conventional energy-requiring technologies.

Constructed wetlands are known to buffer hydraulic and organic load fluctuations demonstrating the resilience and reliability of the systems for effective treatment (Morvannou et al., 2014). Moreover, the presence of plants provides an aesthetic value to CWs (BORDA, 2009; Chang et al., 2012).

Despite the removal of organics, a review of the published literature reveals various performance levels for nitrogen removal as a result of oxygen limitations and lack of organic carbon essential for classical microbial degradation of nitrogenous compounds. High nitrogen content in final effluents threaten receiving aquatic environments by contributing to eutrophication and loss of aquatic life due to oxygen depletion (Lee et al., 2009; Sun et al., 2012).

To understand the limitations and advantages of each type of CW, an overview of the nitrogen transformation and removal processes, specifically via microbial degradation, is discussed in the following section.

2.3.2 Microbial nitrogen removal mechanisms in constructed wetlands

In CWs, nitrogen is typically removed biologically via microbial degradation. Nitrification is the first transformation process, provided that the ammonium concentration exceeds the organic nitrogen[6]. It is a two-step process under aerobic conditions whereby chemoautotrophic bacteria convert ammonium-N (NH_4-H) to nitrate-N (NO_3-N) with nitrite-N (NO_2-N) as the intermediate product (Kadlec and Wallace, 2009; Vymazal, 2007). Initially, *Nitrosomonas* autotrophic bacteria oxidise the NH_4-N to NO_2-N with CO_2 as a carbon source. The NO_2-N is then oxidised to NO_3-N by facultative *Nitrobacter* bacteria. Both oxidation reactions release energy used by the bacteria for cell synthesis. Since both reactions are oxygen dependent, nitrification rates are controlled by the dissolved oxygen (DO) concentration within the bed (Kadlec and Wallace, 2009; Sun et al., 2012; Vymazal, 2007). According to stoichiometry, the oxygen (O_2) demand for complete nitrification is 4.23 mg O_2 per mg NH_4-N (Liu and Wang, 2012). Other parameters affecting nitrification are pH and water temperature. Optimum nitrification rates are at pH levels of 7.5-7.8 and temperatures of 25-35°C (Lee et al., 2009). Nitrification compared to OM degradation, is a slower process. Therefore, OM degradation limits the DO availability for nitrifying bacteria.

Nitrate-N is then available for denitrification. Heterotrophic bacteria use nitrate as an electron acceptor and organic carbon (from microbial cells or organic pollutants in the effluent) as an electron donor for complete removal of nitrogen under anoxic conditions. First, NO_3-N is reduced to NO which is then reduced to N_2 that is released to the atmosphere (Verhoeven and Meuleman, 1999). This results in an increase in alkalinity with optimum rates occurring between pH levels of 7-7.5 and temperatures of 20-25°C (Saeed and Sun, 2012). Plants indirectly influence denitrification as it determines the availability of carbon source which is a limiting factor during denitrification (Kadlec and Wallace, 2009) and influence the oxygen levels around their roots. The amount of organic matter (OM) in the incoming wastewater also affects the rate of denitrification. As mentioned previously, OM degradation reduces DO availability (thus, low nitrification rates) and a lack of biodegradable OM hinders denitrification due to the absence of a carbon source. Thus, CW performance is dependent upon overcoming the conflicting dependence between organic and nitrogen removal (Kadlec and Wallace, 2009; Saeed and Sun, 2012; Stefanakis et al., 2014).

2.3.3 Classification of constructed wetlands

In terms of design, an enhanced understanding of these systems led to the development of different variants that have been exploited for improved pollutant removal from municipal, domestic, industrial, and agricultural wastewaters (Langergraber, 2008; Wu et al., 2015). This is primarily based on the low energy consumption and low operation and maintenance costs associated with CWs, forming an attraction option for developing countries as the design can consist of local resources and labour (Kadlec and Wallace, 2009).

Constructed wetlands (CWs) are broadly classified by the hydraulic flow of the system: surface flow (free water surface flow) and subsurface flow (below the surface).

[6] If the organic nitrogen concentration is greater than the ammonium-N then ammonification will take place which is production of ammonium-N. Since the primary treated effluent in decentralised wastewater treatment systems are rich in ammonium-N, this process has been purposely omitted.

2.3.3.1 Surface flow constructed wetlands

Surface flow (SF) CWs or Free Water SF CWs are typically shallow (not more than 0.6 m in depth) with low flow velocity and usually with soil media. These CWs are densely vegetated and contain areas of free water resembling natural wetlands (Langergraber, 2008; Sun et al., 2012; Vymazal, 2010). The characterisation is based on vegetative growth: emergent, submerged, or free-floating. Wastewater flowing through the CW initiates various physical (UV radiation, sedimentation, and filtration), chemical (precipitation, adsorption, and volatilization) and biological (microbial degradation and plant uptake) processes that transform the pollutants present in the wastewater (Kadlec and Wallace, 2009; Vymazal, 2011). First implemented in North America, these CWs are often used as a polishing or tertiary treatment technology treating municipal effluent from other bioreactors. It is effective in removing organics and suspended solids. At the same time, nitrogen removal is variable because most microbial interaction occurs in the sediment, and the surface flow of wastewater limits contact with microbial populations (Verhoeven and Meuleman, 1999). While this system is suited for all climates, certain processes can be affected by harsh conditions such as nitrogen conversion during ice formation as it prevents the transfer of oxygen into the bed, limiting nitrification (Kadlec and Wallace, 2009).

In the South African context, surface flow CWs are not suitable for dense social housing schemes and informal settlements. This is due to the public health implications since children have easy access to the wastewater. Furthermore, it will attract pest breeding such as mosquitos, which transmit various diseases.

2.3.3.2 Subsurface flow constructed wetlands

Subsurface flow (SSF) CWs also contain emergent plants but usually rooted in gravel and sand. In these systems, wastewater moves below the surface of the bed. Therefore, no free water is visible, and the wastewater is treated by the microbial populations attached to the roots and media. These types of CWs are further divided according to the direction of the hydraulic flow of wastewater entering the system, which may be either horizontal or vertical. Over the last few decades, a combination of different designs and configurations of CWs were introduced to maximize treatment efficiency, especially nitrogen, by exploiting the advantages of each type used (Lee et al., 2009; Vymazal, 2011). Due to the treatment requirements in South Africa to reduce the ammonium-N in primary treated domestic effluent, subsurface flow CWs are more applicable.

2.3.3.2.1 Horizontal flow constructed wetlands

Horizontal flow CWs (HFCWs) are similar to SF CWs in size and vegetation but differ in that the flow is below the media preventing any odour emissions or breeding sites for pests (Kadlec and Wallace, 2009; Vymazal, 2010). The flow through the porous gravel media is continuous, limiting the need for dosing devices or pumps, resulting in low operating costs. This feeding operation results in low oxygen levels within the bed creating anoxic/anaerobic conditions that support denitrifying bacteria. Furthermore, OM degradation is dominated by anoxic/anaerobic bacteria while suspended solids are removed by filtration. Pathogen removal is also high. Aerobic bacteria are also able to colonise the bed near the roots of the planted species, which release oxygen near the rhizome however, nitrification is generally poor is these CWs. Therefore, a pre-nitrification reactor is often needed for higher total nitrogen removal rates. Other limitations of these CWs are the large surface area requirement (up to 5 m^2 / population equivalent) and clogging (Vymazal, 2010).

2.3.3.2.2 Vertical flow constructed wetlands

In 1965, Seidel designed the first vertical flow CWs (VFCWs), which served as an oxygenating pre-treatment step for effluent from anaerobic septic tanks before being fed into HFCWs (Seidel, 1965). Vertical flow CWs (typically consisting of more than one stage) are unsaturated and intermittently or pulse fed to allow for maximum oxygen diffusion into the media. This provides the adequate conditions required by nitrifying bacteria. The intermittent flow can be through pumps or mechanical dosing devices such as gravity siphons (Kadlec and Wallace, 2009; Stefanakis et al., 2014). Siphons are preferred to limit electrical inputs.

Wastewater permeates through the filtration media (usually sand) in a vertical path either in an up or down direction allowing for oxygen to diffuse into the empty pore spaces in the media. The effluent is discharged through a drainage pipe. As a result, these beds require a smaller area (2-4 m^2 / population equivalent) compared to HFCWs (Cooper, 2009) with a depth range of 1-2 m (Wu et al., 2015). Danish systems have inserted ventilation pipes to facilitate the movement of air from the surface to the base of the CW (Brix and Arias, 2005). However, because there are mostly aerobic conditions, these CWs limit denitrification and halts total nitrogen removal. Despite poor nitrogen removal, VFCWs are very efficient in the removal of suspended solids and organics (Molle et al., 2005) and thus, often regarded as a higher treatment CW compared to other CWs. However, based on the operational needs of VFCWs (dosing device and intermittent loading), HFCWs are generally preferred in the BORDA-design decentralised systems (BORDA, 2009).

2.3.4 Design and operational parameters of subsurface flow constructed wetlands

Various parameters play a role in the effective and sustainable function of CWs, and therefore design and operation are crucial to achieving treatment goals. In terms of SSF CWs, the main parameters include the hydraulic loading rate, hydraulic retention time, filter media, depth and plant species (Wu et al., 2015).

2.3.4.1 Hydraulic loading rate

The treatment efficiency of the CW can be influenced by operating conditions such as hydraulic loading rate (HLR) which contributes significantly to the design, operation, pollutant removal, and land area requirements (Chang et al., 2015). The HLR is defined by the flow rate applied to the CW in relation to the surface area of the bed, given as the time-averaged flow rate. Flow rates differ with hourly, daily, and seasonal variations. Thus, VFCWs do not operate under steady-state conditions as the flow rate is affected by intermittent feeding, precipitation, and evapotranspiration (Stefanakis et al., 2014).

2.3.4.2 Hydraulic retention time

Nominal hydraulic retention time (HRT) within a CW is the ratio of the CW volume and the inlet flow rate. However, due to the porosity of the media within SSF CWs, the void fraction must be taken into account when measuring the accurate HRT. For sand and gravel media, the void fraction is 0.3-0.45 (Kadlec and Wallace, 2009).

Lee et al. (2009) attribute higher nitrogen treatment efficiency to higher HRT. This is because the contact time between the incoming wastewater and microbial communities in the media is increased, contributing to the performance of the CW. Furthermore, nitrogen removal requires a higher HRT compared to organic reducing reactions due to the slow-growing nitrifying bacteria (Lee et al., 2009). Typical retention times range from 2-6 days (Wu et al., 2015) however, a longer period may reduce biological oxygen demand (BOD) removal (Saeed and Sun, 2012).

2.3.4.3 Media

The function of the media within a wetland is to serve as a medium for plant and microbial growth and facilitate the permeation of wastewater through the depth of the bed (Kadlec and Wallace, 2009). The size and nature of the wetland media are crucial for microbial attachment, adsorption of pollutants, medium for plant growth, wastewater movement, filtration, and settling of suspended solids (Saeed and Sun, 2012). Moreover, the sorption capacity of a media forms a critical aspect in the removal of specific pollutants such as phosphorus. Wu et al. (2015) highlight that the life span of SSF CWs may be significantly reduced due to clogging. Clogging is a treatment limitation in subsurface flow CWs, especially VFCWs which generally contain sand media. Thus, the choice of media is essential for sustainable systems. The nature of media determines environmental conditions like redox potential inside media pores and overall, influences the performance of VFCWs (Saeed and Sun, 2012). Stefanakis et al. (2014) suggest that the filter media should provide the following characteristics:

a) adequate permeability in proportion to the organic and hydraulic loading rate;

b) coexistence of aerobic and anaerobic pores within the media to enhance organic removal, nitrification, and denitrification; and

c) an internal carbon source to avoid dependency on wastewater carbon source for denitrification.

Failure to achieve this may lead to bed clogging, low pollutant removal efficiency and improper hydraulic bed operation (Stefanakis et al., 2014).

