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Performance of inclined plates settler integrated with constructed wetland for high turbidity water treatment

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Abstract

The purpose of this study was to investigate and demonstrate cost-effective treatment technologies for highly turbid waters, used for domestic purposes in rural areas of Tanzania where conventional community water treatment techniques are not available. Pilot-scale inclined plates settler integrated with constructed wetland (IPS-CW) system was investigated on earth dam water with turbidities ranging from 186 to 4,011 NTU. The IPS was used as a physical pretreatment system preceding the CW, meant for the removal of organic matter, nutrients, and pathogens. Major focus of the IPS-CW system was on turbidity and faecal coliform (FC) removal, and at 5 L/min flow rate mean maximum removal efficiencies of 95.9% and 94.3% were achieved, respectively. Total suspended solids, nitrate (NO_3^-), ammonium, biological oxygen demand (BOD_5) and phosphate removal were studied and removal efficiencies of 97.4%, 91.7%, 71.3%, 91.7% and 49.8% were obtained at 5 L/min flow rate, respectively. Although the use of these combinations of technologies in improving drinking water quality is uncommon, results demonstrated that NO_3^- and BOD_5 met WHO and TBS drinking water standards of $\leq$50 mg/l and $\leq$6 mg/L respectively. Due to low production cost and simplicity in operation, the system is relevant for application in rural communities.

Key words: constructed wetland, earth dams, inclined plates settler, pretreatment of water, turbidity

Highlights

- Provision of feasible treatment units for rural communities lacking access to clean water.
- Validating the use of a combination of the IPS and CW for high turbidity water treatment.
- Treating surface waters to meet the potable water standards.
- Efficient, cost-effective, and easy to operate drinking water treatment unit.

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Graphical Abstract

INTRODUCTION

Safe water supply in rural Tanzania is inadequate, due to limited availability and high cost of conventional water treatment technologies (URT 2016). This leads to the prevalence of avoidable diarrhea, which is responsible for 8% of deaths of children below five years of age (UNICEF 2018). The semi-arid regions and rural areas of Tanzania are facing water scarcity challenges leading to the dependence on earth dams and borrow pits as the source of water for domestic purposes and livestock (Dzimiri *et al.* 2010; Mshida *et al.* 2017; Shen *et al.* 2015). This combined use by humans, livestock and wildlife may be associated with water quality problems, especially high turbidity >1,000 NTU throughout the year, pathogens, blue-green algae, and organic matter (Eliakimu *et al.* 2018) exposing people to potential zoonotic diseases and other diseases. Low cost, user-friendly and efficient community water treatment technologies for physicochemical and microbial removal in highly turbid water are needed (Mtavangu *et al.* 2017) in line with the objective of the Sustainable Development Goals of access to clean water for all (Griggs *et al.* 2013).

Various technologies to treat drinking water are available, though most of these are appropriate for water sources with low levels of turbidity (Chintokoma *et al.* 2015). Examples of such techniques include: reverse osmosis (RO), microfiltration, ultrafiltration, nanofiltration, solar and UV disinfection (Dorea *et al.* 2006; WHO 2016). The common water pretreatment approach includes the use of sedimentation tanks, though in situations of high-turbidity storm waters a common solution is to shut down all operations for some time. Coagulation and flocculation by inorganic and organic compounds are water pretreatment technologies, which are used in turbidity removal (Carty *et al.* 2002). However, the long-term chemical supply may be a problem, hence not cost-effective for rural communities (Dorea *et al.* 2006).

Sedimentation tanks are effective in lowering suspended solids from water, even though large areas of land and high capital cost is involved. Also, they are less effective in removing finer particles, limiting their use in the treatment of water with fine particles (Arcil 2009; Chintokoma *et al.* 2015). Coupling sedimentation tanks with inclined plates enhances the settling characteristics of the sedimentation basin (Tchobanoglous *et al.* 2003). IPS designs have the capacity of sorting out finer particles in suspension at a higher rate. The settler capability per element volume can be increased without significant change of outline of the tank (Wisniewski 2013). Plate stacks are normally stuck in the middle of a parallel inlet and outlet sedimentation channel (Leung & Probstein 1983; Murray & Hanna 2009). The plates split the sedimentation tank into several small settling tanks and reduce settling time by shortening the vertical distance (Murray & Hanna 2009). Causing increased surface area and reduced settling distance of the plates, settling tanks with inclined plates can separate particles faster than conventional tanks. Solid particles separated from the suspension slip down to the surface of the inclined plate by gravitational force and settle at the foot of the sedimentation tank where they are removed (Chintokoma *et al.* 2015). Therefore, a sedimentation tank coupled with inclined plates settler can be a viable pretreatment technology for turbidity removal and other associated contaminants before entering other treatment units (Murray & Hanna 2009). This was proven through a lab-scale study on turbidity removal by the IPS, and the system was able to reduce high turbidity (>1,000 NTU) to Tanzania drinking water standards of turbidity ≤25 NTU (Chintokoma *et al.* 2015; EWURA 2020). Similarly, previous work publicized the potential of IPS for water treatment in emergency relief applications (Dorea *et al.* 2014).

