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DESIGN OF PILOT SCALE HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND SYSTEM TREATING GREYWATER

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ABSTRACT

Worldwide, diarrhea disease, which causes about 2.6 million deaths annually, mostly among children less than 5 years, is primarily spread through food and water contamination. This is often the result of poor sanitation and hygiene associated mostly with crowded urban and peri-urban settlements. One major area of concern is the disposal of greywater from the unsewered low income, high density population areas of the municipality. Integration of conventional sanitation systems in these areas has been a major challenge due to unplanned settlement structures and the limited available space. The aim of this study was to design and evaluate the treatment performance of horizontal subsurface flow constructed wetland systems (HSF CWs) for treatment of greywater to meet the water quality control standards for safe disposal under the principles of sustainable sanitation. HSFCW system experimental plots treating greywater from domestic households were established. The performance results indicate that this wetland system has excellent removal capability for biochemical oxygen demand ranging from 97.3-99%. Consequently, oxygen demand exerted by micro-organisms to oxidize organics present in greywater during the 48 hours HRT dropped by an average of 97.3%. This study has the aim of informing greywater management decisions for urban and peri-urban areas. This knowledge supports formulation of control measures at the source and designing of an appropriate treatment system for safe reuse or disposal.

Keywords: constructed wetlands, greywater treatment, hydraulic, retention time

INTRODUCTION

Greywater discharge often causes water quality deterioration of the receiving water bodies. The discharges contain considerable quantities of organic matter, nitrogen, phosphorous and trace elements and can further degrade the quality of receiving waters (Gjefle, 2011; Sandec, 2006). An appropriate greywater treatment system is essential in sustainable domestic wastewater management.

Several methods for removing pollutants from the greywater stream of domestic wastewater exist. The methodology involves solid removal by sedimentation through sand or mechanical filtration (Kumar and Zhao, 2011). Another method is the biological processes which involve use of submerged bioflters (Kadlec and Knight, 1996; Knight et al., 2000). This process involves oxidation of organic matter and nitrification or denitrification. All these physical, chemical and biological processes are combined and act at the same time in a properly designed and constructed wetland system. However, as observed by Ghunmi et al. (2011) in a review of greywater treatment systems technology performance, detailed design criteria and findings of the operational conditions of most of the tested wetland systems were not reported.

Wetlands provide suitable environmental conditions for growth and reproduction of microbial organisms. Two important groups of these microbial communities are bacteria and fungi. Bacteria and fungi are typically the first to colonies and begin the sequential decomposition of solids and also have the first access to dissolved constituents in wastewater (Gjefle, 2011; Kumar and Zhao, 2011). Their genetic and functional responses mediate physical, chemical and biological transformation of pollutants, which can be managed in engineered environment. These constructed wetlands which are created under engineered environment help in achieving the desired transformations in wastewater treatment. Knight et al. (2000) observed that microbial metabolism depends, among others things, on environmental conditions such as temperature, dissolved oxygen (DO), pH, and concentration of chemicals substrate undergoing transformation. All these conditions are an important consideration during the design of constructed wetland systems.

There are several methods for designing constructed wetland systems (Kadlec and Knight, 1996). The design has evolved from empirical rules of thumb and simple first-order models to detailed modeling of any processes involved in pollution reduction (Sklarz et al., 2010; Kumar and Zhao, 2011). The main designs are based on hydraulic retention time and kinetic (k-C*) models that describes the pollutant removal. Though, the interaction between substrate, vegetation, water and microorganisms are not known (Kadlec and Knight, 1996; Langergraber et al., 2009; Kumar and Zhao, 2011), flow hydraulics and hydrodynamics of the system influence all treatment processes.

It is worthwhile to note that the first order degradation kinetic has been used to predict removal process for the majority of pollutants of interest in constructed wetland systems. Such pollutants include organic materials, suspended solids, nitrogen and phosphorous (Kadlec and Knight, 1996; Knight et al., 2000; Sklarz et al., 2010). Although the limitation of the first-order rate equation has been recognized (Kadlec and Knight, 1996), it is still the most appropriate design equation describing pollutant removal.

Though constructed wetlands have generally been modeled extensively, the biochemical degradation and transformation process taking place and the associated flow dynamics are rarely explained. However, one detailed wastewater treatment model that attempts to explain treatment process is the CW2D (Constructed Wetland 2-Dimension). This is an extension of Hydrus-2D, variably saturated water flow and solute transport software package (Langergraber and Simunek, 2005; Langergraber et al., 2009). CW2D was developed to model the physical, chemical and biological processes taking place at the same time in a vertical flow constructed wetland system.