Nivala et al. (2013) recommend that the media should be modified to the location of the intended CWs to be economically feasible as washed, well-graded sand is not available in all regions of the world. Sand and gravel are often inexpensive media types that are readily available. If using sand, the grains must be fine enough to retain organics (not too small or poorly sorted) and coarse enough to reduce clogging (Stefanakis et al., 2014). Poor media hydraulic conductivity may lead to clogging reducing the treatment efficiency of the CW. However, loading rates are the dominant factors in determining media filter efficiency (Chang et al., 2015). Nitrification rates are higher in gravel media with denitrification favoured in fine sediments (Saeed and Sun, 2012).

Conversely, Stefanakis and Tsihrintzis (2009) compared the use of different porous media and found no significant differences between the treatments. They believed that the contact time with the media and wastewater are facilitated by the gravitational flow of effluent through the depth of the bed and not the type of media.

2.3.4.3.1 Flow through porous media

In terms of flow characteristics in SSF CWs, the fundamentals of flow through porous media must be understood. A porous media consists of a continuous solid phase with voids spaces in between (Das, 2010; De Nevers and Grahn, 1991; Roth, 1995). Flow in media is dependent upon the pore size and the volume it occupies inside the media. The pores coexist as very fine pores through which fluid transits with difficulty and wider pores with large fractures through which fluid flows (Mory, 2013). Porosity, a characteristic of the media pores, is the ratio of void volume to total volume and is dependent upon grain size and sorting (Lopez de San Roman Blanco, 2004; Mory, 2013). Poorly sorted sediments have small particles occupying void spaces between large particles therefore, reducing the amount of fluid that can flow through and the converse is true (Bear, 1972; Bruch et al., 2014; Lopez de San Roman Blanco, 2004).

Grain size affects hydraulic conductivity with smaller grains having small pores, less area available for the flow of water i.e. it has a high surface area per unit volume hence, more frictional resistance and low hydraulic conductivity. The converse is true for large grains (Holdich, 2002; Lopez de San Roman Blanco, 2004).

The relationship between hydraulic conductivity and porosity can be expressed using the Carmen-Kozeny equation:

$$K = \frac{(\rho g)}{\mu} \frac{n^3}{(1-n)^2} \frac{d_m^2}{180} \tag{1}$$

Where:

K is the hydraulic conductivity (m/s); ρ is the density of the fluid flowing (kg/m^3); g is the acceleration due to gravity (9.8 m/s^2); n is porosity (dimensionless); d_m is the representative grain size; and μ is the dynamic viscosity of the fluid (N s/m^2);

Flow through a media can be quantified by permeability (Mory, 2013). A media is said to be permeable if it has continuous voids (Murthy, 2002). Media permeability is related to hydraulic conductivity by Equation 2 (Bear, 1972):

$$K = \frac{(k\rho g)}{\mu} \tag{2}$$

Where:

K is the hydraulic conductivity (m/s); k is the media permeability (m^2); ρ is the density of the fluid flowing (kg/m^3); g is the acceleration due to gravity (9.8 m/s^2) and μ is the dynamic viscosity of the fluid (N s/m^2).

Hydraulic conductivity is the ease with which water flows within a permeable media (Lopez de San Roman Blanco, 2004) and is a function of both media and fluid properties. The sediment properties include size, sorting, shape, packing, and porosity whilst the fluid properties are viscosity and density (these remain constant at room temperature of 20°C (Engler, 2010; Lopez de San Roman Blanco, 2004). Darcy relates flow through a media with the hydraulic conductivity of the media and hydraulic gradient by Equation 3, which can be also written as Equation 4 (Bear, 1972):

$$Q = -KA\frac{(h_1 - h_2)}{L} \tag{3}$$

Where:

Q is the flow rate through the media (m^3/s); K is the hydraulic conductivity (m/s); A is the cross-sectional area of the filter media (m^2); h_1-h_2 (hydraulic gradient) is the piezometric head at inlet and outlet of the media bed of length L (m) in the flow direction.

$$Q = -KAi \tag{4}$$

Where:

i is the hydraulic gradient (dimensionless). Darcy's law is only valid for laminar flow (Holdich, 2002; Lopez de San Roman Blanco, 2004).

Hydraulic conductivity is one of the major factors affecting wetland performance as HRT depends on it. This consequently affects treatment performance, therefore hydraulic conductivity has to be maintained for stabilisation of the HRT (Priya and Urmila, 2013; Sundaravadivel and Vigneswaran, 2001). Effective hydraulic conductivity can result in the accumulation of particulate matter, non-homogeneous biomass development, which consequently leads to clogging (Giraldi et al., 2010; Knowles and Davies, 2009; Molle et al., 2006; Pedescoll et al., 2009). Hydraulic conductivity can be regarded as constant within the media if packing is uniform within the media bed (Holdich, 2002).

The constant head test is used in the laboratory to determine the hydraulic conductivity of the media given by Equation 5 (Pedescoll et al., 2009):

$$K = \frac{d^2 \ln(2L/D)}{8LT} \ln \frac{h_1}{h_2} \tag{5}$$

Where:

K is the hydraulic conductivity (m/s); d is the tube diameter (m); h_1 and h_2 are the height of water at time zero and T (s); L is the submerged length of the tube (m).

2.3.4.4 Depth

The depth of media in HFCWs range from 0.3-0.8 m with a bottom slope of 1-3% to maintain the gravitational flow through the bed (Vymazal et al., 2006). In VFCWs, the depth may range from shallow (0.45 m) to deep (1.2 m) with a bottom slope of 1-2% (Stefanakis et al., 2014).

Due to the deeper VFCWs, depth affects the redox potential and DO concentrations thus, influencing the biological reactions responsible for pollutant removal. Furthermore, it determines the type of plants to be used in a CW (Chang et al., 2015). Organic matter is degraded in the top 0.2 m of the filter depth as this layer is populated with microbial biomass due to the high DO concentrations (Stefanakis et al., 2014). In terms of nitrogen removal, deeper beds promote anoxic conditions required for denitrification (Kadlec and Wallace, 2009).

2.3.4.5 Plants

The use of vegetation has generally been accepted to enhance pollutant removal in CWs since the most reactive zone of the bed is in the rhizosphere (Stottmeister et al., 2003; Wu et al., 2015). Plants release oxygen near their roots creating an oxidation-reduction potential for the aerobic dependent reactions such as nitrification, and the uptake of nutrients, such as nitrate and phosphorus. Plant roots influence the CW hydraulic efficiency by reducing the velocity of flowing water thus, increasing the contact time between the media, roots and wastewater resulting in improved pollutant removal. Likewise, plants prevent clogging due to wind movement which prevents media surface area blocking improving the hydraulic conductivity of the bed (Saeed and Sun, 2012; Stefanakis et al., 2014).

Zhang et al. (2009) comment that despite this, the quantitative role of plants in a CW is debatable and the uptake of nutrients is often minute compared to the incoming influent concentration. Verhoeven and Meuleman (1999) explain that the storage of nutrients is not permanent and often at the end of a plant's life cycle, much of these nutrients are leached back into the system by decaying litter during senescence. Some authors argue that regular harvesting events may counteract this issue by removing the stored nutrients, especially nitrate, while some have maintained this practice is negligible for nutrient removal (Vymazal, 2005).

Plants grow and regenerate in spring, fully develop in summer, senescence and die in winter and, harvested in late Autumn (Stefanakis et al., 2014). *Phragmites australis* is the most commonly used species for wastewater treatment in CWs due to their extensive, longer-lived root system and high root zone aeration, amenability to unmaintained systems and competitiveness with other species (Saeed and Sun, 2012). Ideally, the choice of vegetation depends on the availability of local species and its adaption and tolerance to the nutrient and organic load entering the system. The second criteria is for the survival and treatment potential of the species selected (Wu et al., 2015). Plants are sensitive to stress and the quality of the wastewater being treated should not cause major physiological changes to the species that will harbour the overall treatment of the CW. Other common species are *Typha* (cattails), *Scirpus*, and *Schoenoplectus* (bulrushes) (Kadlec and Wallace, 2009). Zurita et al. (2009) showed higher treatment efficiency in VFCWs with more than one species due to the greater distribution of the rooting system. Similar findings were documented by Zhang et al. (2010)

and Zhu et al. (2010), who found plant species richness to be positively correlated with plant biomass production and retention of nitrogen in the filter media thus, improving the overall performance of the system.

2.3.5 Operation and maintenance requirements

While CWs have simple operation and maintenance requirements, these are biological systems and thus, require regular monitoring for operational problems (such as the dosing device in VFCWs and clogging in both CWs) and pertinent maintenance activities. Blockages upstream of the CWs must also be monitored.

Performance monitoring forms an integral component in the successful operation of CWs. A comparison between removal efficiencies (via final effluent quality analysis) will allow for hydraulic load variations to be manipulated to improve performance. In terms of plants, harvesting and weed control form the two most common maintenance requirements (Kadlec and Wallace, 2009).

2.3.6 Application of constructed wetlands in South Africa

In South Africa, full-scale systems were implemented in the early 1980s with the first attempt in Mpophomeni CWs located in the KwaZulu-Natal province (Wood, 1995). The last inventory indicated that more than 70 CWs were used to treat wastewater from domestic, industrial, mining, agricultural, and storm water runoffs amongst others (Wood et al., 1999). More recently, CWs are being used to acid mine drainage (Sheridan et al., 2013) and winery effluent (Sheridan et al., 2014). However, the long-term performance evaluations of CWs, especially SSF CWs as a secondary treatment for anaerobically treated domestic wastewater, is still lacking from literature.

To fully implement CWs in the attempt to fill the gap in urban sanitation, long-term monitoring of new and existing applications of CWs in South Africa will aid in developing a brief design guideline for use in dense social housing schemes.

CHAPTER 3:SAMPLING METHODOLOGY

This chapter provides the description of the design of the demonstration-scale subsurface flow CW system at the NM site (inclusive of all modifications between 2016 and 2018) and the sampling method adopted during the monitoring campaign (Section 3.1). The design and operation of the pilot-scale vertical flow constructed wetlands is also described (Section 3.2).

3.1 DEMONSTRATION-SCALE HYBRID CONSTRUCTED WETLAND SYSTEM

An aerial view of the hybrid CW system is given in Figure 3.

3.1.1 Siphon chamber

The AF effluent from Train 1 flows into a chamber (2.6 m x 3 m; l x b) housing a FLOUT® siphon (Appendix 4) that intermittently discharges a fixed volume onto the vertical down-flow CW. Uneven flow distribution in the ABR in February 2017 resulted in high loading through Train 1 (almost 30 m^3/d). This caused the ballast weight of the siphon to fall, reducing its floating capacity. The continuous flow to the VFCW, resulted in permanent surface water accumulation of 0.2 m in depth and ultimate clogging by April 2017. The ballast weight was subsequently replaced in August 2017 after which the siphon restored to normal function (refer to Appendix 4 for a brief description of how the siphon functions). A pressure transducer (dipperLog Nano b, Heron Instruments Inc.) was installed inside the siphon chamber to record the frequency and loading per dose. The average dose volume to the VFCW is 1.87 m^3.

3.1.2 Design of the vertical flow constructed wetland

The area of the vertical subsurface down-flow CW (VFCW) is 96 m^2 (9.8 m x 9.8 m; l x b) (Appendix 5) with a design hydraulic loading rate (HLR) of 0.14 m/d. To maintain the hydraulic head through the system for gravitated flow, the VFCW was constructed at half of the recommended depth of 1.5 m. Thus, the VFCW has a shallow drainage manhole preventing outflow measurements.

The 0.55 m filter layer includes well-graded (C_u = 4.64) unwashed Umgeni river sand (D_{10} = 0.4 mm) and 0.15 m drainage layer of 4-25 mm coarse gravel (D_{10} = 4.4 mm). In October 2017, a thin layer (≈ 0.05 m) of coarse sand to fine gravel (0.5-2 mm) was added to the surface of the bed and compacted to cause temporal surface water accumulation (flooding) and thus, improve the retention time within the bed.

