PERFORMANCE OF INCLINED PLATES SETTLER INTEGRATED WITH CONSTRUCTED WETLAND FOR HIGH TURBIDITY WATER TREATMENT

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Masters in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

The purpose of this study was to investigate and demonstrate a cost-effective treatment technology for high turbid water, commonly used for domestic purposes in rural areas of Tanzania where conventional water treatment techniques are not available. A study was conducted on the water quality status of five permanent earth dams within Monduli district during the wet and dry seasons, by analyzing physicochemical and microbial characteristics. The water characteristics of the five earth dams tested were significantly correlated ($p < 0.05$) and most of the tested parameters including turbidity and faecal coliform (FC) were above the Tanzania Bureau of Standards (TBS) drinking water standards. In this study, a pilot-scale inclined plates settler integrated with constructed wetland (IPS-CW system was tested on Nadosoito dam water with turbidities ranging from 186 to 4011 NTU. The IPS-CW system was meant to remove organic matter, nutrients and pathogens, with major focus on turbidity and FC removal, at the test flow rates of 20, 15, 10 and 5 L/min. The system removed substantial amount of contaminants, thereby achieving maximum removal efficiency of 95.9% and 94.3% for turbidity and FC respectively. Although using this combination of technologies in improving drinking water quality is uncommon, nitrate and biochemical oxygen demand met the TBS and World health Organization drinking water standards of ≤ 50 mg/l and ≤ 6 mg/L respectively. Due to low production cost and simplicity in operation, the system can be implemented in rural communities with high turbidity water sources however, further disinfection is required to ensure zero FC.

DECLARATION

I, Atwebembela John Kasenene do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other Institution.

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Name and Signature of Candidate Date

The above declaration is confirmed

Prof. Karoli N. Njau ____________ 4/8/2021 ____________

Name and Signature of Supervisor (1) Date

Prof. Revocatus L. Machunda ____________ 4/8/2021 ____________

Name and Signature of Supervisor (2) Date

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for examination of a dissertation entitled; *"Performance of inclined plates settler integrated with constructed wetland for high turbidity water treatment"* to be accepted in partial fulfillment of the requirements for the Degree of Master of Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology Arusha, Tanzania.

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DEDICATION

I dedicate this work to my family especially my mother and father for giving me a strong foundation and supporting me throughout my academic life, they were my advisers and always believed in me.

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LIST OF ABBREVIATIONS AND SYMBOLS

AfDB	African Development Bank
APHA	American Public Health Association
BOD_5	Biochemical Oxygen Demand
COSTECH	Commission of Science and Technology
CW	Constructed Wetland
DO	Dissolved Oxygen
Dr	Doctor
DVC-ARI	Deputy Vice Chancellor Academic Research and Innovation
DVC-PFA	Deputy Vice Chancellor Planning Finance and Administration
EC	Electrical Conductivity
EWURA	Energy and Water Utilities Regulatory Authority
FAO	Food and Agriculture Organisation
FC	Faecal Coliform
GoT	Government of Tanzania
GPS	Geographical Positioning System
HLR	Hydraulic Loading Rate
HSSFCW	Horizontal Subsurface Flow Constructed Wetland
IPS	Inclined plates settler
Max	Maximum
Min	Minimum
MoW	Ministry of Water
NH_4^+	Ammonium
NM-AIST	Nelson Mandela African Institution of Science and Technology
NO_3^-	Nitrate
NTU	Nephelometric Turbidity Unit
PO_4^-	Phosphate
Prof	Professor

RO	Reverse Osmosis
RT	Retention Time
RWT	Raw Water Tank
SD	Standard Deviation
TBS	Tanzania Bureau of Standards
TDS	Total Dissolved Solids
Temp	Temperature
TSS	Total Suspended Solids
Turb	Turbidity
UNICEF	United Nations Children's Fund
URT	United Republic of Tanzania
VC	Vice Chancellor
WHO	World Health Organisation