Constructed wetland systems are considered to be attached-growth biological reactors, and their performance can be estimated with first-order plug flow kinematics for BOD and nitrogen removal (Reed, et al., 1995). The basic relationship used to describe the treatment components is given in Equation 1 as:

$$\frac{C_e}{C_i} = \exp(-K_T t) \qquad (1)$$

Where C_e = Effluent pollutant concentration, mg/L

C_i = Influent polluant concentration, mg/L

K_t = Temperature dependant first-order reaction rate constant, d^{-1}

t = Nominal hydraulic residence time, d

The nominal hydraulic residence time is calculated from Equation 2 as:

$$t = \frac{LWy}{Q} \qquad (2)$$

Where L = Length of the wetland cell, m

W = Width of the wetland cell, m

y = average depth of water in the wetland, m

Q = Average flow through the wetland, m^3/d

Designs of constructed wetlands

The principles of designing a subsurface flow constructed wetland system are based on assumptions of plug-flow movement of water through the wetlands with first-order reaction kinetics primarily by biological degradation (Langergraber et al., 2009, Kumar and Zhao, 2011). It is assumed that the process behaves like an attached biological reactor involving microbes. The basic relationship used to simultaneously describe the two components is given in Equation 3.

$$A_h = Q_d \ln\left(C_e - C_i\right) / K_{BOD} \qquad (3)$$

Where A_h = Bed surface area

Q_d= Average flow rate (m^3/d)

K_{BOD} = BOD rate constant

To encourage plug-flow through the bed and avoid flow over the bed surface, bed slope of 1-5% is commonly used. The hydraulic gradient at the outlet is increased by progressively lowering the outlet (Green and Upton 1994). Bed cross sectional area is calculated from Darcy's law given as

$$A_C = \frac{Q_d}{K_s * \left(\partial h / \partial S \right)} \qquad (4)$$

Where Ac = Cross sectional area of bed (m^2)

K_s = Hydraulic conductivity (m/s)

dh/ds = Slope of bed (m/m)

Modifications on model equation

The k-C* model developed by Kadlec and Knight (1996) to reflect treatment wetland performance data is a modification of Equation 3 (Kickuth model). The main difference between the two models is that the Kadlec and Knight model has a non-zero background concentration and is also a reversible first-order reaction equation rather than the irreversible equation. In a study by IWA, 2000), background concentrations of BOD are reported to lie in the range of 1-10mg/L. The K-C* model is given in Equation 5 as:

$$\ln\left(\frac{C_e - C^*}{C_i - C^*}\right) = \frac{K_v \, y \, A}{Q} = -\frac{KA}{Q} \qquad (5)$$

Where K_v = Volumetric rate constant (d^{-1})

C* = Non-zero background concentration of BOD_5 (mg/L)

Values of K and C* are site specific and the variability is caused by temperature, wetland plant (type and density), strength of influent and hydraulic variables (Kadlec and Knight, 1996; Kadlec, 2000; Stein et al., 2007).

Kadlec (2000), further proposed an amendment on the K-C* model to include a water balance component across the wetland as shown in Equation 6.

$$\frac{C_e - C'}{C_i - C'} = \left(1 + \left[\frac{\alpha x}{q}\right]^{-\left(1+\frac{K_A}{\alpha}\right)}\right) \qquad (6)$$

Where $C' = C^* \left(\frac{K_A}{K_A + a}\right)$

α = Precipitation (m/d) – evapotranspiration (m/d)

q = Hydraulic loading rate (m/yr)

x = Distance from inlet per length of wetland (Fractional distance from the wetland)

a = Constant equal to K for subsurface flow constructed wetland with Darcian flow

The amendment incorporates the effects of precipitation and evapotranspiration since these two parameters have opposing effects and thus, influence the system hydraulics. While precipitation causes dilution, evapotranspiration causes concentration effect.

A further modification by Shepherd (Kumar and Zhao, 2011) due to inadequacies in first-order model, introduced a two parameter time-dependent retardation model for COD removal in a high waste stream. The modification replaces the background concentration by two other parameters K_o and b (Kumar and Zhao, 2011). The model assumes that a high waste stream contains multiple pollutants of variable ease of degradation. As a result, easily degradable substances with faster removal kinematics are gradually replaced with less biodegradable substances with slower removal kinematics. This leaves a solution with less biodegradable constituents. The model seeks to account for the steady decrease in pollutant concentration with increased treatment time rather than a constant residual value (background). The continuous change in solution composition can be represented by a continuous varying volumetric first-order rate constant K_v given by Equation 7.

$$K_V = \frac{K_o}{b\tau + 1} \qquad (7)$$

Where K_o is initial first-order volumetric rate constant, d^{-1}

b is time based retardation coefficient, d^{-1}

τ is retention time (d)

According to Kumar and Zhao (2011), the model was considered to be appropriate for constructed wetlands design because it allows a steady decrease in COD (or any other component) with increased treatment time rather than a constant residual COD, C* value.