The distribution system was replaced from four d 110 mm perforated pipes (Appendix 5) to eight d 75 mm pipes with alternate perforations (i.e. not in pairs as designed previously) to extend the distribution of the wastewater (Appendix 6). The VFCW was then planted with shoots (0.1 m above the ground) of *Cyperus sexangularis* and *Typha capensis* in late October 2017 (5-6 plants/m^2). A double layer of shade net is lined at the bottom of the bed to prevent groundwater contamination.

3.1.3 Design of the horizontal flow constructed wetland

The treated effluent then flows into a horizontal sub-surface flow CW (HFCW) with a surface area of 66 m^2 (8.1 m x 8.15 m; l x b) and depth of 0.9 m (Appendix 7). The filter media consists of 50-80 mm stones. The bed was also planted with *C. sexangularis* and *T. capensis* from shoots harvested from the VFCW in late October 2017. To temporarily impound the bed and saturate more of the filter depth, a d 110 mm flexible hose was installed at the outlet pipe Appendix 8. The discharge from the HFCW flows into the trunk sewer so that none of the treated effluent is released into the immediate environment (field or river).

Figure 3: Aerial view of the hybrid sub-surface flow constructed wetland system (taken September 2019)

Photo credit Jodache Naidoo, Pulse Control Systems

AF = anaerobic filter; HFCW = horizontal flow constructed wetland; SC = siphon chamber; SS1 = vertical flow constructed wetland sampling chamber; SS2 = horizontal flow constructed wetland sampling sump; VFCW = vertical flow constructed wetland

The direction of flow is denoted by the red arrows.

3.1.4 Additional installations: sampling sumps for composite sampling

The low head in the outlet sump of the VFCW and the flow pulse with a long low-flow tail made flow measurements and sampling problematic. Furthermore, monthly grab samples of the CW effluent from 2015 to 2016, indicated variable effluent quality (Appendix 9a) even during a 24-hour hourly sampling campaign in January 2017 (Appendix 9b). This was suspected to be due to the variation in the residence time in the CWs due to the pulsing nature of the feed. Thus, flow proportional or composite sampling was considered a more appropriate sampling strategy.

After approval from EWS (in terms of safety and budget implications), the CWs were shut down in late September 2018 in order to install sampling sumps for composite sampling. Manhole rings, d 750 mm with a height of 0.25 m, were used to construct the underground sumps. Eight rings were stacked allowing for a volume capacity of 440 L with a working depth of 1 m (i.e. below the inlet pipe to the sump). Cross connections between the inlet and outlet pipes of the sump allowed for the CWs to operate under normal conditions when sampling did not occur (Appendix 10a and b). Construction and commissioning of the sumps were completed by the end of October 2018. An aerial view of the sumps is given in Appendix 10c.

3.1.5 Sampling campaign (February-May 2019)

In November 2019, both CWs were started-up and left undisturbed for three months. Sampling began in February 2019 for 16 weeks allowing for eight sampling events per CW. From January 2019, a daily log was maintained for the weather, flow from Train 1 and any other events which may cause deviations in the performance of the CW system. The outflow profiles from the CWs were determined on three separate occasions over the 16-week period. Sampling for chemical and microbiological analyses on the final effluent from each respective CW took place every Friday.

3.1.5.1 Environmental and physical conditions upstream of the CWs

The environmental conditions (air and water temperature) were recorded daily on-site. Recorded rainfall data was sourced from the eThekwini Municipality monitoring databases. The total daily flow was monitored from on-site SAFMAG (Flowmetrix) electromagnetic flowmeters on the outlet of each ABR train and recorded using an Omniflex Teleterm M3G SD Card Logger (Model No.: C2363A-O). All operational and maintenance activities during the sampling campaign were recorded.

3.1.5.2 Flow monitoring

Inflow

The siphon dosing rate and volume/dose were calculated using logged data from the pressure transducer.

Outflow

Outflow measurements were measured by the fill and drain process. The sump was demarcated into five intervals equating to 88 L per 0.2 m. A Zilmet V180F submersible pump was installed temporarily to empty each sump when required. The dead volume inside the sump to accommodate for the maximum height of the pump was 44 L thus, the first measurement was done at 44 L and thereafter for every 88 L until a volume of 396 L had drained from the CW. A stopwatch was used to measure the fill and drainage times. Once the sump was full, the pump was switched on for 30 s to mix the entire drainage. The outflow from the pump was then directed to the normal piping system (i.e. VFCW to HFCW or HFCW to sewer) while the inflow into the sump was uninterrupted and not measured. Thus, the error associated with the flow loss into the sump while the pump was draining the sump was not calculated. This process was repeated until the entire drainage from a single dose of the siphon was collected equating to 4.7 fills for an average dose volume of 1.87 m^3.

3.1.5.3 Chemical and microbiological monitoring of constructed wetland effluent

Anaerobic filter effluent

The AF effluent was sampled from the siphon chamber. Three 1 L grab samples (30-second intervals between each) were taken weekly. As individual samples were taken, these are not referred to as replicates.

Loading rate

The organic, nutrient and pathogen loading to the VFCW was calculated using Equation 6.

$$\textbf{Loading rate}\ (\mathbf{g.m^{-2}.d^{-1}}) = \mathbf{q} \times \mathbf{C_i} \quad (6)$$

Where:

q is the hydraulic loading rate (m/d); C_i is the concentration of the AF effluent (mg/L).

Constructed wetland effluent

Each fill of the sump was well mixed by the action of the pump before draining the sump. Three 1 L replicates were taken from each of the first four fills and 0.7 L from the last fill. The final composite sample therefore composed of sub-composites of each sample taken during each fill of the sump. It must be noted that the VFCW effluent refers to treatment of the AF effluent in the VFCW only while the final effluent refers to treatment in the hybrid CW system (i.e. the VFCW and HFCW connected in series).

Chemical and microbiological analyses

A Jenway 3540 pH & Conductivity meter and BOECO - DO-580 was used to measure pH and electrical conductivity (EC), and dissolved oxygen (DO) concentration, respectively. Alkalinity (ALKY), total COD (CODt); ammonium-N (NH_4-N), nitrate-N (NO_3-N) and total nitrogen (TN) and orthophosphate-P (PO_4-P) was measured with a Merck NOVA 60 Spectroquant. The biodegradable COD (both soluble and particulate fractions) from the CODt concentration was measured by the Oxygen Uptake Rate (OUR) using a BM-Evo Respirometer.

All determinants measured with the Spectroquant were prepared and analysed according to the standard operating procedure (SOP) supplied with the test kit supplied by Merck. Total suspended solids was measured according to Standard methods (2540 D) (APHA, 2017). All samples, except for CODt and TN, were filtered (using a Whatman 1.2 µm pore size filter paper) and the filtrate was prepared for analysis to avoid interference by the TSS concentration on the measurement by the spectrophotometer.

Indicator bacteria, *E. coli* bacterial cell counts, was measured using the Merck Petrifilm 3M plate and recorded as colony forming units (CFU)/1 mL converted to CFU/100 mL.

All analyses, except for the bCOD, were done in the NM laboratory on-site. The bCOD fraction was measured at the Pollution Research Group laboratory, University of KwaZulu-Natal.

Performance of each constructed wetland

The performance of each CW was measured by the removal efficiency and mass removal rate of the suspended solids, organic and nutrient content in the AF effluent.

- Removal efficiency

Percentage removal (removal efficiency) of each pollutant was measured by Equation 7.

$$\textbf{Removal efficiency (\%)} = \left(\frac{C_i - C_o}{C_i}\right) \times 100\% \qquad (7)$$

Where:

C_i is the concentration of the AF effluent (mg/L) and C_o is the concentration of the CW effluent (mg/L).

- Mass removal rate

The mass removal rate of organic and nutrient content was calculated by Equation 8.

$$\textbf{Mass removal rate } (g.m^{-2}.d^{-1}) = q\ (C_i - C_o) \qquad (8)$$

Where:

q is the hydraulic loading rate (m/d); C_i is the concentration of the AF effluent (mg/L) and C_o is the concentration of the CW effluent (mg/L).

3.1.5.4 Vegetation

Plant density was measured counting the number of individual plants of the particular species in a given area before and after the monitoring period. Before the sampling event, the plant cover in the VFCW was scarce comprising mostly weeds and the invasive*, Canna indica*. A full harvest was done in December 2018 and the beds were replanted with shoots, ≈ 0.15 m in height, of *Cyperus sexangularis* and *Typha capensis*.

Plant nutrient content was measured at the end of the sampling campaign. Two plants of each species were taken from different quadrants on the surface of each CW to determine any difference in nutrient uptake.

Nutrient content was measured on a dry matter basis via ICP analyses at the Soil Analytical Laboratory at the KwaZulu-Natal Department of Agriculture and Rural Development, Cedara.

3.2 PILOT-SCALE VERTICAL FLOW CONSTRUCTED WETLANDS

3.2.1 Design, construction, and operation

The above-ground pilot-scale VFCWs were also constructed from d 750 mm manhole rings, 0.25 m in height (Figure 4). The single-stage VFCWs are 1 m and 1.5 m in height, respectively while each stage of the two-stage VFCWs is 1 m in height.

The media gradation of the pilot-scale VFCWs was adapted from personal communication with Prof. Langergraber (BOKU University, Vienna) based on a successful full-scale two-stage VFCW application in Austria (Langergraber et al., 2014) and locally available sieved media. The filter layer consists of 2-3 mm coarse sand with a drainage layer of 16-32 mm gravel. Langergraber (2017) suggested that an intermediate layer of 4-8 mm gravel would maintain filter stability by inhibiting the washing out of any fine particles in the above filter layer into the drainage layer. Therefore, linings or geotextiles within each column was not needed. The media gradation of each column is given in (Table 1).

Figure 4: Pilot-scale vertical flow constructed wetlands treating anaerobically treated domestic effluent

Photo credit Jodache Naidoo, Pulse Control Systems

The CWs are numbered sequentially (1 to 6) from right to left.

Table 1: Media gradation of the pilot-scale vertical flow constructed wetlands

	Depth (m) and grain size of media (mm)		
	Filter layer	Intermediate layer	Drainage layer
Single-stage VFCWs			
CW 1 and 3	0.5 m (2-3 mm)	0.2 m (4-8 mm)	0.3 m (16-30 mm)
CW 2 and 4	1 m (2-3 mm)		
Two-stage VFCWs			
CW 5a and 6a	0.5 m (2-3 mm)	0.2 m (4-8 mm)	0.3 m (16-30 mm)
CW 5b and 6b	0.6 m (0.5-2 mm)	0.1 m (4-8 mm)	

Anaerobic filter effluent from Trains 2 and 3 was pumped to a 1000 L feeding tank. A pressure pump (Grundfos) connected to a programmable logic controller (National Instruments) was used to pump 5 flushes to equal volume (16.5 L) to each VFCW. Thus, the design hydraulic loading rate was 0.19 m/d, adapted from Langergraber et al. (2008) for coarse sand to fine gravel media. The columns were left unplanted to reduce the start-up time and fed for six weeks undisturbed.

3.2.2 Sampling

In week 7, a 1 L composite sample from the drainage of a single dose was collected from CWs 1-4, 5b and 6b for analysis. The quality of the effluent from CW 5a and 6a was assumed to be the same as CW 1 and 3 due to the identical depth, HLR and media gradation. Thus, no sampling occurred for these columns. Sampling was done weekly until Week 15 (end of October 2019). All analyses were done on-site. The quality of the effluent was measured by the same determinants as the demonstration-scale CW system (refer to section 3.1.5.3).

CHAPTER 4:RESULTS AND DISCUSSION

This chapter is written in two parts: Section 4.1 describes the performance of the demonstration-scale CW system and compares the final effluent quality with the General Authorisations limits for discharge, while Section 4.2 presents the preliminary performance data of the pilot-scale vertical flow constructed wetlands during start-up.

4.1 PERFORMANCE OF THE DEMONSTRATION-SCALE CONSTRUCTED WETLANDS

The flow conditions, organic and nutrient loadings to the CW system during the monitoring period (January-May 2019) is presented here. The performance assessment is based on the quality of the effluent quality from each CW.