Constructed wetlands are low-cost technologies that use locally available materials, simple to operate, repair, and maintain but also require low energy (Mtavangu *et al.* 2017; Njau *et al.* 2011). The presence of macrophytes, substrates and microbial community results in complex inter-connected physical, chemical and biological mechanisms in removing water contaminants (Vymazal 2007; Zhang *et al.* 2012). Constructed wetlands are 'eco-friendly' alternatives for secondary and tertiary treatment of municipal, agricultural, and manufacturing wastewater (Kadlec & Wallace 2008). The pollutants removed by constructed wetlands comprise organic constituents, suspended solids, nutrients, pathogens, heavy metals, and other toxic or hazardous pollutants (Kadlec & Wallace 2008; Tchobanoglous *et al.* 2003). Still, different findings have reported on the effectiveness of horizontal subsurface flow constructed wetland (HSFCW) in treating turbid water and other contaminants such as pesticides and organic matter (Kipasika *et al.* 2014; Lema *et al.* 2014). However, external factors like pH, temperature, dissolved oxygen, hydraulic loading rate and hydraulic retention time affect pollutant removal mechanisms (Deng *et al.* 2011; Wang *et al.* 2012a, 2012b). Most of the studies use CW for wastewater treatment but also a few studies have documented the use of CW for improvement of river waters, dam waters, and stormwater runoff for drinking water purposes (Ewel 1997; Froebrich *et al.* 2006; Huang *et al.* 2007; Kadlec & Wallace 2008; Kurzbaum *et al.* 2012; Mtavangu *et al.* 2017). Considering the targeted location (rural area), material availability and accessibility, the water quality problem within the studied earth dam, and the reported capacity of the CW to deal with such contaminants (Eliakimu *et al.* 2018). The CW was seen as a better secondary treatment technology for the selected water source. Thus, this research evaluated the performance of a pilot scale integrated system of inclined plates settler and constructed wetland as a feasible treatment technology for community water with high turbidity and other physicochemical and microbial contaminants.

MATERIALS AND METHODS

Study area

The pilot-scale study of the inclined plates settler integrated with the constructed wetland for high turbid water treatment was conducted at Nadosoito earth dam in Monduli district, Tanzania. The pilot treatment plant is located at latitude 3° 24′ 57″S and longitude 36° 22′ 48″E. Figure 1 shows some of the permanent earth dams in Monduli district which are used for domestic purposes and livestock.

Pilot scale design and setup

The water treatment system that was evaluated in this study consists of a sedimentation tank coupled with the inclined plates setter (physical treatment unit) and a horizontal subsurface flow constructed wetland (biological treatment system).

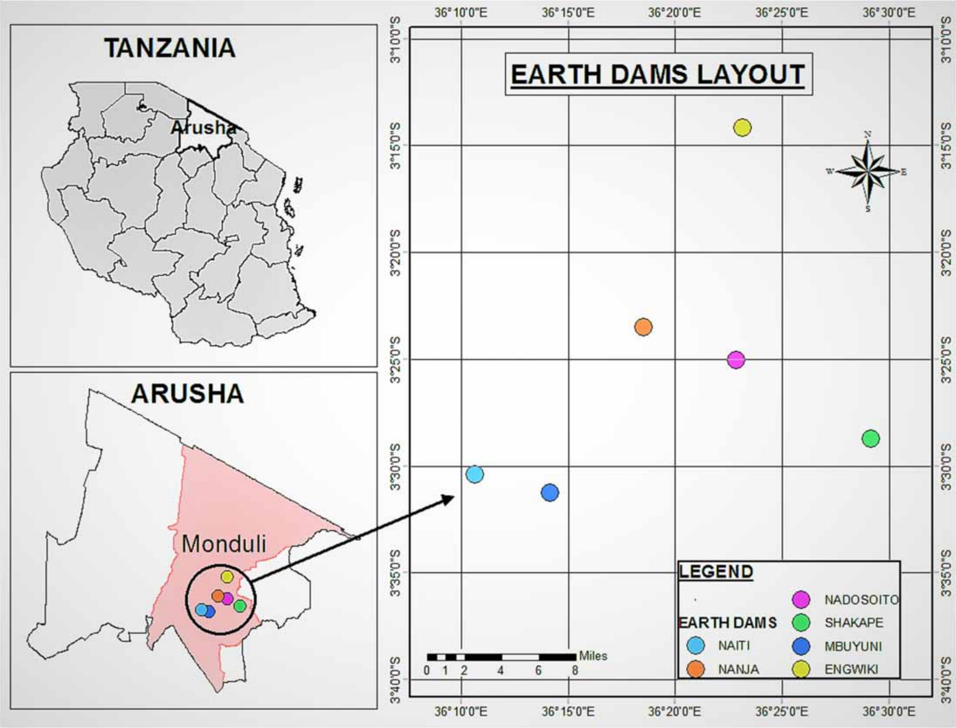

Figure 1 | Map of Tanzania showing permanent earth dams in the vicinity of the study area which are used for domestic purposes.

Sedimentation tank coupled with inclined plate settlers (IPS)

The sedimentation tank coupled with the IPS was constructed with concrete walls and aluminum plates. The tank had dimensions of 6.9 m length, 1.2 m width, and 2.1 m effective height, and the IPS plate had dimensions of 3 m length, 1.2 m width, effective height of 1.7 m, inclination height of 2.4 m, and 45° inclination angle as represented in Figure 2. The IPS system was operated at flow rates of 5, 10, 15, and 20 L/min, and the effluent from this system was fed to the CW.