Kadlec (2000) recognizes the limitations of these models in the design of treatment wetlands and further observes that none of the models can correct the degree of treatment influenced by short circuiting. This highlights the importance of wetland hydraulics in improving design models. Designing of constructed wetlands requires a multidisciplinary input of knowledge involving biological and ecological sciences, aquatic chemistry, landscape architecture, hydrological engineering, and flow hydraulics. However, the focus of this study is on low strength domestic wastewater stream (greywater).

MATERIALS AND METHODOLOGY

Design of greywater treatment system

Development of treatment system involved consideration of technically factors in addition to institutional and social issues gathered from the baseline study. These issues influenced controlled decision making during the planning and preliminary design stages. Additionally, a guide to project development after Reeds et al. (1995) that involved characterization of greywater by defining the volume and composition to be treated was used. A conception framework of the procedure followed during design is presented in Figure 1.

Figure 1: Conception framework for greywater treatment

The hydrodynamic parameters (flow rate, loading rate, porosity and hydraulic residence time) were computed using the baseline data obtained during greywater characterization process. Additional data gathered included influent and effluent pollutant concentrations obtained from National Environmental Management Authority- Kenya, guidelines. Hydraulic loading rate of 0.01-0.1mg/day obtained from literature was also used as a guide during calculations (Tanner, 2001; Vymazal, 2001). The system size was based on its organic and hydraulic loading rates. To avoid creating another environmental problem in form of malaria mosquito breeding sites, HSFCW system was chosen and water surface maintained at 15 cm below the water level in the system.

The wetland bed consisted of an excavation lined with plastic membrane 10mm, 2.0m long, 0.5m wide with an average depth of 0.85 m, in a sand bed planted with vetiver grass. The sand bed comprised graded sand and a drainage system. A compromise of substrate composition was used as recommended by Cooper (1999). The author recognizes the importance of the type of wastewater to be treated and the flow rate required as guiding principles in material selection.

The under drains consisted of 50mm diameter PVC pipe containing drain holes overlaid with 0.2m layer of sand. The under drain system supported 0.7m of sand media. Influent flow was greywater from school kitchen and hand wash facility. The greywater was passed through a two compartment pre-treatment chambers of 0.75 and $0.25m^3$ respectively. The hydraulic application rate was 278 mm/day with a nominal hydraulic residence time of 2 days.

Samples of greywater at the inlet and outlet were collected over a period of 12 weeks and analyzed in the laboratory. Pollutant removal efficiency was calculated as percent mass removal given in Equation 8.

$$100\,\frac{m_i - m_o}{m_i} \qquad (8)$$

Where m_i and m_o = mass loading rates at inflow and outflow respectively.

The flow rate was controlled using a 120mm diameter gate valve connected to a flow meter. Calibration was conducted at the inlet and outlet, using a beaker and a stopwatch. An overflow pipe was provided for a constant hydraulic grade line, in order to maintain a constant head as the head was maintained at 15cm below the sand surface. Monitoring program began 4 months after planting in order to give sufficient time for the establishment of vegetation and bio-film. To minimize sample deterioration, and thus avoid poor results in the measurement of BOD_5, samples were stored in a chilled cool box. Though chilling samples is not necessary if analysis is within 2 hours, samples were chilled (APHA, 1985) and analyzed within 3 hours of collection.

The pH, DO, EC, and temperature were measured in-situ. Ammonia nitrogen, nitrate nitrogen and nitrite nitrogen were analyzed in the laboratory, in accordance to procedures in the APHA (1985). Bi-weekly samples were collected at the inlet and outlet of the treatment system between 09.00-10.00 hours. Total inorganic nitrogen (TIN) was calculated as the sum of NH_4-N, NO_2-N and NO_3-N in the greywater, the organic fraction of nitrogen was assumed to be relatively low. According to Sklarz et al., 2010, the organic fraction of nitrogen in wastewater accounted for about 12% of total nitrogen (TN) and therefore, this component was assumed to be relatively low and thus neglected in the study. Removal efficiency according to Equation 8 was analyzed.

Physical methods

Temperature and pH were determined in situ whilst DO was measured immediately after sample collection using a Temperature, DO and pH analyzer/meter (HQ40d dual input multi-parameter digital meter with pHC 101 and LDO 101 probes), portable dissolved oxygen meter. TDS, EC and salinity were measured using VWR EC 300 meter after calibration of the instrument in the laboratory. Biological Oxygen Demand (BOD_5) was measured using the procedure of five day Biochemical Oxygen Demand from Standard Methods for Examination of Water and Wastewater (APHA, 1985).

RESULTS

The design for the system at Crater View was based on both hydraulic and hydrodynamic parameters summarized in Table 1.