4.1.1 Flow in relation to environmental conditions

The flow through Train 1, feeding the CW system, ranged from 1.7-104.4 m^3/d (Figure 5a) with an average flow of 17.7 m^3/d over the monitoring period. Low flows were experienced during blockages upstream of the overall treatment system while high flows were over holiday periods. The daily cumulative flow through Train 1 was on average 47.6% of the total daily flow into the system (Appendix 12a). A scheduled desludging event of the settler in mid-March 2019, stabilised the flow below the design of 13.9 m^3/d. Power outages and load shedding events limited daily flow measurements at that specific time.

The average daily rainfall and air temperature during the sampling period was 1.6 mm/d and 22.6°C, respectively (Figure 5b). Rainfall does not appear to impact on the daily flow except during an unusually high rainfall event in March 2019. There was no correlation between the flow and the subsequent high rainfall event in April 2019.

4.1.2 Siphon dose volume

During January-May 2019, the average siphon dose frequency was eight times per day at a volume of 1.87 m^3 discharged over 3:28 (mm:ss). The loading rate per dose was 0.53 m^3/min, while the cumulative daily flow to the VFCW was 15.6 m^3/d. This equated to an HLR of 0.16 m/d, higher than the design of 0.14 m/d.

Throughout the sampling period, the siphon worked consistently with no disruptions. However, daily logging of the water level changes in the siphon chamber was limited during mechanical problems with the pressure transducer (PT). Comparison with the Train 1 daily flow showed minimal losses from the AF to the siphon chamber feeding the CW system and accuracy of the flowmeter readings (Appendix 12c).

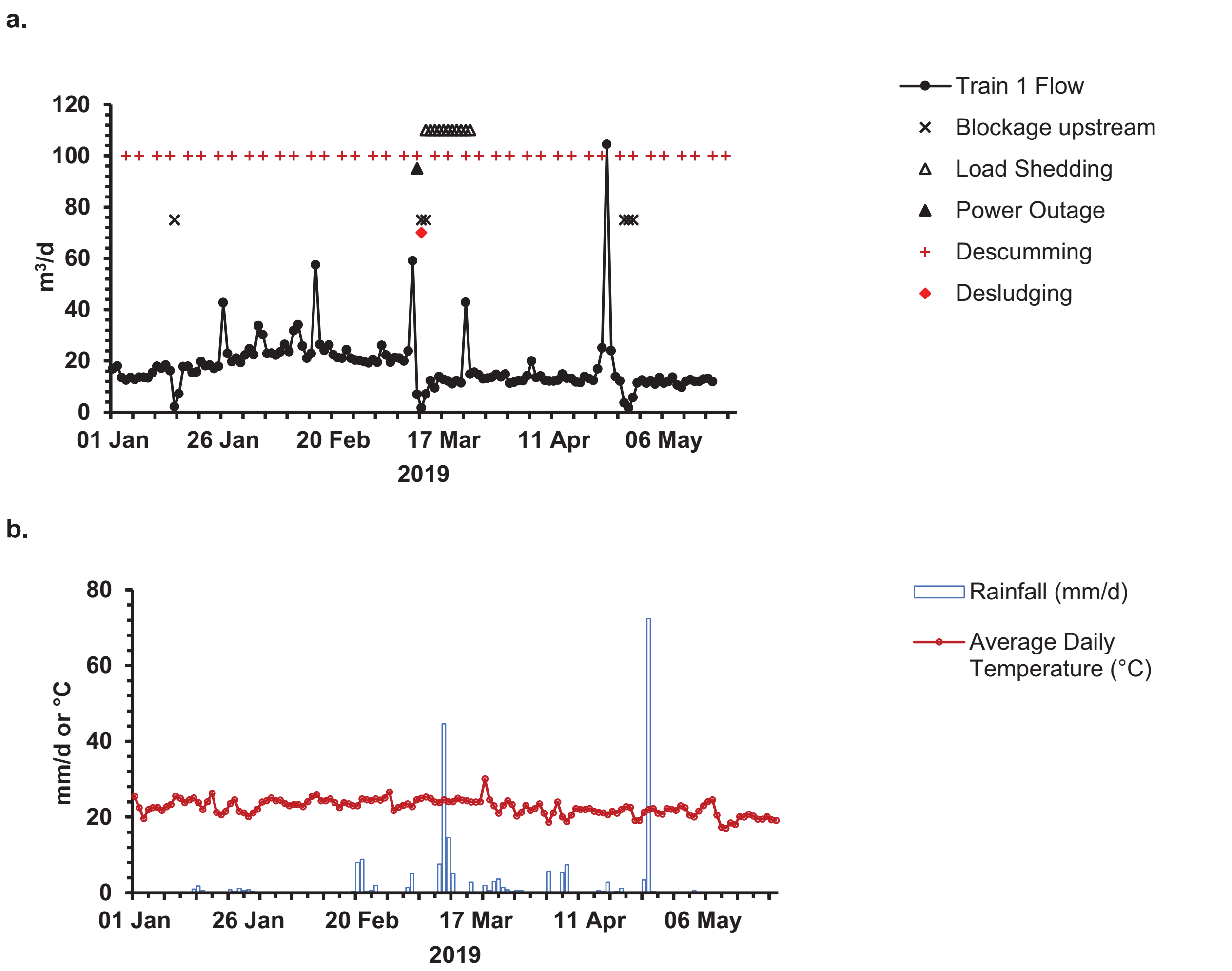

Figure 5: Flow and environmental conditions during the monitoring period a. daily cumulative flow through Train 1 in relation to routine maintenance activities and problems upstream of the Newlands Mashu decentralised wastewater treatment system; b. daily rainfall and temperature (January-May 2019)

4.1.3 Chemical and microbiological loading

Organic loading to the VFCW was 58.3 g COD m^{-2} d^{-1} of which 76.3% was biodegradable (inclusive of the soluble and particulate fractions). Nutrient loading, measured only by nitrogen, was 9.9 g N m^{-2} d^{-1}. This was similar to the quality of the AF effluent described by Pillay et al. (2013). Average inlet faecal coliforms (quantified by *E. coli* bacterial cell count) was 3.2 x 10^5 CFU/100 mL (Table 2).

4.1.4 Drainage profiles

Typical drainage profiles from the VFCW and HFCW is presented in Figure 6. In the VFCW, the average time taken for draining an entire dose volume of 1.87 m^3 was 3:59 (hh:mm) at an average outflow rate of 0.6 L/s (Figure 6a). Using the maximum porosity of 0.45 for sand and gravel as discussed by Kadlec and Wallace (2009), the retention time of a single dose should be 61 min, however the measured drainage time was almost 4 hours. This implies, that the layer of the 0.5-2 mm coarse sand added on the surface aided in improving the retention time in the bed.

In the HFCW, the average time taken for collection of an entire dose volume from the siphon was 4:32 (hh:mm) while the average outflow was 0.4 L/s (Figure 6b). Considering the CWs operated in series, the average detention time in the HFCW was only 33 minutes. Using a porosity or void fraction of 0.3 since gravel media will usually have a higher hydraulic conductivity equates to an actual retention time of 33.6 minutes as in the drainage profile. This implies that the flexible hose at the outlet pipe did not increase the head as predicted thus, not impounding the bed for higher retention time.

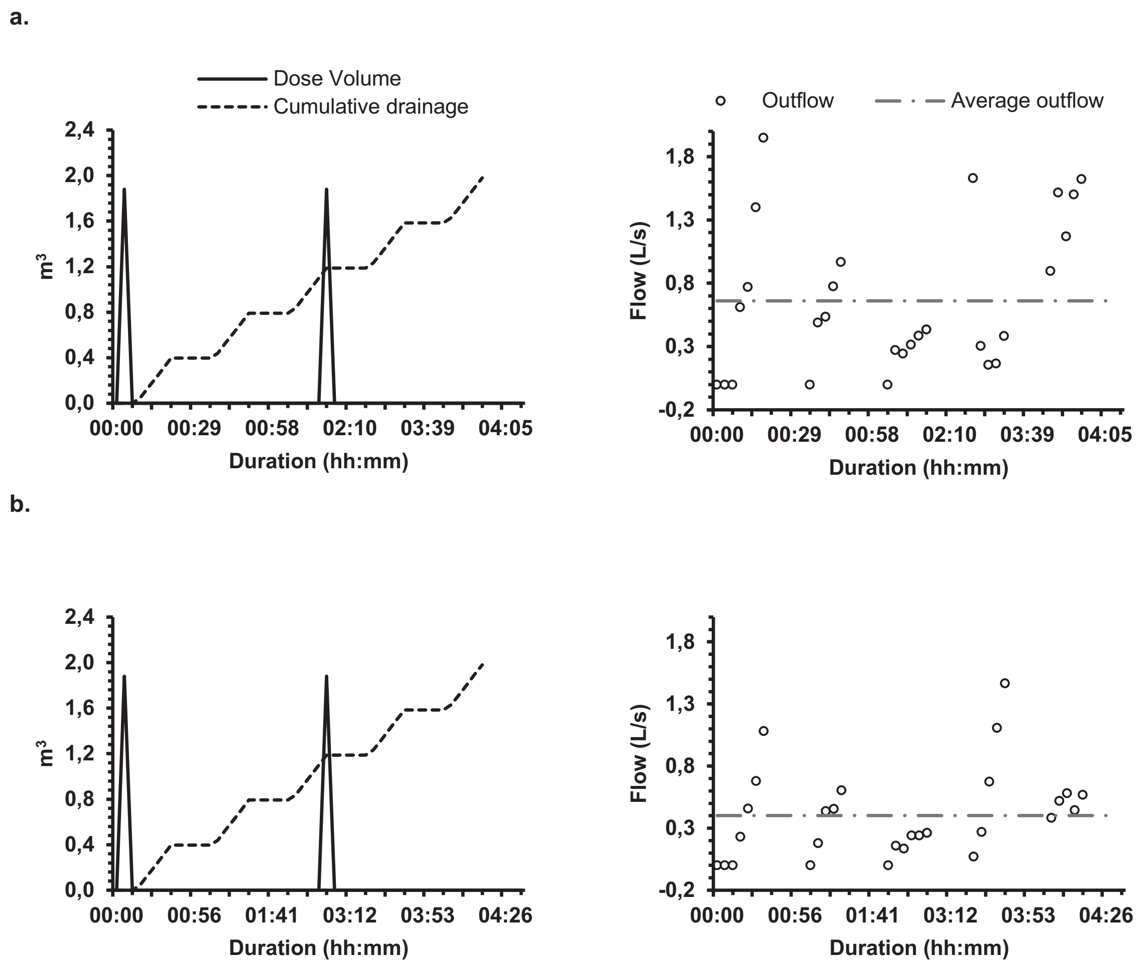

Figure 6: Typical drainage profiles from the demonstration-scale constructed wetlands a. vertical flow constructed wetland; b. horizontal flow constructed wetland

4.1.5 Performance of the hybrid constructed wetland system

Mass removal rates of CODt and total N were 48.7 g COD m^{-2} d^{-1} and 1.2 g N m^{-2} d^{-1} after the VFCW with overall mass removal being 51.2 g COD m^{-2} d^{-1} and 3.7 g N m^{-2} d^{-1}, respectively. Organic (CODt) and nutrient (NH_4-N and PO_4-P) removal efficiencies were 83.8, 92.4, and 22.1% after the VFCW, with overall removal (after the HFCW) being 88.2, 97.8 and 55%, respectively (Table 2). It appears that the majority of the OM degradation and ammonium-N transformation occurs in the VFCW since both processes are oxygen dependent.