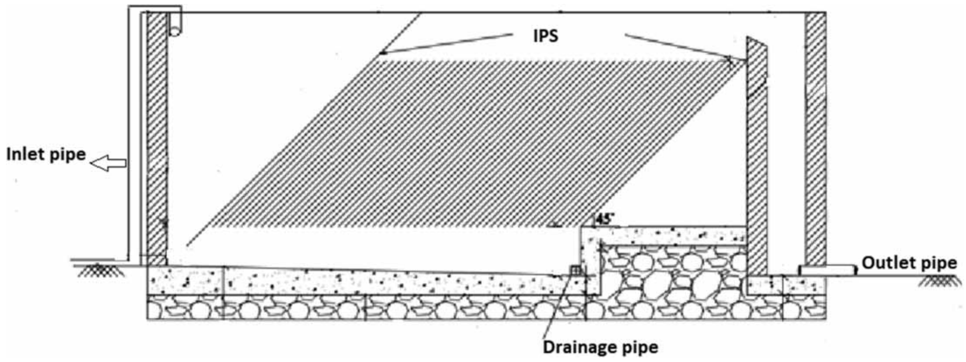

Figure 2 | Section view of Sedimentation tank coupled with inclined plates settler.

Horizontal subsurface flow constructed wetland (CW)

The CW was constructed by solid concrete blocks with an internal lining to avoid seepage, with dimensions of 12 m length, 4 m width, and 1 m depth. The CW had a slope of 0.004 and was filled with graded aggregates of size 12–19 mm and boulder stones of size 50–100 mm to a depth of 0.6 m with an average porosity of 0.4. The CW was planted with *cyperus alternifolius* plants as shown in Figure 3.

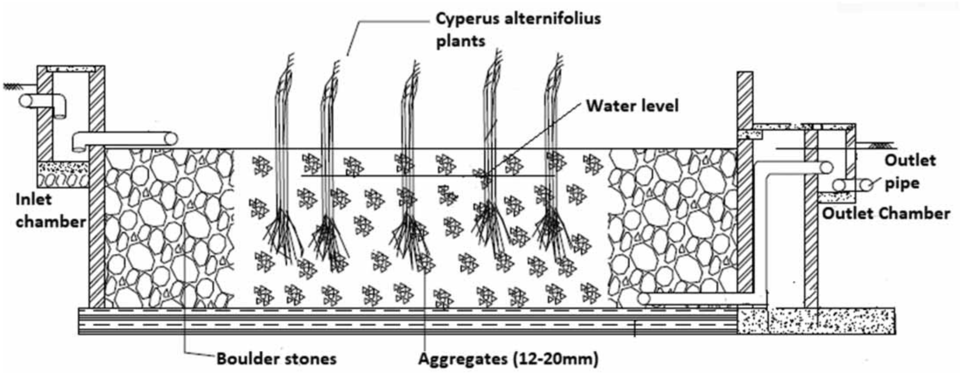

Figure 3 | Cross-section area of a horizontal subsurface flow constructed wetland.

Process flow diagram

The process flow diagram for treating turbid water >1,000 NTU from Nadosoito earth dam found in Monduli district is as shown in Figure 4. The water from the dam is collected at the water collection sump and pumped to elevated feed tanks at about 3 m high. The water from elevated tanks flows by gravity to the sedimentation tank coupled with inclined plates settler that feeds the constructed wetland. The treated water from the constructed wetland is discharged to an underground storage tank and a hand pump is used to provide water to the community users.

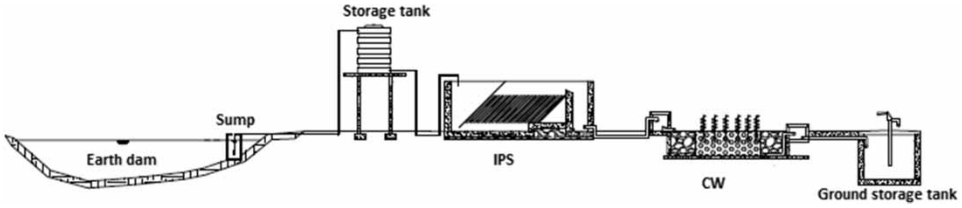

Figure 4 | Process flow diagram of the pilot scale IPS-CW treatment system setup at Nadosoito earth dam.

Sample collection

Three points in the integrated IPS-CW treatment system were selected for water sample collection: inlet of the IPS, an outlet of the IPS (inlet of the CW), and the outlet of the CW. All samples for physicochemical study were collected in polyethylene sampling bottles of 1,000 ml volume while the water samples for microbial analysis were collected in a 400 ml glass bottle. All polyethylene sampling bottles were washed and rinsed with distilled water and then re-rinsed with the sampled water in the integrated system while the glass bottles were washed, rinsed, and sterilized by an autoclave machine. Collected water samples were stored in a cool box at 4 °C and transported to the NM-AIST laboratory for analysis. The entire process of sample collection followed the standard methods for the examination of water and wastewater (APHA 2012). The pilot IPS-CW plant was investigated from January to June 2020, with a total number of 25 tests whereby at the flow rate of 5, 10, 15, and 20 L/min the system was tested 8 times, 7 times, 5 times, and 5 times respectively.