Table 1: Greywater Treatment System Hydraulics

The treatment performance of Crater View Secondary School wetland was evaluated based on the percentage removal of selected pollutants according to Equation 8. The mean removal efficiency of the wetland was 99.7% (BOD_5), 96.5% (TSS), 97.2% (NH^+_4-N), 8.3% (TP) and 17.7% (FC) and is presented in Table 2.

Table 2: Influent- effluent laboratory sample analysis

It was also observed that, the system was capable of removing nutrients mainly ammonium (97.2%) and total phosphorous (88.3 %). Figure 2 gives a plot of the average influent (TPI) and effluent (TPE) concentrations from the system.

Figure 2: Total phosphorous influent and effluent concentrations

TSS removal by HSFCW system is high in Figure 3 at 96.5 %. TSS in the greywater is removed by wetlands due to the physical process of filtering action of the bed media. Influent TSS was reduced effectively and the corresponding results are presented in Figure 3.

Figure 3: Average concentration of TSS in the influent/effluent

The mean influent faecal coliform of 4.97 log.Numbers/100ml in the greywater was reduced to 4.07 logs. Numbers/100ml corresponding to a removal efficiency of 17.7 % as presented in Figure 4. Therefore, poor removal of micro-organisms was noted since average removal was 0.9 cfu/100 ml with residual faecal coliforms of 4.07 cfu/100 ml being observed for indicator organisms.

Figure 4: Average influent /effluent faecal coliform concentration

DISCUSSION

Constructed wetlands system design

Literature continues to show plug-flow models being used (Crites, 1998; Rousseau et al., 2004). In plug-flow, design considerations are based on expected inlet concentrations and flows, target outlet concentrations and temperature ranges for the treatment sites. However, the use of empirical equations to predict system performance whereby a mathematical relationship from pre-existing data is used, leads to inappropriate designs because these relationship are only based on statistical relationship and provide no information on internal dynamics. This argument is supported by findings reported by Toscano, et al. (2006) in a study of decentralized systems for the protection of public health and environment for the development of long-term strategies in management of water resources. As such, wastewater treatment processes consists of a sequence of complex, physical, chemical and biochemical processes and their dynamics are non-linear and usually time varying.

Depending on the strength of wastewater, a HRT of 0.8 hours to 2.8 days is recommended by Pidou et al. (2007). For this study, a HRT of 2.0 days was adopted which is in agreement with recommendations by Pidou et al. (2007), for low strength wastewater streams such as greywater. Ghunmi et al. (2011) further observed that greywater stored for more than 48 hours at 19-26^{0}C deteriorates in quality. Biological degradation of wastewater produces malodorous compounds, causing esthetic problem, pathogens and mosquito breeding which are health threats if not managed well.

Constructed wetland performance evaluation

The ability of HSFCWs to remove various selected pollutants from greywater ranged between 17.7% and 99.7%. The average BOD_5 concentration in the wetland dropped from 104.0 to 0.33 mg/L (99.7%) with a corresponding average DO concentration drop from 3.01 to 0.08 mg/L (97.3%) as the greywater flowed through the wetland in a nominal residence time of two days. The observed good organic matter removal is supported by earlier findings by Pidou et al. (2007) who reported that biological and extensive CW treatment technologies are effective in organic matter removal. Biological treatment is a natural process achieved by creating an environment suitable for the survival and reproduction of various bacterial cultures and their exposure to organic substances present in wastewater. In sub-surface constructed wetland systems, organic matter is removed by aerobic bacteria attached to porous media and plant roots (Vymazal, 1998). The expected role of plants is therefore to create aerobic conditions and support aerobic bacteria in the sand media (Green and Upton 1994).

Many treatment wetlands report BOD_5 residue of 10 mg/L (APHA, 1995; Toscano, et al., 2006) which is used as a guideline in minimum allowable discharge standard for BOD_5. The overall criterion for water and wastewater systems from hygiene point of view is that the risk of infection from environmental sources once the effluent is released to receiving water bodies should never exceed a background level. However, this background levels differs with time and between various regions of the world. The constructed wetland in this study shows good ability to treat greywater. Treated greywater quality was more stable, but still showed some variability as seen in Figure 2 for phosphorous removal process. The good phosphorous removal could be associated with vetiver wetland plants used in the study. Other possibilities are physical processes of phosphorous removal through sedimentation of particulate phosphorous and sorption of soluble phosphorous. In another study by Maina et al. (2010), using vertical flow sand system with vetiver plants, a 47-91% phosphorus removal under different loading rates was reported**.** These results are consistent with other studies reported in literature for example; similar results are reported by Vymazal (2005) for wastewater treatment. The author observed that removal of nutrients nitrogen (40-55%) and phosphorous (40-60%) was low in constructed wetlands compared to organics and solid removal.