Low (12.5%) nitrate-N removal was observed in the HFCW. The total N concentration in the HFCW effluent ranged from 26-52 mg/L with a major component being nitrate-N ranging from 10.5-41.7 mg/L. The lack of biodegradable COD in the VFCW effluent was the limiting factor in reducing denitrification. Furthermore, the low denitrification rates are indicative of low or the absence of a carbon source in the gravel media within the HFCW. Fu et al. (2017) used plant-based materials of macrophytic plants as natural, cheap carbon-sources by adding fermenting tissues of the plant species on a VFCW for improved nitrogen removal. Total-N removal was 92.8% with the main removal processes being a combination of anaerobic ammonium oxidation (ANAMMOX) and classical denitrification.

The action of the pump in the sampling sumps resulted in suspended matter from the walls of the sump to interfere with actual TSS concentration in the drainage from each CW. Therefore, the actual TSS in the CW effluent is suspected to be much lower than indicated and perhaps ranging below the GA limit of 25 mg/L in the effluent of both CWs.

Overall, pathogen removal was higher after the HFCW, with die-off suspected to be the main removal process.

For the duration of the 16-week sampling campaign, the final effluent quality (after treatment in hybrid CW system), ≥ 85% of the samples (n = 8) were compliant to the GA limits for discharge for organics (CODt), ammonium (NH_4-N), orthophosphate (PO_4-P), pH and electrical conductivity (EC). The number of samples compliant for faecal coliforms (*E. coli*) and TSS was 83.3 and 75%, respectively (Table 2).

It is evident that the minor upgrades to the VFCW aided in the overall treatment efficiency of the CW system compared to performances discussed in previous reports (Pillay et al., 2013; Schoebitz, 2013). Despite, producing high quality of effluent after the HFCW, poor nitrate-N removal limits the discharge of the treated effluent if applied in full-scale application. The limited denitrification is not suspected to be a design flaw. Low-cost, alternative organic carbon sources need to be identified that can be passively applied without damaging the bed.

4.1.6 Plant density and uptake of nutrients

By May 2019, the surface of the VFCW was almost completely covered with equal density of the two planted macrophytes with very few weed species (Appendix 13). Despite the complete vegetation cover, plant uptake of nutrients was poor with the nitrogen content higher than the phosphorus content (Table 3). While planted CWs do perform better than unplanted CWs (Kadlec and Wallace, 2009; Stefanakis et al., 2014; Vymazal, 2007), the plant species in the VFCW do not appear to assimilate the nutrients from the feed significantly to contribute to total nutrient removal. The location of the plants on the surface of the bed does not influence nutrient uptake (Table 3). However, due to the oxygen transfer capacity at the root zone, the presence of plants does contribute to the microbial degradation processes in nutrient removal.

The density of *Typha capensis* was greater in the HFCW compared to *Cyperus sexangularis*, and it is unclear why. The total plant density compared to the surface area of the bed was 85% (Appendix 13). The vacant areas were due to disturbance near the outlet sump. As with the VFCW, plant uptake of nutrients from the feed of the HFCW is not substantial (Table 3).

Table 2: Final effluent quality over the monitoring period (January-May 2019)

	AF Effluent[7]			VFCW Effluent			HFCW Effluent			% of Compliant samples	GA Limit
	n	Range (min-max)	Mean (± Std Dev)	n	Range (min-max)	Mean (± Std Dev)	n	Range (min-max)	Mean (± Std Dev)		
CODt [mg/L]	40	140-860	357.8 (± 198.7)	21	24-115	53.5 (± 28.3)	23	4-86	38.1 (± 26.2)	87%	75
NH_4-N [mg/L]	48	22-68	52 (± 12)	24	0-16	4.3 (± 4.7)	24	0-5	1 (± 1.6)	100%	6
NO_3-N [mg/L]		DNM		24	3.8-53.8	29.6 (± 13.8)	24	10.5-41.7	**26.8** (± 10.2)	12.5%	15
TN [mg/L]	48	26-74	61 (± 12.9)	24	27-69	49 (± 11.5)	24	26-52	37.9 (± 9.2)		
PO_4-P [mg/L]	48	2.6-17	8.3 (± 3.4)	22	3.5-7.1	5.1 (± 1)	22	1.3-6.4	3.1 (± 1.3)	100%	10
TSS [mg/L]	48	18-130	49.3 (± 23.1)	24	4-72	36.3 (± 18.1)	24	1-68	20.5 (± 19.8)	75%	25
pH	48	7.2-8.3		24	5.6-7.9		24	6.4-7.9		100%	5.5-9.5
EC (mS/m)	48	75.9-105.3	95 (± 7.9)	24	53.7-81.7	70.8 (± 7.3)	24	49.3-76.2	65.2 (± 7.1)	100%	150
Alkalinity [mg $CaCO_3$/L]	48	92.3-412	318.5 (± 78)	24	0-160.5	17.8 (± 37.7)	24	0-87	23.5 (± 20.6)		
DO [mg/l]		DNM		24	1.7-2.9	2.1 (± 0.2)	24	1.3-2.5	2 (± 0.3)		
***E. coli* (CFU/100 ml)**	48	3×10^4-8.2×10^5	3.2×10^5	24	0-3.7×10^5	5.5×10^4	24	0-2.8×10^3	508	83.3%	1 000
***E. coli* Log Removal from AF**				0.8			2.8				

Red Bold font denotes above GA limit

[7] From Train 1 of the ABR

Table 3: Plant dry matter nutrient content in the vertical and horizontal flow constructed wetlands (May 2019)

	Cyperus sexangularis		***Typha capensis***	
VFCW				
Mean Fresh Mass (kg)	7.45		0.55	
Mean Dry Mass (kg)	4.23		0.32	
Location on CW surface	Nitrogen (%)	Phosphorus (%)	Nitrogen (%)	Phosphorus (%)
Front left	2.41	0.27	1.98	0.22
Back right	2.08	0.27	2.63	0.37
HFCW				
Mean Fresh Mass (kg)	8.2		1.35	
Mean Dry Mass (kg)	4.7		0.76	
Location on CW surface	Nitrogen (%)	Phosphorus (%)	Nitrogen (%)	Phosphorus (%)
Front left	-	-	2.13	0.39
Back right	1.64	0.23	2.28	0.27

- denotes no plant species were present in that quadrant

4.2 START-UP PERFORMANCE OF THE PILOT-SCALE VERTICAL FLOW CONSTRUCTED WETLANDS

4.2.1 Feed conditions

Each column operated continuously at an HLR of 19 m/d for 15 weeks. The organic and nitrogen loading rate was 45.3 g COD m^{-2} d^{-1} of which 88.8% was biodegradable (inclusive of the soluble and particulate fractions) and 14.2 N m^{-2} d^{-1}, respectively. It should be noted that the nitrogen loading to the pilot-scale VFCWs was 43% higher than the loading to the demonstration-scale CW system (Table 4).

4.2.2 Final effluent quality

Nitrification, indicated by nitrate-N in the effluent, was evident after six weeks in all configurations however, poor CODt removal in the single-stage VFCWs is indicative that the columns have not reached steady-state. Average removal efficiencies of CODt were 17, 14 and 56% from the single-stage; single-stage with extended filter depth and two-stage VFCWs, respectively while removal of NH_4-N was 34, 9 and 88%, respectively. This implies that nitrification is the dominant oxygen dependant process since the bCOD in the effluent from all columns was still relatively high, ranging from 39.9-88.8% across all configurations. Total N removal was poor but higher in the two-stage VFCWs compared to the single-stage designs. Overall, the final effluent quality from each configuration was compliant for TSS, PO_4-P, pH, EC, and faecal coliforms but not for CODt, NH_4-N and NO_3-N (Table 4). Currently, the preliminary start-up performance gives evidence of the higher treatment efficiency of the two-stage VFCW over single-stage VFCWs. However, long-term monitoring is necessary.

In an attempt to mitigate the poor nitrate removal in single stage VFCWs, Langergraber et al. (2008) designed a two-stage VFCW. In the first stage, a 0.5 m filter layer with 2-3.2 mm sand was used followed by an impounded drainage layer. Essentially, an elbow joint was used to extend and elevate the outlet of the drainage pipe which is a simple and cost-effective method of increasing the HRT. They found that the use of the coarser sand in the filter layer restricted full nitrification of the influent (approximately 80 % nitrification was observed) and the complete mineralization of the organic matter (OM). The concentration of nitrates and OM in the effluent as it percolated through the media allowed for denitrification in the impounded layer (Langergraber et al., 2008).

Table 4: Final effluent quality of the pilot-scale vertical flow constructed wetlands (weeks 9-15 after start-up)

			Single-stage VFCW								**Two-stage VFCW**			
			Filter depth: 0.5 m (2-3 mm)				Filter depth: 1 m (2-3 mm)				1st stage Filter depth: 0.5 m (2-3 mm) 2nd stage Filter depth: 0.6 m (0.5-2 mm)			
	AF effluent[8]		CW 1		CW 3		CW 2		CW 4		CW 5b		CW 6b	
	n	Mean (± Std Dev)	n	Mean (± Std Dev)	n	Mean (± Std Dev)	n	Mean (± Std Dev)	n	Mean (± Std Dev)	n	Mean (± Std Dev)	n	Mean (± Std Dev)
CODt [mg/L]	7	238.6 (± 38.5)	7	195.5 (± 31.2)	7	200.1 (± 25.9)	7	182.8 (± 29.2)	7	212.8 (± 33.3)	6	97.7 (± 25.9)	4	111.5 (± 33.8)
bCOD [%]	3	88.8	2	66.2	1	49		DNM		DNM		39.9		61.9
NH_4-N [mg/L]	7	64.7 (± 39)	7	41.8 (± 2.8)	7	43.1 (2.4)	7	62.2 (± 6)	7	55.4 (± 4.4)	6	4.9 (± 2.6)	4	10.8 (± 2.1)
NO_3-N [mg/L]		DNM	7	20.1 (± 1.9)	7	19.1 (± 3.2)	4	0.6 (± 0.6)	6	4 (± 2.4)	6	40.6 (± 7.4)	4	39.1 (± 6.3)
TN [mg/L]	7	74.9 (± 3.1)	7	77.9 (± 1.5)	7	78.6 (± 2.1)	7	72.4 (± 3.6)	7	73.8 (± 4.7)	6	57.7 (± 5.7)	4	61.3 (± 5.4)
PO_4-P [mg/L]	6	8.3 (± 0.8)	6	8.7 (± 0.4)	6	10 (± 2.1)	6	9.4 (± 2.1)	6	10 (± 0.8)	5	5.5 (± 0.3)	3	5.3 (± 0.2)
TSS [mg/L]	6	26.7 (± 14.2)	6	14.2 (± 3.3)	6	13.2 (± 2.8)	6	4.7 (± 2.7)	6	13.3 (± 2.3)	5	0 (± 0)	3	0 (± 0)
pH (min-max)	7	7.5-7.7	7	7.5-7.8	7	7.5-7.7	7	7.2-8.5	7	7.1-7.4	6	6.8-7.3	4	7-7.1
EC (mS/s)	7	113.4 (± 4.4)	7	106 (± 3.4)	7	105.2 (± 4.2)	7	114.2 (± 3.5)	7	112.3 (± 3.7)	6	74.2 (± 3.2)	4	71 (± 3.8)
ALKY [mg $CaCO_3$/L]	7	6.1 (± 0.7)	7	4.5 (± 0.2)	7	4.4 (± 0.4)	7	7.1 (± 0.4)	7	6.6 (± 0.5)	6	0.9 (± 0.4)	4	1.3 (± 0.2)
***E. coli* (CFU/100 mL)**	6	0 (± 0)	6	24 (± 42)	6	1.2 (± 2.4)	6	7.7 (± 16)	6	0 (± 0)	5	1 (± 1)	3	0 (± 0)
Heterotrophs (#/100 mL)	6	52 (± 80)	6	35 (± 31.6)	6	24.8 (± 18.5)	6	13.3 (± 12)	6	28.5 (± 19)	5	49.2 (± 46.9)	3	29.7 (± 4.9)

DNM = Did not measure

[8] From Trains 2 & 3 of the ABR

CHAPTER 5:CONCLUSIONS AND RECOMMENDATIONS

This study analysed the performance of a demonstration-scale subsurface flow hybrid (VFCW-HFCW) constructed wetland system treating anaerobically treated domestic wastewater. In addition, the application of single verses two-stage down-flow VFCWs were investigated for higher total nitrogen removal.