Sample analysis

Some of the physicochemical parameters were analyzed onsite: dissolved oxygen (DO), electrical conductivity (EC), pH, total dissolved solids (TDS), temperature, and turbidity using a HANNA multiparameter and turbidity meter respectively. Total suspended solids (TSS) was analyzed by direct measurement with a spectrophotometer (HACH DR 2800), Nitrogenous species (NO_3^- and NH_4^+) and PO_4^- were determined with a HACH DR 2800 spectrophotometer. Biochemical oxygen demand (BOD_5) was analyzed by a closed manometer, as per the standard methods for examination of water and wastewater at the NM-AIST laboratory (APHA 2012). Bacteriological water quality was examined by analyzing faecal coliform indicator bacteria (FC). Membrane filtration method was used to analyze FC, whereby water samples were filtered through membrane filters of 0.45 μm pore size and 47 mm diameter then the filter papers containing the samples were placed in petri dishes containing the MFC-agar medium and incubated at 44.5 °C for 24 hours to allow the growth fecal bacteria indicator (Tchobanoglous *et al.* 2003).

Data analysis

Research data were analyzed by different statistical software including Origin Pro 9 and Excel. Descriptive statistics were carried out to summarize the data obtained, to establish the removal performance of the treatment systems, and to draw representative graphs of the system performance.

$$\text{Parameter removal efficiency} = \frac{\text{Mean influent parameter } - \text{Mean effluent parameter}}{\text{Mean influent parameter}} * 100\%$$

RESULTS AND DISCUSSION

Variation of physicochemical parameters

The general performance of the IPS-CW treatment system is governed by the water flow rate and the loading of water pollutants. The treatment system reduces turbidity and other chemical and microbial parameters, due to different physical, chemical, and microbial processes that are taking place in the treatment systems.

pH

pH is an important factor in water treatment systems as it affects different chemical and biological processes (Law *et al.* 2011). In the IPS-CW treatment system, pH showed a general increasing trend from the inlet of the IPS to the outlet of the constructed wetland at all set flowrates as shown in Table 1. This trend might be due to the anaerobic decomposition of organic matter and the dissolution of inorganic compounds in water (Masbough *et al.* 2005; Mtavangu *et al.* 2017).

Temperature

Temperature is a water quality parameter that is important in different biological treatment systems as it affects the rate of physicochemical and microbial activities and hence pollutant removal (Jing & Lin 2004; Akratos & Tsihrintzis 2007). The temperature at the IPS-CW treatment system varied greatly due to different weather conditions, with a maximum temperature of 28.84 °C and minimum value of 20.99 °C as shown in Table 1.

Dissolved oxygen (DO)

DO concentration in the IPS treatment system reflected minor differences at the inlet and outlet of the system, with the majority of the result showing a decreasing trend from the inlet to the outlet of the

Table 1 | *In situ* parameters from the integrated IPS-CW

			Flow rates (L/min)			
Parameters	**Sampling points**	**Units**	**20**	**15**	**10**	**5**
pH	IPS inlet	–	8.32 ± 0.2	8.21 ± 0.2	7.9 ± 0.2	7.94 ± 0.1
	IPS out/inlet CW	–	8.31 ± 0.1	8.27 ± 0.2	8.12 ± 0.2	8.06 ± 0.1
	CW outlet	–	8.64 ± 0.1	8.51 ± 0.1	8.39 ± 0.1	8.38 ± 0.1
Temperature	IPS inlet	°C	25.12 ± 0.5	25.17 ± 0.9	22.41 ± 0.5	25.61 ± 0.8
	IPS out/inlet CW	°C	25.8 ± 1	24.98 ± 0.8	22.43 ± 0.7	25.64 ± 0.8
	CW outlet	°C	24.6 ± 0.5	24.69 ± 0.6	22.58 ± 0.7	25.46 ± 0.9
DO	IPS inlet	mg/L	3.87 ± 0.2	5.15 ± 0.6	5.42 ± 0.5	4.33 ± 0.2
	IPS out/inlet CW	mg/L	3.86 ± 0.1	5.16 ± 0.5	5.32 ± 0.5	4.24 ± 0.2
	CW outlet	mg/L	3.55 ± 0.1	3.86 ± 0.2	3.78 ± 0.2	3.85 ± 0.2
EC	IPS inlet	µS/cm	278.6 ± 26.2	225.8 ± 24.9	292.6 ± 47.6	294.65 ± 50
	IPS out/inlet CW	µS/cm	287.4 ± 28.9	233.2 ± 31.2	299.29 ± 47.4	307.8 ± 49.1
	CW outlet	µS/cm	328 ± 32.1	331.6 ± 33.7	361 ± 28.9	327.5 ± 48.8
TDS	IPS inlet	mg/L	142 ± 13.5	113.6 ± 12.9	146.14 ± 24.5	148.56 ± 24.8
	IPS out/inlet CW	mg/L	143.6 ± 14.5	116.6 ± 15.6	149.57 ± 22.7	156.28 ± 25.1
	CW outlet	mg/L	164 ± 16.3	147.6 ± 13.7	180.29 ± 16.7	156.75 ± 20.1

system, while the constructed wetland treatment system showed a generally decreasing trend from the inlet to the outlet of the CW. The observed DO decreasing trend in Table 1 might have been attributed to the physical, chemical, and biological processes taking place in the integrated systems (Martins *et al.* 2003; WHO 2006).