Phosphorous is biologically removed by plant uptake. Periphytons and micro-organisms also take up phosphorous but part of it is released again after cell death. The main removal mechanism is adsorption to the filter and/or soil particles, adsorption to the detritus layer and precipitation with certain metals such as iron, aluminum, calcium and magnesium if present (Kadlec and Knight 1996; Vymazal, 2005). It is further reported that removal of nitrogen in most HFCWs is generally low compared to vertical systems (Langergraber et al., 2009). A possible explanation for this achievement could be that in saturated horizontal constructed wetlands, nitrogen is removed by nitrification and denitrification processes. Most treatment systems cannot achieve high removal of total nitrogen or ammonia and nitrate-nitrogen because of their inability to provide simultaneous aerobic and anoxic conditions for denitrification. Compared to unsaturated vertical flow systems that provide conditions for nitrification, horizontal flow systems provide good conditions for denitrification which occurs in the presence of available organic substances. However, even from the design principles, most treatment wetlands are designed primarily to remove organic matter and solids (Vyamazal, 2005) but not the nutrients.

Total suspended solids (TSS)

Filtration occurs by impaction of particles onto the roots and stems of the macrophytes or onto the sand (soil/gravel) particles in the HSFCW system (Vymazal, 1998; Avsar et al., 2007). HSFCW system in this study reduced TSS by a good margin since the average removal of 96.5% falls within the good performance limits reported in literature. For example, Avsar et al. (2007) reported a 90.4% average removal of TSS for all the three sets of CW systems established.

Nitrogen removal

The main nitrogen removal process is plant uptake in the form of NH_4^+ (ammonium) without the need to metabolize. Ammonium was reduced by an average of 97.2% in the treatment system. This was good performance compared to 63.8% average reduction reported by Avsar et al. (2007). However, all the pollutant removal processes studied by the author were having different operating conditions unlike for HSFCW system studied.

Pathogens removal

The faecal coliform removal was due to sedimentation, filtration and absorption. Similar findings are reported by USEPA, (1988) where surface flow system was studied with respect to the contribution of vegetation to removal of total coliform bacteria in constructed wetlands. With a hydraulic application rate of 5 cm/day and hydraulic residence time of 5.5 days, total coliform removal was 99%. In another study in Listowel Ontario Canada, though under surface flow constructed wetland system, faecal coliform removal efficiency from domestic wastewater was approximately 90 % when operated at a 6-7 day residence time (USEPA, (1988). It therefore follows that the HSFCW system did not succeed in lowering the quantity of pathogenic microorganisms to acceptable levels probably because of a low HRT of 2 days.

However, performance efficiencies alone are insufficient to make informed decisions since purification is achieved by a wide variety of physical, chemical and (micro) biological processes. In HSFCWs, these processes are additionally guided by horizontal flow of wastewater through an artificial filter bed consisting of a soil matrix mainly composed of sand or gravel. This matrix is colonized by a layer of attached microorganisms that forms a so-called biofilm (Rousseau et al., 2004). These results are supported by the view presented by Ghunmi et al. (2011) that the internal structure and the operational conditions, namely HRT and SRT, determine the performance of the physical and biological system.

CONCLUSION

The hydraulic parameters of HSFCW are useful and effective in the design of greywater treatment systems. The system is effective in organic matter reduction, solids and nutrients removal. It has excellent removal capability for biochemical oxygen demand. As the greywater passed through the system, in a period of 48 hours the BOD_5 levels dropped by an average of 97.3% and a corresponding residual level of 0.33 mg/l was observed. This was way below the maximum allowable residual level of not more than 10 mg/l for discharge into natural environments. Therefore, HSFCW system was successful in reducing the BOD_5 to a level that will have no significant impact on the receiving streams as seen from the oxygen demand exerted by microorganisms.

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REFERENCES

1. APHA. Standard Methods for Examination of water and wastewater 17th edition. American Public Health Association, Washington, DC 1985.
2. APHA. Standard Methods for the Examination of Water and Wastewater. 19th edition.