5.1 CONCLUSION

The final effluent from the demonstration-scale CW system at Newlands Mashu cannot be discharged safely to the aquatic environment. Poor denitrification rates in the HFCW resulted in 87.5% of the composite samples with nitrate-N concentrations above the GA limit for discharge. The rate-limiting factor was found to be the absence of biodegradable COD in the VFCW effluent and within the HFCW as a carbon source for denitrification. Therefore, even if the VFCW was deeper (1.5 m) as originally recommended, the lack of a carbon source may have still inhibited nitrate removal. Currently, the hybrid design of the secondary treatment modules cannot be employed for dense social housing schemes where safe discharge of the final effluent to the river is needed.

If decentralised sanitation is employed in the urban context, especially for dense social housing schemes, improved total nitrogen removal must be considered when designing the secondary treatment modules. The nitrification rates in the pilot-scale two-stage VFCWs were higher compared to the single-stage designs. However, the start-up performance was not adequate to conclude that these CWs have higher total N removal.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

It would not be economically feasible to conduct further design upgrades to improve the performance of the NM hybrid demonstration-scale CW system. However, as a passive way to improve denitrification rates, the addition of plant-based carbon sources on the CW bed surface needs to be investigated. A cheap option will be to ferment harvested plant material from the CWs itself before the dying season. Once applied, further monitoring (at least 12 months) is necessary to determine if fully compliant effluent is achieved and test the sustainability of the system.

For the unplanted pilot-scale VFCWs, long term monitoring is necessary. However, the VFCWs should be planted with the same species as the demonstration-scale CWs (*C. sexangularis* and *T. capensis*) due to its local availability (10 km radius of the NM site). Furthermore, the changes in flow configuration must be done to determine if higher loading improves performance. It would be interesting to determine the effect of impounding the first stage of the two-stage VFCWs on total N removal. Moreover, the effect of load variation on system performance must also be ascertained to establish if parallel beds can be employed for load/rest operation to minimise or mitigate the occurrence of clogging in these CWs.

European household wastewater characterisation indicates that ≈ 80% of the total N load in wastewater streams is derived from urine (Henze, 1997). An EOOS designed urine diversion (UD) flushing pedestal has been tested at the Pollution Research Group in the University of KwaZulu-Natal and preliminary data have indicated that 75% of the urine was separated (data unpublished). If UD flushing toilets are installed at the household level in combination with decentralised wastewater treatment with two-stage vertical flow constructed wetlands (VFCWs) downstream, it is predicted that the nitrate-N concentration in the final effluent will decrease from 26.8 ± 10.2 (final effluent concentration from the current monitoring campaign) to 9.9 ± 3.3 mg/L. This will achieve fully compliant effluent quality with the GA limits for discharge.

Based on the data from this study and the predictions above, a water use licence application was submitted for a new social housing scheme in the eThekwini Municipality whereby a populous informal settlement will undergo formal housing upgrades. The application was successful to use the housing development as a demonstration for the concept of UD, primary anaerobic treatment, and two-stage VFCWs as an option for dense social housing schemes, where limited land availability precludes agricultural reuse of the treated wastewater. Furthermore, the data from the pilot-scale VFCWs will guide the design and operation of the demonstration-scale two-stage VFCWs. The lessons learned from this study and the future second-generation decentralised wastewater treatment system will aid in guideline formation and policymaking for the roll-out of decentralised sanitation on a wider, national scale.

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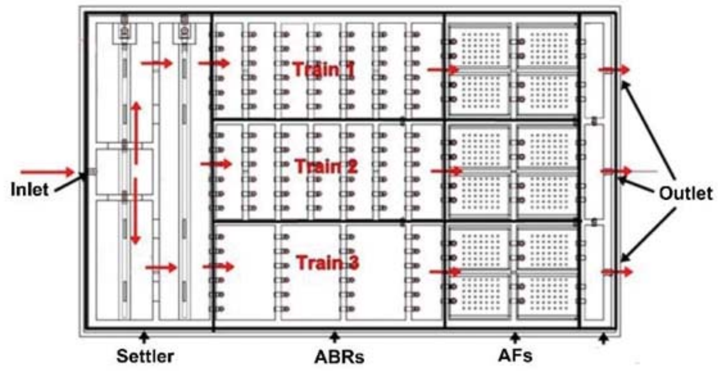
APPENDICES

Appendix 1 is a schematic of the design of the primary treatment modules indicating the pipe distribution. None of the trains are interlinked preventing any mixing of the effluent.



Appendix 1: Illustrative plan view of the primary treatment modules of the Newlands Mashu decentralised wastewater treatment system (inserted from Schoebitz (2013))

The red arrows indicate the direction of flow.

The limits are based on the discharge of the final effluent under Section 21(f) of the National Water Act (Act 36 of 1998): "*discharging waste or water containing waste into a water resource through a pipe, canal or any conduit*". The highlighted determinants in Appendix 2 were the minimum pollutants measured by the project team during the performance evaluation of the CW system.

Appendix 2: The General Authorisation limits for discharge of domestic wastewater (up to 2000 m^3/d)

TABLE 2.1: Wastewater limit values applicable to discharge of wastewater into a water resource

SUBSTANCE/PARAMETER	GENERAL LIMIT	SPECIAL LIMIT
Faecal Coliforms (per 100 ml)	1000	0
Chemical Oxygen Demand (mg/l)	75 (i)	30(i)
pH	5,5-9,5	5,5-7,5
Ammonia (ionised and un-ionised) as Nitrogen (mg/l)	6	2
Nitrate/Nitrite as Nitrogen (mg/l)	15	1,5
Chlorine as Free Chlorine (mg/l)	0,25	0
Suspended Solids (mg/l)	25	10
Electrical Conductivity (mS/m)	70 mS/m above intake to a maximum of 150 mS/m	50 mS/m above background receiving water, to a maximum of 100 mS/m
Ortho-Phosphate as phosphorous (mg/l)	10	1 (median) and 2,5 (maximum)
Fluoride (mg/l)	1	1
Soap, oil or grease (mg/l)	2,5	0
Dissolved Arsenic (mg/l)	0,02	0,01
Dissolved Cadm ium (mg/l)	0,005	0,001
Dissolved Chromium (VI) (mg/l)	0,05	0,02
Dissolved Copper (mg/l)	0,01	0,002
Dissolved Cyanide (mg/l)	0,02	0,01
Dissolved Iron (mg/l)	0,3	0,3
Dissolved Lead (mg/l)	0,01	0,006
Dissolved Manganese (mg/l)	0,1	0,1
Mercury and its compounds (mg/l)	0,005	0,001
Dissolved Selenium (mg/l)	0,02	0,02
Dissolved Zinc (mg/l)	0,1	0,04
Boron (mg/l)	1	0,5

Appendix 3 shows the final effluent quality (after the horizontal flow constructed wetland) of the Newlands Mashu decentralised wastewater treatment system through random grab sampling by a skilled EWS field technician.

Appendix 3: Final effluent quality from the Newlands Mashu decentralised wastewater treatment system (May 2014–July 2015)

	CODt [mg/L]	**NH_4-N [mg/L]**	**TSS [mg/L]**	**pH**	**EC (mS/m)**	***E. coli* (CFU/100 mL)**
n	17	17	17	17	17	17
Range (min-max)	34-159	0.2-56	1-11	6.3-7.4	62-112	3×10^2-3.1×10^4
Mean (± Std Dev)	77.2 (± 32.8)	24.6 (± 20.7)	3.4 (± 2.9)		78.8 (± 14.9)	9.6×10^3 (± 9×10^3)
GA limit	75	6	25	5.5-9.5	150	1×10^3

The design of the siphon, as supplied by the manufacturer, is shown in Appendix 4. The arm of the float box rests on a levelling platform. The attached ballast weight assists in regulating the floating characteristics of the siphon. Buoyancy forces (1) thrust an upward force on the float box while the weight of displaced water exerts a downward force according to Equation 9:

$$\mathbf{F_B = \rho g V} \qquad (9)$$

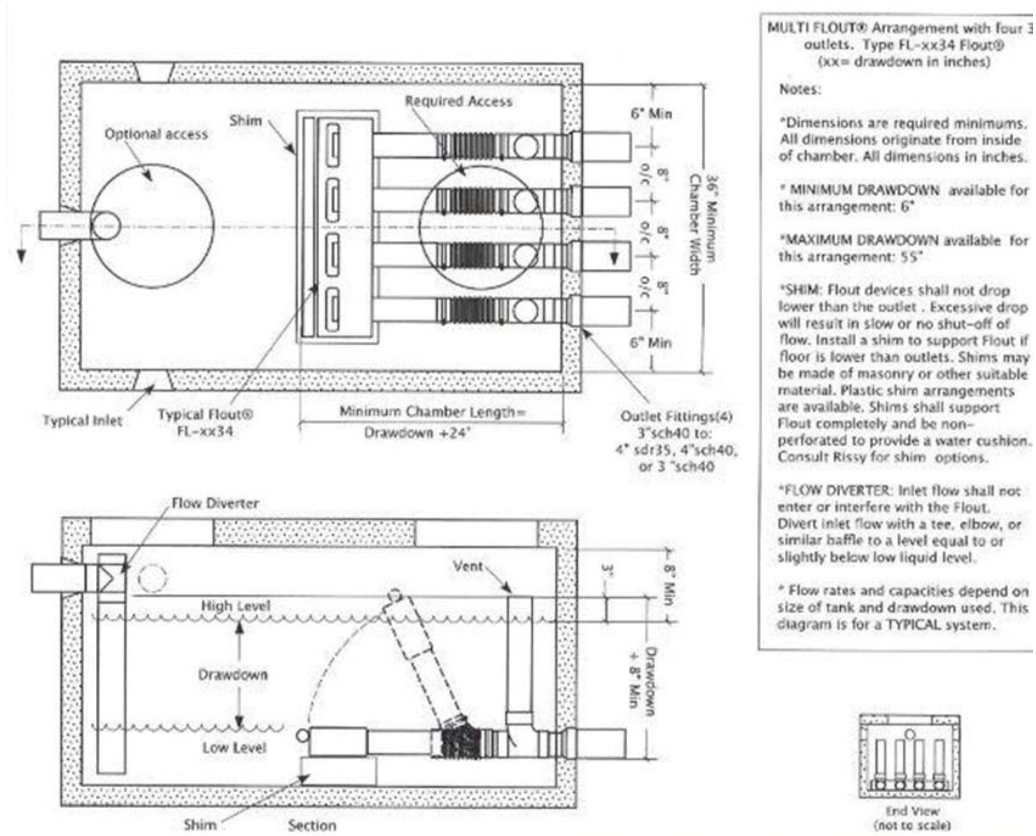
Where:

F_B is the force of buoyant on the float box (N); ρ is the density of wastewater (kg/m^3) and V is the volume of displaced wastewater (m^3).

A plan view of the VFCW as supplied by BORDA is presented in Appendix 5. Before construction, locally available media (unwashed river sand) was used, as opposed to the recommended 2-4 mm fine gravel, as the filter media to reduce the costs of using sieved media. A thin layer of gravel (7-13 mm) was added on the surface of the bed to prevent surface water accumulation and possible clogging after a dose from the siphon.

Appendix 4: Details of the siphon (mechanical dosing device) a. Technical specifications; b. top view after installation in the siphon chamber

a.



b.