Electrical conductivity and total dissolved solids

Results from Table 1 show that EC and TDS were increasing from influent values of the IPS to the effluent values of the CW. This increasing trend of EC and TDS in the IPS-CW treatment systems might have been caused by the dissolution of ions during the breakdown of contaminants in water, as suggested by Mtavangu *et al.* (2017).

Aluminum

Aluminum is a naturally occurring metallic element in water. Aluminum-containing treatment systems such as the coagulation process might lead to the addition of aluminum concentration in water. In this study, aluminum plates have been used in water treatment, therefore its concentration was monitored and showed a generally decreasing trend. A mean influent value of 0.51 ± 0.2 entered the system and was reduced by the IPS to 0.3 ± 0.1 and final aluminum concentration was reduced by the CW to 0.03 ± 0.01. Therefore, aluminum plates did not add the concentration of aluminum in water. The integrated IPS-CW was capable of reducing the value of aluminum to allowable drinking water standards by TBS and WHO of aluminum concentration <0.2 mg/L (EWURA 2020; WHO 2011). The reduction of aluminum might have been due to chemical precipitation, adsorption, and sedimentation processes (Jayaweera *et al.* 2007).

Turbidity removal

Turbidity is the water quality parameter that reflects the presence of suspended matter, fine organic and inorganic matter, soluble colored organic compounds, algae, and other microscopic organisms making water unsuitable for use without treatment (Mandal 2014). During the integrated IPS-CW system testing, influent turbidity ranged from 186 to 4,011 NTU, with mean values of IPS and CW turbidity removal rates presented in Figure 5. The results in Table 2 indicate that turbidity removal

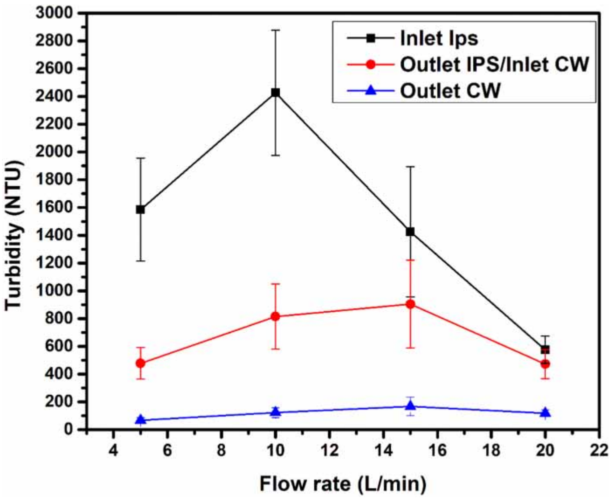

Figure 5 | Variation of mean turbidity in the system as a function of water flow rate.

Table 2 | Performance of the IPS, CW and the integrated IPS-CW treatment systems in water pollutant removal

			Flow rate (L/min)			
Parameter	**Treatment unit**	**Units**	**20**	**15**	**10**	**5**
Turbidity	IPS	%	20.4 ± 5.6	36.9 ± 4.2	62.5 ± 8.4	66.7 ± 4.5
	CW	%	73.9 ± 4.8	82 ± 1,4	85.7 ± 1.2	88.3 ± 1.9
	IPS-CW	%	79.9 ± 2.6	88.6 ± 1.3	94.8 ± 1.2	95.9 ± 1
FC	IPS	%	62.3 ± 4.4	67.5 ± 3.9	67.8 ± 3.2	68.2 ± 1.9
	CW	%	71.1 ± 0.9	78.4 ± 2.7	80.2 ± 1.8	82 ± 1.4
	IPS-CW	%	89.1 ± 1.3	93 ± 1.4	93.9 ± 0.7	94.3 ± 0.6
TSS	IPS	%	52.9 ± 8	59 ± 9.7	64.3 ± 9.3	80.8 ± 3.3
	CW	%	73.4 ± 9.2	80.8 ± 1.3	86.7 ± 2	87.4 ± 2.2
	IPS-CW	%	88.6 ± 2.7	92.2 ± 1.8	96.1 ± 0.6	97.4 ± 0.8
NO3^{-}	IPS	%	52.2 ± 0.7	60.7 ± 4.7	67.8 ± 4.5	73 ± 3.1
	CW	%	51.5 ± 0.7	59.1 ± 1	64.8 ± 1.6	68.8 ± 1.5
	IPS-CW	%	76.8 ± 0.5	84 ± 1.8	88.6 ± 1.7	91.7 ± 0.9
NH4^{+}	IPS	%	26.4 ± 7.1	28.1 ± 4.9	44.6 ± 5.8	44.7 ± 3
	CW	%	12.4 ± 1.2	18.7 ± 3.9	39.7 ± 7.8	47.7 ± 6.8
	IPS-CW	%	35.6 ± 6.1	42.3 ± 1.6	66 ± 6.6	71.3 ± 3.8
PO4^{-}	IPS	%	20.6 ± 4.9	23.4 ± 2.6	37.6 ± 5.7	38.1 ± 4.7
	CW	%	8.9 ± 1	14.5 ± 0.4	17.8 ± 2.7	19.6 ± 2.9
	IPS-CW	%	27.9 ± 3.7	34.5 ± 2.2	49.3 ± 3.9	49.8 ± 4.9
BOD	IPS	%	28.3 ± 11.7	46.7 ± 3.3	50 ± 5.8	57.8 ± 5.2
	CW	%	42.6 ± 4.9	55.6 ± 5.6	55.6 ± 12.2	83.3 ± 10.5
	IPS-CW	%	50 ± 14.4	66.7 ± 8.7	83.3 ± 6.7	91.7 ± 5.3