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

Safe water supply in rural parts of Tanzania is inadequate, due to the limited and the cost of conventional water treatment technologies (United Republic of Tanzania [URT], 2016), leading to the prevalence of avoidable diarrhea which is liable for 8% deaths of children below five years of age (United Nations Children's Emergency Fund [UNICEF], 2018). Therefore, knowledge on water quality and sources of contamination in surface water sources is vital as it affects human and ecological health (Zamani *et al.*, 2012). Most of the rural areas in the semi-arid regions of Tanzania face water scarcity challenges leading to the dependence on the 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). The combined use by human, livestock and wildlife may be associated with water quality problems, especially high turbidity > 1000 NTU throughout the year, pathogens, blue-green algae and organic matters (Eliakimu *et al.*, 2018); exposing people to potential zoonotic diseases and other diseases. Therefore, low-cost, user-friendly and efficient community water treatment technologies for physicochemical and microbial removal in high turbid water are needed (Mtavangu *et al.*, 2017). Notably, one of the 17 Sustainable Development Goals is the access to clean water for all by 2030 (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). The treatment techniques include reverse osmosis (RO), ultrafiltration, nanofiltration, sedimentation, sand filtration, coagulation and flocculation, and disinfection processes (Dorea *et al.*, 2006; World Health Organization [WHO], 2016). The standard water pretreatment approach includes the use of sedimentation tanks. Although in situation of high-turbid storm waters common solution is to shut down all operations for some time. Coagulation and flocculation by inorganic and organic compounds are also water pretreatment technologies used in turbidity removal (Carty *et al.*, 2002). However, the long-term chemical supply may be a problem hence not cost-effective to rural communities (Dorea *et al.*, 2006).

Sedimentation tanks lower suspended solids from water although they require, large piece of land and high initial capital cost. They are also 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). Inclined Plate Settler (IPS) designs can sort out finer particles in suspension at a higher rate. The settler capability per element volume can be increased without significant change of the outline of the tank (Wisniewski, 2013). 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 there being removed (Chintokoma *et al.*, 2015). Therefore, 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 technology was proven through a lab-scale study on turbidity removal by the IPS, and the system was able to reduce high turbidity (> 1000 NTU) to Tanzania drinking water standards of turbidity ≤ 25 NTU (Chintokoma *et al.*, 2015; Energy and Water Utilities Regulatory Authority [EWURA], 2020). Previous work also publicized the potential of the IPS for water treatment in emergency relief applications (Dorea *et al.*, 2014).

Constructed wetlands (CWs) are low-cost water and wastewater treatment 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 a 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 municipal, agricultural, and manufacturing wastewater treatment (Kadlec & Wallace, 2008). The pollutants removed by constructed wetlands comprise of 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 wetlands (HSSFCWs) 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 its pollutants removal mechanisms (Deng *et al.*, 2011; Wang *et al.*, 2012a; Wang *et al.*, 2012b). Most of the studies use CWs for wastewater treatment but also, few studies have documented the use of CWs for the 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 dams, the HSSFCW was seen as a better secondary treatment technology for Nadosoito earth dam (Eliakimu *et al.*, 2018). Thus, this research evaluated the performance of a pilot-scale inclined plates settler integrated with constructed wetland as a feasible treatment technology for community water with high turbidity and other physicochemical and microbial contaminants from permanent earth dams in Monduli district.

1.2 Statement of the problem

Inadequate safe water supply is the primary cause of water-related diseases that predominantly affect people living in developing countries (WHO, 2016). Diarrhea is the most prevalent disease, causing high mortality rate to children below five years of age in sub-Saharan Africa (Boschi-Pinto *et al.*, 2006; Mshida *et al.*, 2017; Thiam *et al.*, 2017). In Tanzania, these waterborne diseases are associated with the limited surface water treatment techniques, especially in rural communities (UNICEF, 2018).

Dams are important water sources for communities living in the semi-arid and rural areas of Tanzania especially in Arusha, Singida and Shinyanga regions (Mistry of Water [MoW], 2014). They constitute an essential point of interaction between human and animals posing a real risk to water-related diseases (Eliakimu *et al.*, 2018). The water quality in these earth dams is mostly unknown but definitely not safe for human consumption without treatment. Moreover, recent researches have documented the presence of cyanobacteria, faecal coliforms, turbidity and other contaminants in some of the Monduli earth dams (Eliakimu *et al.*, 2018; Mtavangu *et al.*, 2016).

Although surface water is unsafe for direct consumption and might cause waterborne diseases, it was noted that earth dams are the primary source of domestic water for majority of the population in Monduli district (Mshida *et al.*, 2017; Mtavangu *et al.*, 2016). Also, the same water sources are used by livestock and wildlife for drinking and bathing (Eliakimu *et al.*, 2018). As far as literature is concerned, this is the first time a combination of the IPS and CW is used in treating highly turbid water to meet the drinking water standards. At the lab scale, the use of IPS reported good performance for rendering highly turbidity water useful for domestic purposes (Chintokoma *et al.*, 2015). Hence, this study is meant to validate the laboratory scale reactor to a pilot system.