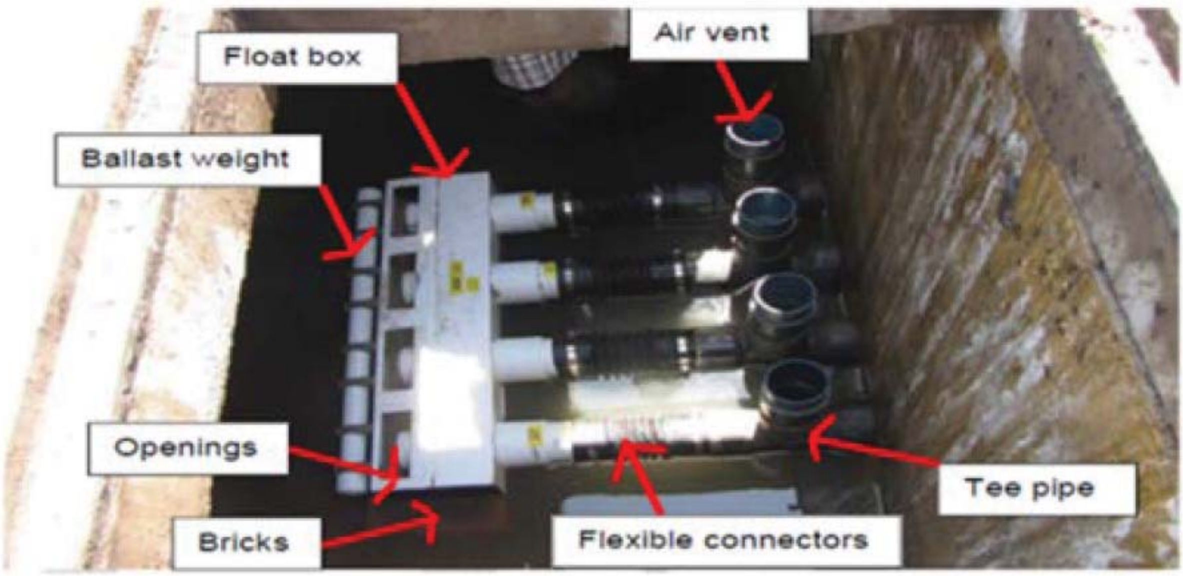
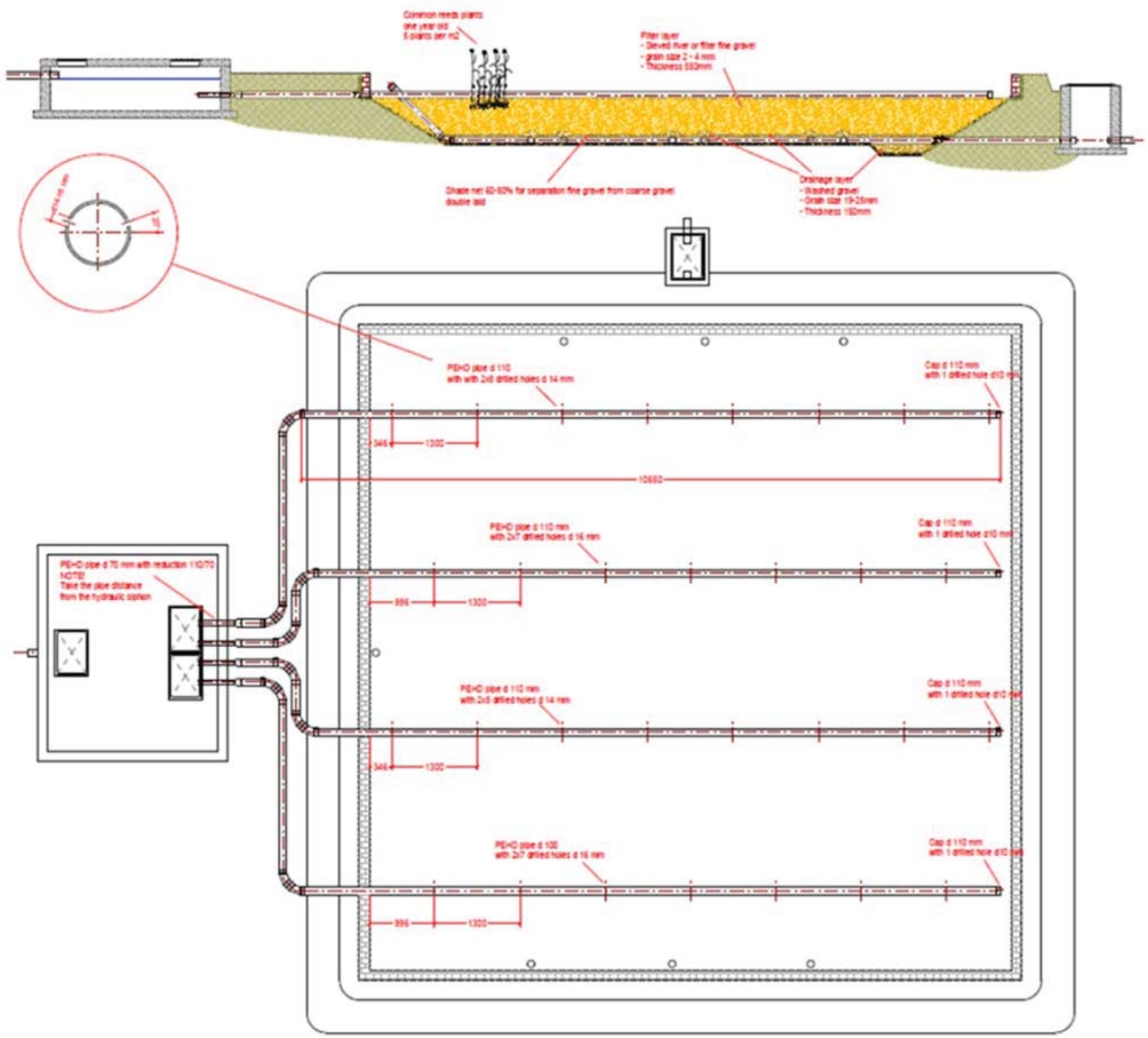


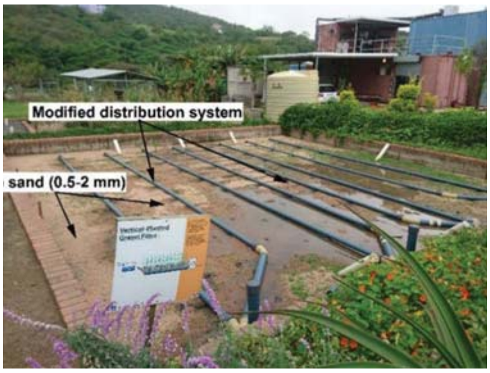
Photo credit: Phatang Sananikone (BORDA); annotated by Rennia Mwenje (PRG, UKZN)

Appendix 5: Plan view of the vertical flow constructed wetland at the Newlands Mashu decentralised wastewater treatment system (before upgrades)



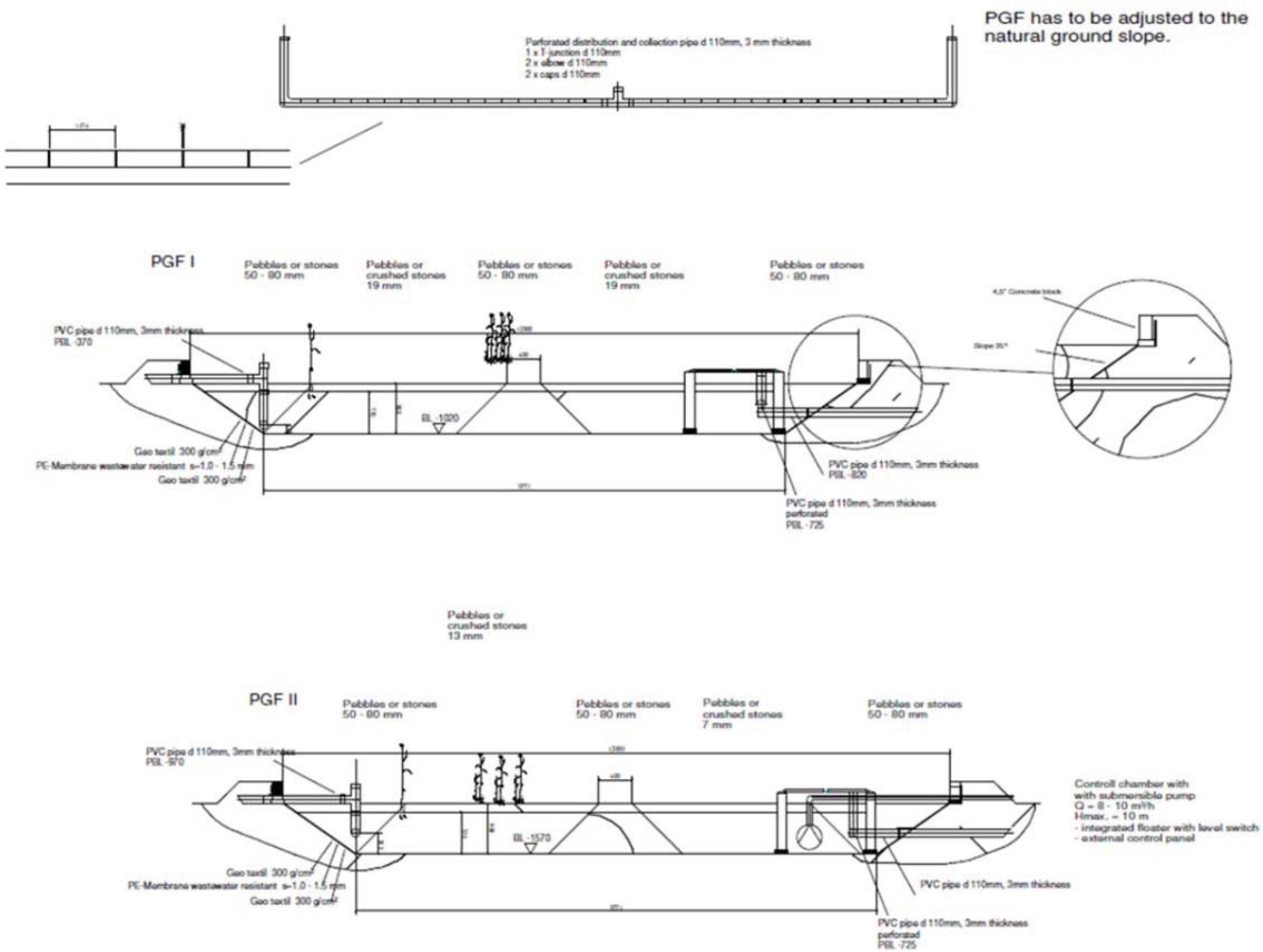
Appendix 6: Modifications to the demonstration-scale vertical flow constructed wetland. a. Redesign of the distribution system on the surface of the VFCW for even distribution of the wastewater; b. Temporal surface water accumulation after dosing to improve the retention time within the bed

a. 

b. 

Appendix 6a demonstrates the BORDA implemented upgrades to the VFCW during October 2019. The distribution system on the surface of the bed was upgraded from four d 110 mm pipes to eight d 75 mm pipes. The pipes were perforated with alternate holes to increase the dispersion of the wastewater on the surface. The addition of a thin layer of coarse sand to fine gravel (0.5-2 mm) was added on the surface and the bed and manually compacted to reduce the void spaces between the media grains and thus, the permeability of the filter media. This modification results in temporal surface water accumulation after the dose from the siphon thus, increasing the retention time with the bed (Appendix 6b).

Appendix 7: Plan view of the horizontal flow constructed wetland at the Newlands Mashu decentralised wastewater treatment system



Appendix 8 demonstrates the modifications of the outlet sump of the HFCW. In February 2018, the sump was replastered to retain its water-tightness (Appendix 8a). In addition, a flexible hose was installed on the outlet pipe of the bed (Appendix 8b) to control how much of the filter media is saturated. This is referred to as impounding and improves the retention time and wastewater contact time with the microbiological film on the media.

Appendix 8: Modification to the horizontal flow constructed wetland. a. Outlet sump replastered; b. flexible hose connected to the outlet pipe to control what depth of the bed is saturated.

a.

b.

Appendix 9: Vertical flow constructed wetland effluent quality a. monthly grab sampling; November 2015-September 2016; b. 24-hour hourly sampling 26-27 January 2017

a.