efficiency by the IPS increases with the decrease in flow rate (increase in hydraulic residence time of 0.66–2.65 days), which is from 20.4% to 66.7% at 20 and 5 L/min flow rates respectively. The CW was able to further reduce high values of turbidity at all flow rates, with the highest removal percent being achieved at the flowrate of 5 L/min. Generally, the mean performance of the IPS-CW system in turbidity removal ranged from 79.9% to 95.9% at flow rates of 20 and 5 L/min, respectively. In addition, during system testing, when the influent turbidity was ≤300 NTU the integrated IPS-CW system was able to reduce the values of turbidity of water to required Tanzania drinking water standards of turbidity <25 NTU (TBS 2005) at all tested flow rates.

Water turbidity removal at the IPS was mainly governed by the reduced depth and increased area of sedimentation (Xing *et al.* 2006) whereby suspended solids and colloidal matter were concentrated and allowed to slip down the surface of the inclined plate by gravitation force and settle at the foot of the sedimentation tank where they were being removed at set time intervals (Chintokoma *et al.* 2015; Xing *et al.* 2006). Moreover, turbidity reduction by the CW was led by filtration and sedimentation aided by the reduced interspaces between gravel and plant roots hence removing suspended particles (Mtavangu *et al.* 2017). Also, despite the fluctuation in the influent turbidity to the system, the effluent parameter deviation was highly reduced after treatment especially at lower flow rates, reflecting the capacity of the system to handle varied pollutant loading rates.

Faecal coliform (FC) removal

FC bacteria present in water may indicate the existence of pathogenic organisms. FC concentration at the inlet of the IPS ranged from 420 to 2,880 CFU/100 ml. The raw water was allowed to flow into the IPS for pretreatment then allowed to flow to the constructed wetland for further treatment. Figure 6 shows that both treatment stages were efficient in the removal of FC bacteria present in the water, with a higher removal rate exhibited at lower flow rates and the CW performing better than the IPS system. The integrated IPS-CW treatment system exhibited varied removal efficiency depending on the set flow rates, with mean maximum removal efficiency of 94.3% at 5 L/min flow rate. The attained final concentration of FC did not reach the allowed standard of 0 CFU/100 mL for safe water.

The removal of FC in the IPS is thought to have been mainly aided by sedimentation processes of the attached bacteria on solid particles supported by the entrapment by the biofilm developed on the surface of the inclined plates. While in the CW, the major process is through filtration by the gravels and plant roots, as well as other processes such as natural die-off and predation by larger organisms (Ansa *et al.* 2015; Garcia *et al.* 2010; Mtavangu *et al.* 2017; Wu *et al.* 2016).

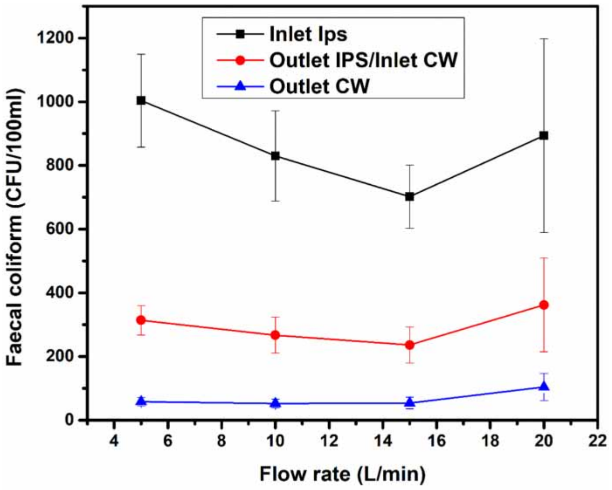

Figure 6 | FC removal by the integrated IPS-CW.

Total suspended solids (TSS) removal

Influent TSS concentration at the IPS ranged from 510 to 9,780 mg/l, and the integrated IPS-CW was able to reduce a significant amount of TSS concentration in the water, as shown in Figure 7. The system exhibited mean maximum TSS removal efficiency of 97.4% at the 5 L/min flow rate as presented in Table 2. These results indicate that TSS removal increases with an increase in hydraulic residence time through the sedimentation process in the IPS and sedimentation and filtration in the CW (Garcia *et al.* 2010; Xing *et al.* 2006).

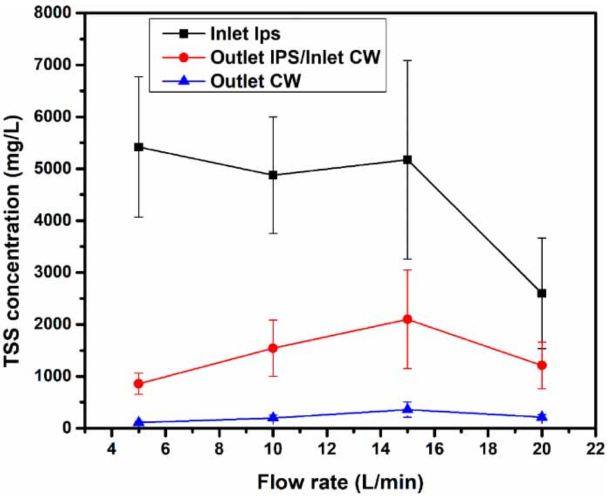

Figure 7 | TSS removal by the integrated IPS-CW.