American Public Health Association, Washington, DC 1995.
3. Avsra Y, Tarbeah H, Kimchie S, Ozturk I. Rehabilitation by constructed wetlands of available wastewater treatment plant in Sakhnin, Ecologic engineering 2007; 29: 27-32.
4. Crites R, Tchobanoglous G. Small and decentralized wastewater management systems. McGraw-Hill New York 1998.
5. Cooper PF. A review of the design and performance of vertical flow and hybrid reed bed treatment systems. Water science Technology 1999; 40: 1-9.
6. Ghunmi AL, Zeeman G, Fayyad M, van Lier JB. Grey water treatment systems: A review. Critical Reviews in Environmental Science and Technology 2011; 41 (7): 657-698.
7. Gjefle K. Sanitation for all-An engine of economic growth for Urban Africa. Sustainable Sanitation Design (SuSana Design) and the Association of international waters Studies (FIVES), Norwegian forum for environment and Development Working group on Water and Sanitation, Oslo 2011.
8. Green MB, Upton J. Constructed reed beds: a cost effective way to polish wastewater effluent for small communities. Water Environ Res 1994; 66: 188-192.
9. International Water Association. Constructed wetlands for pollution control: Processes, performance, design and operation. IWA scientific and Technical report No 8, IWA publishing 2000. Kadlec R H, Knight R L, Vyamazal J, Brix H, Cooper P, Haberl R. (eds)
10. Kadlec RH. The inadequacy of first-order treatment wetland models. Ecological Engineering 2000; 15: 105-119.
11. Kadlec RH. Detention and mixing in free water wetlands. Ecological Engineering 1994; 3:345 – 380.
12. Kadlec R H. Deterministic and Stochastic aspects of constructed wetland performance and design. IWA; water science and Technology 1997; 35(5): 149-156
13. Kadlec RH, Knight RL. Treatment Wetlands, CRC/Lewis Publishers, Boca Raton FL 1996: 893.
14. Kadlec RH. The inadequacy of first-order treatment wetland models. Ecological Engineering 2000; 15: 105-119.
15. Knight RL, Clarke RA Jr, Bastian R K. Surface flow treatment wetlands as a habitant for wildlife and humans. Water science Technology 2000; 44: 27-38.
16. Kumar JLG, Zhao YQ. A review of numerous modeling approaches for effective, economic and ecological treatment wetlands, Journal of Environmental Management 2011; 92: 400-406.
17. Langergraber G, Simunek J. Modeling Variably Saturated Water Flow and Multicomponent Reactive Transport in Constructed Wetlands. Vadose Zone Journal 2005; 4: 924-938.
18. Langergraber G, Giraldi D, Mena J, Meyer D, Pena M, Toscano A, Brovelli A, Korkusuz, E A. Recent developments in numerical modeling of subsurface flow constructed wetlands. Science Total Environment 2009; 407(13): 3931-3943.
19. Maina CW, Mutua BM, Oduor SO, Raude JM. Water quality and self-purification ability of River Njoro, Kenya. Egerton Journal of Science and Technology 2010; 10: 123-138.
20. Mitchell C, McNevin D. Kinetic analysis of BOD and solids removal in subsurface flow constructed wetlands. Water Research 2001; 35(5): 1295-1303.
21. Rousseau D, Vanrolleghem P, De Pauw N. Model-based design of horizontal subsurface flow constructed treatment wetlands: a review, water research 2004; 38: 1484-1493.

22. US EPA. Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment, EPA/625/1-88/022. Center for Environmental Research Information, Cincinnati 1988.
23. Reed SC, Crites RW, Middlebrooks EJ. Natural systems for waste management and treatment. McGraw-Hill New York 1995: 433.
24. Reed SC, Crites RW, Middlebrooks EJ. Natural systems for waste management and treatment. McGraw-Hill New York 1995: 433.
25. Sandec. Water and Sanitation in developing countries. Report No 14/06: Swiss Federal Institute of Aquatic sciences and technology Switzerland 2006.
26. Sklarz MY, Gross A, Soares MMI, Yakirevich A. Mathematical model for analysis of recirculating vertical flow constructed wetlands. Water Research 2010; 44: 87-116.
27. Stein A J, Nestel P, Meenakshi JV, Qaim M, Sachdev HPS, Bhutta ZA. Plant breeding to control zinc deficiency in India: how cost effective is bio-fortification? Public Health Nutrition 2007; 10: 492-501.
28. Tanner CC. Plants for constructed wetland treatment systems-a comparison of the growth and nutrient uptake of eight emergent species, Ecological Engineering 2001; 7: 59–83.
29. Toscano A, Langergraber G, Consoli S, Cirelli G L. Modeling pollutant removal in a pilot scale two stage subsurface flow constructed wetlands. Ecological Engineering 2006; 35(2): 281-289.
30. Pidou M, Parsons SA, Raymond G, Jeffrey P, Stepheson T, Jefferson B. Fouling control of membrane coupled photo catalytic process treating greywater, Water Research 2007; 10: 1016: 113-120.
31. Vymazal J. Types of constructed wetlands for wastewater treatment: Their potential for nutrient removal. In Transformations of nutrients in natural and constructed wetlands; Backhuys Publishers: leiden, The Netherlands 2001:1-93.
32. Vymazal, J. Removal of nutrients in various types of constructed wetlands. Science of Total Environment 2007; 380: 48-65.
33. Vymazal J. Removal of BOD_5 in constructed wetlands with horizontal subsurface flow: Czech experience. In: Proceedings of the 6th International conference on constructed wetlands for wastewater treatment, Aquas de Sao Pedro, Brazil 1998: 167-175.
34. Vyamazal, J. Constructed wetlands with horizontal sub-surface flow and hybrid systems for wastewater treatment. Ecological Engineering 2005; 25:478-490.