	CODt [mg/L]	NH_4-N [mg/L]	NO_3-N [mg/L]	PO_4-P [mg/L]	TSS [mg/L]	pH	EC (mS/m)
n	14	28	28	28	28	28	28
Range (min-max)	21.1-106	0-59.2	0.4-55.9	2.2-10.7	0-17	6.1-7.7	64-115
Mean (± Std Dev)	68 (± 24)	**14** (± 12.6)	**25** (± 15.7)	6.1 (± 1.9)	5 (± 5)		85 (± 22)
% Removal from AF effluent	73.5	77		59.1	84.4		
GA limit	75	6	15	10	25	5.5-9.5	150

b.

	CODt [mg/L]	NH_4-N [mg/L]	NO_3-N [mg/L]	PO_4-P [mg/L]	TSS [mg/L]	pH	EC (mS/m)
n	24	24	24	24	24	24	24
Range (min-max)	61-299	0-9.6	20.8-41.9	5.9-6.6	0-40	6.3-6.5	69-83
Mean (± Std Dev)	**152** (± 86)	2.7 (± 2.9)	**29.6** (± 5.4)	6.2 (± 0.2)	7.2 (± 9.4)		75.3 (± 3.2)

Cross-connections made from d 110 mm PVC flexible hose ensured that the sampling sumps were only used during sampling events Appendix 10a and b.

Appendix 10: Sampling sumps for composite sampling of the drainage from each demonstration-scale constructed wetland a. vertical flow constructed wetland sampling sump; b. horizontal flow constructed wetland; c. aerial view indicating the location of the sumps

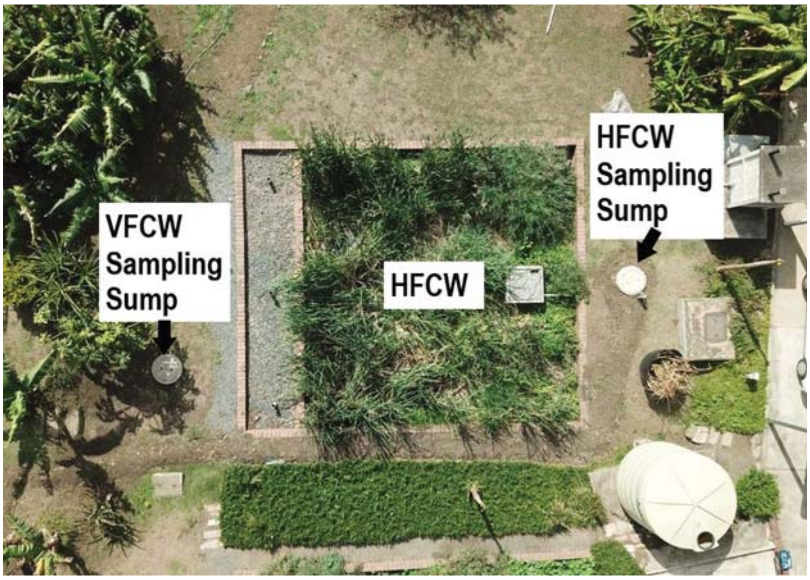
a.

VFCW Sampling Sump

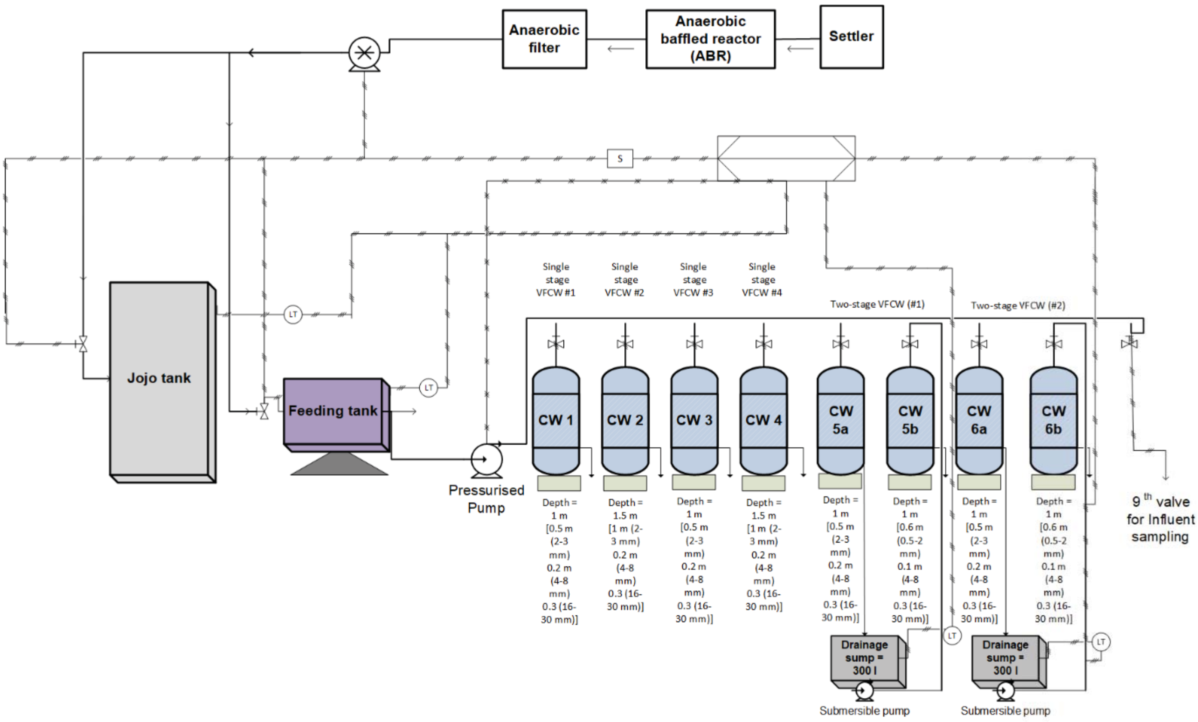
b.

HFCW Sampling Sump

c.



Appendix 11: Process flow diagram of the pilot-scale vertical flow constructed wetlands treating anaerobically treated domestic effluent



The three designs of the pilot-scale VFCWs is presented in Error! Not a valid bookmark self-reference.. Each design has two replicates:

CW 1 and 3: Single-stage VFCWs with normal (0.5 m) filter depth

CW 2 and 4: Single-stage VFCWs with increased (1 m) filter depth

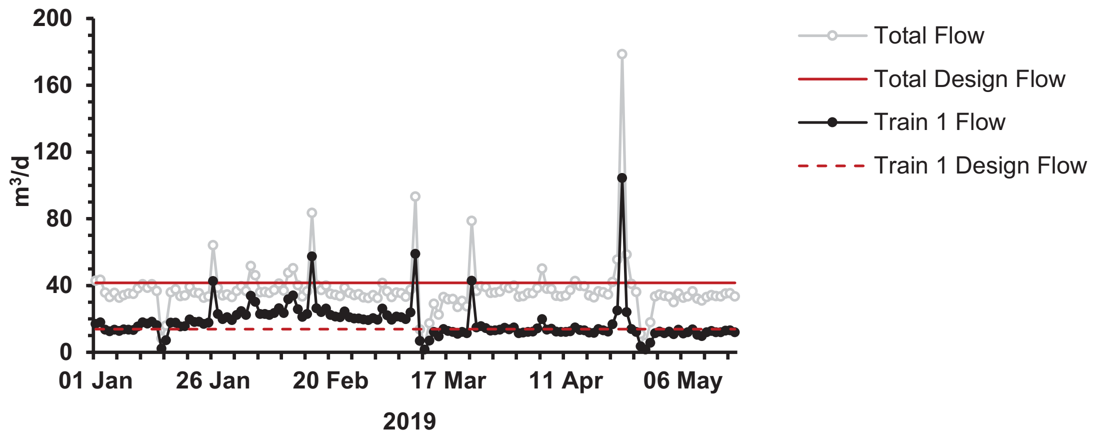
CW 5 and 6: Two-stage VFCWs

.

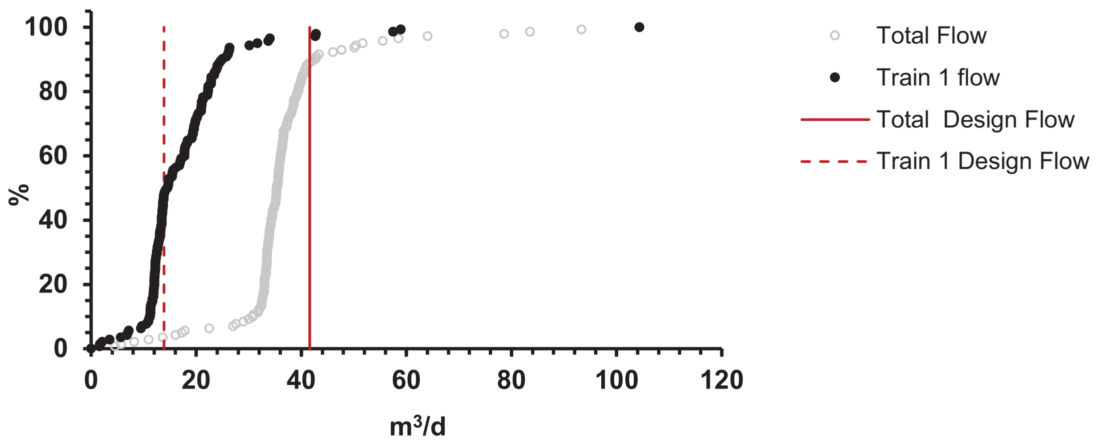
Appendix 12 shows the cumulative frequency of the daily flow into the entire DEWATS and Train 1 over the monitoring period. In terms of the daily hydraulic loading, the CW system received a higher than design flow 52.1% of the monitoring period. Again, the scheduled desludging event in March 2019 regulated the flow around the design for the remainder of the sampling period

Appendix 12: Daily flow a. flow through Train 1 in comparison to the total flow to the system; b. cumulative frequency of the Total and Train 1 flow between January and May 2019; c. cumulative daily siphon dose volume in relation to daily Train 1 flow

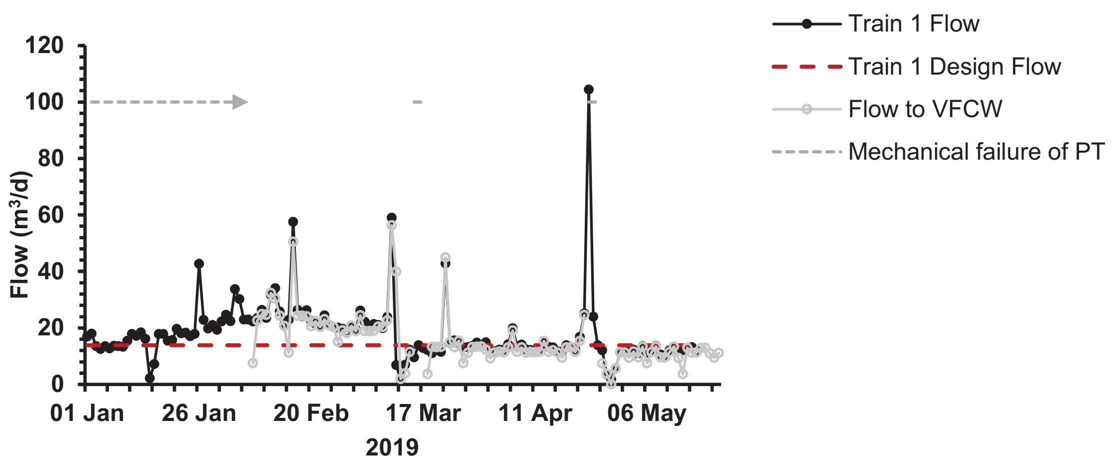
a.



b.



c.



PT = Pressure Transducer

Appendix 13 illustrates the change in plant density over the 16-week monitoring campaign of the demonstration-scale constructed wetlands

Appendix 13: Plant density in demonstration-scale constructed wetlands before and after monitoring campaign a. vertical flow constructed wetland; b. horizontal flow constructed wetland

December 2018 May 2019

a.

b.