Nitrate (NO_3^-) removal

Nitrate concentration that entered the system ranged from 4.2 to 143 mg/L and the concertation was changing rapidly due to surface runoff of fertilizers and manures from the surrounding farms, uptake by phytoplankton, and denitrification by bacteria in the dam (WHO 2006). Although the concentration of nitrate in some of the test events were within the Tanzanian Standards of 10–75 mg/L of NO_3^-, still the system was able to reduce the high nitrate concentration events to allowable Tanzanian (TBS 2005) and WHO standards of drinking water, as shown in Figure 8. The IPS and the integrated IPS-CW system mean performance ranged from 52.2% to 73% and 76.8% to 91.7% at all set flow rates, respectively, as shown in Table 2. The main removal mechanism of organic and inorganic nitrogen in the IPS is through particle setting and volatilization. In the constructed wetland, nitrate removal was aided by different physical, biological, and chemical processes such as particle settling (sedimentation), volatilization, sorption, assimilation by plants, algae, and bacteria, and transformation processes conducted by microbes (denitrification) (Caselles-Osorio *et al.* 2017; Garcia *et al.* 2010).

Ammonium (NH_4^+) removal

The presence of ammonia in water indicates organic pollution from animal and human wastes and the possibility of bacterial contamination (Eliakimu *et al.* 2018; WHO 2006). Ammonium concentration entering the system at the IPS ranged from 0.55 to 7.29 mg/L. The integrated IPS-CW treatment system was able to reduce a significant amount of ammonium concentration in water as presented in Figure 8(c), and maximum removal efficiency of 71.3% was obtained at 5 L/min flow rate.

The removal of ammonium at the IPS might have been attributed to sedimentation and nitrification processes (Xing *et al.* 2006) and the presence of dissolved and free oxygen in the system. While at the CW, the removal of ammonium might have been caused by sedimentation, plant uptake, and nitrification processes (Caselles-Osorio *et al.* 2017; Stenstrom & Poduska 1980). The removal of ammonium in the system was lower compared to the other parameters studied. The lowest removal efficiency was observed at the constructed wetland, which might be due to the limited amount of oxygen in the CW as it was being consumed by other processes (Vymazal 2007).

Biological oxygen demand (BOD_5) removal

Influent BOD levels from the earth dams to the treatment system varied with the maximum value of 20 mg/L of BOD. The pilot IPS-CW plant was able to reduce all values of BOD that entered, to