1.3 Rationale of the study

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). The treatment techniques include reverse osmosis (RO), ultrafiltration, nanofiltration, sedimentation, sand filtration, coagulation and flocculation, and disinfection processes (Dorea *et al.*, 2006; WHO, 2016). The standard water pretreatment approach includes the use of sedimentation tanks. Although in situation of high-turbid storm waters common solution is to shut down all operations for some time. Coagulation and flocculation by inorganic and organic compounds are also water pretreatment technologies used in turbidity removal (Carty *et al.*, 2002). However, the long-term chemical supply may be a problem hence not cost-effective to rural communities (Dorea *et al.*, 2006). Thus, this research evaluated the performance of a pilot-scale inclined plates settler integrated with constructed wetland as a feasible treatment technology for community water with high turbidity and other physicochemical and microbial contaminants from permanent earth dams in Monduli district

1.4 Research objectives

1.4.1 General objective

To evaluate the performance of inclined plates settler integrated with the constructed wetland for highly turbid water treatment.

1.4.2 Specific objectives

(i) To determine the water quality of the selected major permanent earth dams within Monduli district.

(ii) To evaluate the performance and validate the field application of inclined plates settler integrated with the constructed wetland (IPS-CW) in treatment of high turbidity water at the Nadosoito dam.

1.5 Research questions

(i) What is the water characteristic of the selected permanent earth dams in Monduli district?

(ii) What is the efficiency of inclined plate settler integrated with constructed wetland in treating high turbidity surface waters?

1.6 Significance of the study

This study provides a solution to the need for safe water in the rural communities that depend on earth dams for domestic water supply. As far as literature is concerned, this is the first time IPS integrated with CW is used for water treatment to produce potable water. This innovation will be applicable and useful to many areas (rural and urban) where turbidity is a challenge. This research aims at safeguarding human health from water borne-diseases and increasing access to safe drinking water. Furthermore, the study provides reference line information on the water quality status of major permanent earth dams within the Monduli district.

1.7 Delineation of the study

This research evaluated the performance of a pilot-scale inclined plates settler integrated with constructed wetland as a feasible treatment technology for community water with high turbidity and other physicochemical and microbial contaminants from permanent earth dams in Monduli district.

CHAPTER TWO

LITERATURE REVIEW

2.1 Water quantity and quality

Rainfall is the main source of water in Tanzania (URT, 2016). More than half of the Country receives an average amount of 800mm of rainfall or less per year (URT, 2016). Moreover, 80% of Tanzania's population live in rural areas (URT, 2013), and it is estimated that approximately 40% and more of the rural population lack access to safe water sources (Mohamed *et al.*, 2016). Hence water shortage is a common challenge, particularly in rural areas where studies reveal that people travel long distances of an average of 2 to 3 kilometers daily in search of water while carrying heavy containers of approximately 20 to 25 liters per journey (URT, 2016). In 2012 the water requirement for 19 capitals of Tanzania administrative regions was 463 543 m^3 each day, but the amount supplied was 305 195 m^3 for each daytime (Kessy & Mahali, 2017; URT, 2016). Merely 50% of 53 million people of Tanzania get access to improved water sources, which are safe, and just 34% of Tanzania's residents have improved sanitation facilities (UNICEF, 2018). Water shortage challenges affect most people in the rural and semi-arid areas; specifically women and girls, consume a lot of time travelling to collect water (UNICEF, 2018). Studies indicate that a more significant extent of the population needs water supply facilities therefore, a research gap exists on exploring new ways of obtaining clean water that will increase the availability of safe water to both rural and urban communities (URT, 2016).

In arid and semi-arid regions of Tanzania, water quality and quantity limit water supply options (MoW, 2014; URT, 2016). Therefore, alternative water sources apart from natural surface waters have been adopted. In Tanzania mainland, 639 dams had been constructed as of September 2009 (MoW, 2014). In Monduli district, 26 dams have been constructed purposely for domestic use and livestock keeping, still more are being renovated as a plan to increase water accessibility (Ministry of Water Data Base, 2021). Dams are structures used to store water for domestic purposes, irrigation, flood control, industrial use and hydropower generation (Alparslan *et al.*, 2010). Well situated and designed dams retain water throughout the dry seasons, thus adding utilizable water resources. The earth dams are significant in areas where the amount of water variation in dry and wet seasons is enormous. However, large storage reservoirs have destructive effects on the environment (land degradation), demanding immigration and causing communal interference (FAO, 2016).