Table 1: Greywater Treatment System Hydraulics

Sr.No	Name	Description
1	Pre-treatment	Two chamber (0.25 & 0.75 m^3) litter trap, coarse organic matter; grease trap of cleaning interval not more than 4 times/yr
2	Surface area	Horizontal subsurface flow constructed wetland (HSFCW); length of 2m and width of 0.5m
3	Inlet	Stone distributor; slotted pipe for greywater distribution, inlet depth = 0.96m
4	Treatment volume	Fine gravel (D_{60} = 3.5mm, C_u = 1.8); initial porosity = 40%; with an average wetted depth of 0.875m; Saturated hydraulic conductivity was 17m/day
5	Outlet	Outlet depth = 0.86m; variable effluent outlet height; Retention period 2 days
6	Flow	Flow rate is set at 1m^3/day; hydraulic loading rate (HLR) is 0.21mm/day
7	Other Design considerations	bottom slope of 1.5%; gravel media; geo-membrane of 1mm thickness lining
8	Gravel size	Building sand locally available (3-8mm in size)

Table 2: Influent- effluent laboratory sample analysis

Parameter/ concentration	EC	salinity	DO	TDS	BOD_5	TSS	TP	FC	NH_4^+
Units	µS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	Log.no/ 100ml	mg/l
Influent	1929	1.0	3.01	1257	104.0	255	2.43	4.97	3.17
Effluent	1644	0.8	0.08	1084	0.33	9	0.29	4.09	0.09
% reduction	13.7	20.	2.9	13.8	99.7	96.5	88.3	17.7	97.2