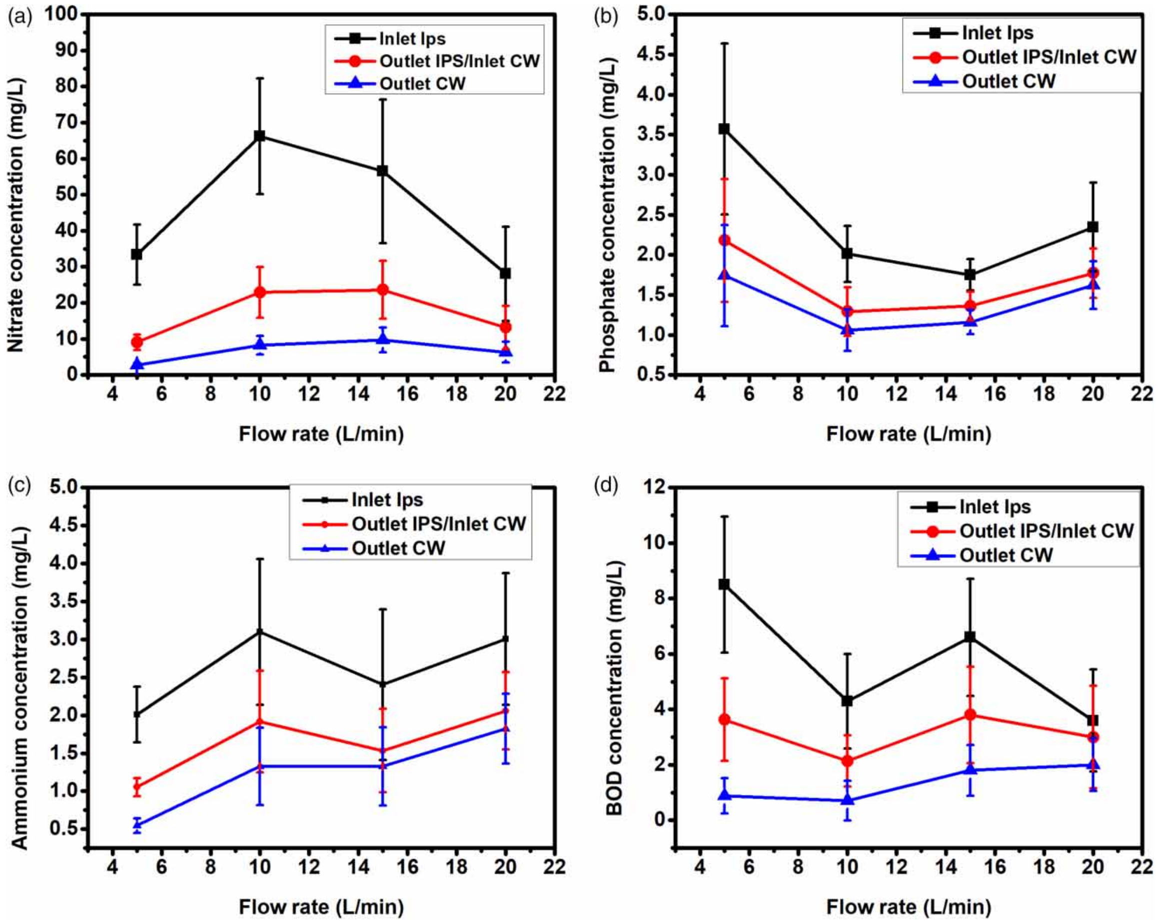

Figure 8 | Average nutrients and organic matter removal by the integrated IPS-CW (a) NO_3^- (b) PO_4^{3-} (c) NH_4^+ (d) BOD_5.

allowable Tanzania standards of drinking water of BOD ≤6 mg/L, as shown in Figure 8(d). Also, the system exhibited mean maximum BOD removal efficiency of 91.7% at a flow rate of 5 L/min, as presented in Table 2.

In this system, sedimentation, filtration, adsorption, oxygenation, and microbial metabolism are considered to be the main mechanisms for BOD removal (Karathanasis *et al.* 2003).

Phosphate (PO_4^{3-}) removal

Phosphate concentration that entered the IPS-CW system ranged from 0.58 to 9.98 mg/L, with mean maximum removal efficiency of 49% at 5 L/min as presented in Table 2.

The removal of phosphate might have been attributed to sedimentation in the IPS and CW, plant uptake and substrate sorption in the CW (Garcia *et al.* 2010), though these processes occurred at smaller rates leading to a low removal percent of phosphate by both treatment units with the CW exhibiting lower removal rates compared to the IPS as shown in Table 2.

Performance of the IPS, CW and the integrated IPS-CW treatment systems in water pollutant removal

The results in Table 2 show the average performances of individual water treatment systems at various flow rates together with the combination of the two systems in pollutant removal. Generally, the performance of the system was affected by the weather conditions (rainfall, temperature, and wind) together with the operation conditions (residency time, water pollutant loading rate, and sludge removal frequencies). The system encountered higher pollutant load than the designed system capacity especially for the TSS and turbidity that entered the system; also, there was high fluctuation of influent parameters. The exposure of CW to a high level of turbidity for a long period may result in clogging of the system, thus shortening its operational life span. To minimize the limitation, frequent backwash of the settled sludge at the IPS was carried out. Also, temperature can act as a limiting factor toward the performance of the system as it affects the settling and vertical velocity of suspended solids in the system as suggested by Takata & Kurose (2017).

IPS is a treatment unit targeted at suspended solids removal, as demonstrated by previous studies (Abou-Elela *et al.* 2015; Chintokoma *et al.* 2015; Dorea *et al.* 2006, 2014). Although in this study, the system was evaluated for turbidity, TSS, nitrate, ammonium, phosphate, and faecal coliform removal and it was able to exhibit maximum removal efficiency of 66.7%, 80.8%, 73%, 44.7%, 38.1%, and 68.2% at the flow rate of 5 L/min respectively. The removal of these parameters is thought to have involved different processes such as sedimentation, nitrification, and denitrification, disinfection by UV light, and natural die-off processes. The performance of the IPS was affected by the flow rates and sludge removal frequency, whereby at small flow rates (10 and 5 L/min) and sludge retention time of two weeks the removal efficiency of parameters was increasing and also at the mentioned flow rates the variation of the treated parameter was reduced despite the great variability in the influent parameters, this might have been contributed by the increased residence time for parameter treatment.

In this study, the CW proved efficient in specified parameters removal, as shown in Table 2, and the removal rate was mostly affected by the residence time, whereby the maximum removal efficiency was attained at residence of 1.5 days (38 hours and 24 minutes). The CW performed better than the IPS in the removal of turbidity, FC, TSS and BOD. This is thought to have been contributed by different processes such as filtration, sedimentation, predation and microbial metabolism.

The results of the integrated IPS-CW system show that the performance of the system in the removal of the selected parameter was high, as presented in Table 2.

CONCLUSIONS

Results of the study show that the integrated IPS-CW system is an appropriate pre-treatment combination for waters with higher turbidity values, typically used in rural areas without water supply systems. It was possible to reduce the turbidities as high as 1,585 NTU to acceptable levels by Tanzanian drinking water standards. The removal of turbidities at higher flow rates can be improved by the introduction of coagulants at the IPS to improve the sedimentation process. This will enable the system to operate well even when the turbidities are above 3,000 NTU. Together with turbidity removal, the system was able to remove a substantial amount of nutrients and pathogens, which are not required in potable water. It was also observed that despite the high efficiencies for water pollutant removal, further treatment is necessary to make the water safe for human consumption. There is a need for introducing a disinfection step at the end to ensure that there are no pathogens in the treated water. This study has also shown that the system is robust and feasible for handling variations in turbidities as high fluctuations in levels of contaminants entering the system were faced. Due to low production cost and simplicity in operation, the system is relevant for application in rural communities.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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