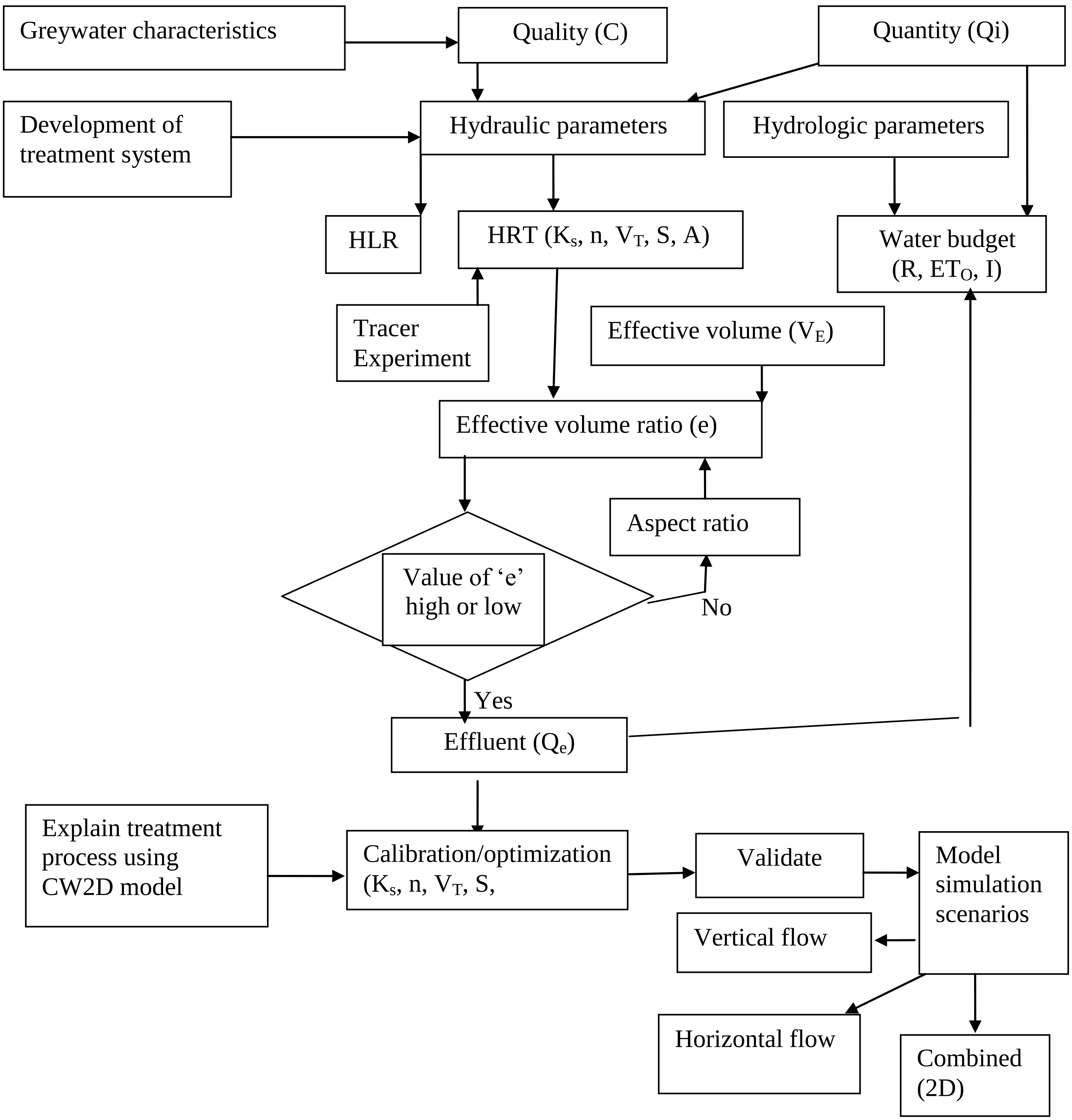

Figure 1: Conception framework for greywater treatment

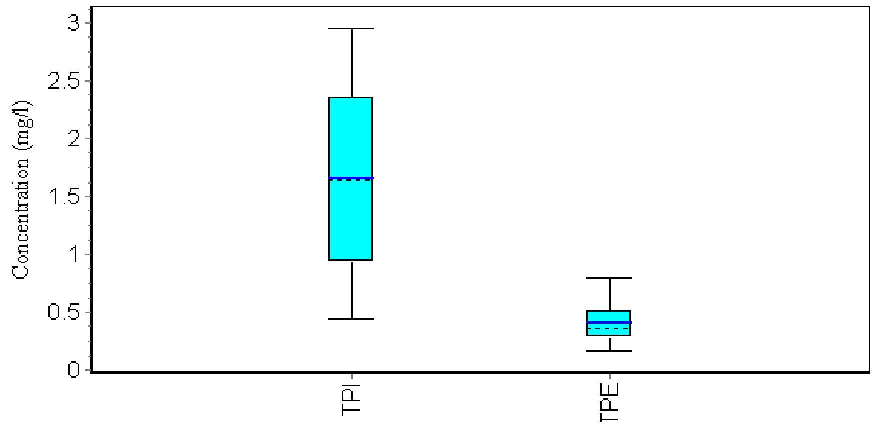

Figure 2: Total phosphorous influent and effluent concentrations

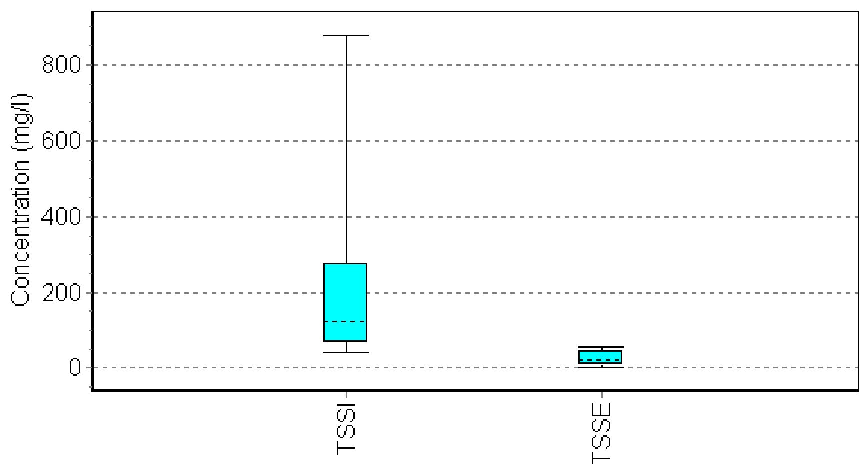

Figure 3: Average concentration of TSS in the influent/effluent

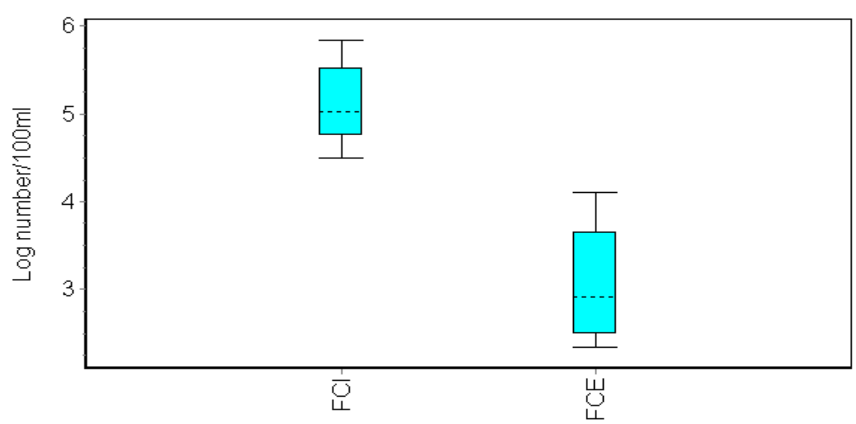

Figure 4: Average influent /effluent faecal coliform concentration