Water quality assessment is a useful means for identifying pollution sources and their impacts on the water quality and the surrounding community, hence help to manage different water resources (Varol *et al.*, 2012). Naturally occurring phenomenon and various anthropogenic activities including destructive land use, unregulated abstractions and the release of pollutant in water bodies affects the quantity and quality of water (Varol *et al.*, 2012). As presented in different studies, most of the surface water sources are contaminated with organic matter, nutrients, suspended solids and pathogens (Eliakimu *et al.*, 2018; URT, 2016; Winton *et al.*, 2019), and various villages use the same water sources for domestic purposes (Mshida *et al.*, 2017). The ingresses of contaminants into the water sources disturb the socio-economic roles, biodiversity and inter alia of the storage reservoirs. For example earth dams loses storage capacity over time due to sediment trapping process thereby challenging the management of storage structures (Winton *et al.*, 2019). The physiochemical and microbial characteristics of water offers a good description of the state of water, throughput and sustainability of the source (Amiri & Nakane, 2009). Variations in physical properties such as temperature, clearness (turbidity and color), chemical components of water such as dissolved oxygen (DO), PH, chemical oxygen demand (COD), nitrogenous species, phosphate and biological characteristics offer important information on water quality, sources of variations (contaminants) and associated influences on the functions of the storage reservoir and biodiversity (Megersa & Tullu, 2018).

A study was conducted to investigate water quality status from three types of surface water sources; earthen dams, rivers and open springs in Arusha, Tanzania (Mtavangu *et al.*, 2016). The results revealed that most of the water quality parameter tested were above the acceptable drinking water standards by TBS and WHO in all of the water sources. However, the earth dams water quality showed a greater variation from the other water sources, by showing higher values of turbidity > 1000 NTU in all seasons (Mtavangu *et al.*, 2016). Also, higher values of Faecal coliform, Total suspended solids and nitrates were observed in the earth dam, indicating high level of contamination (Mtavangu *et al.*, 2016). High turbidity in water, decreases oxygen diffusion, harbors microorganisms (pathogens) consequently posing a risk to human health (Senay *et al.*, 2002; WHO, 2011). Additionally, the seasonal changes in the water quality makes the water less palatable and unfit for domestic use especially during the dry seasons when the water tends to be sour, and it is also reported to affect livestock (Eliakimu *et al.*, 2018). The dams are reported to be heavily polluted, and thus become breeding site for vectors causing waterborne diseases such as diarrhea, dysentery, salmonella, typhoid fever, and cholera (Eliakimu *et al.*, 2018). Despite the poor water quality in earth dams, they remain the primary sources of drinking water for most people and animals living in rural areas of Monduli district as shown in Table 1. Therefore, frequent water quality checks in open water sources are mandatory, as they help in the management of water sources against pollution and help in the design and implementation of relevant treatment technology for the water sources (URT, 2016).

Table 1: List of studied earth dams in Monduli district, population of people and the animals they serve

Name of the Earth dam	Number of People	Number of Animals
Nadosaito	>6000	>10000
Nadojeshini	>5000	>3000
Mti Mmoja	>100	> 400
Nanja	>100	>1500
Naiti	>1000	>4000
Oloturo	>200	>5000
Kipok	>150	>6000

Mtavangu *et al.* (2016)

2.2 Available water treatment technologies

Globally there different water treatment technologies that are efficient and relevant for water pollutants removal, involving physical, chemical, biological and a combination of the treatment methods (Tchobanoglous *et al.*, 2003). An efficient and suitable water treatment technology needs to meet the targeted people’s real needs, should be simple to operate and maintain, should be affordable and should consider other environmental factors such as nature of the water source (Sorlini *et al.*, 2015). Water treatment technologies' applicability is dependent on the nature of pollutants such that: settle-able solids and colloids are removed by sedimentation, filtration, and coagulation technologies. While, faecal coliforms, organic compounds, and nitrogenous compounds are removed by disinfection, chemical oxidation, membrane filtration, sand filtration and biological filter treatment technologies (Sorlini *et al.*, 2015; WHO, 2016). On the other hand, turbidity removal in water involves the use of sedimentation tanks, sand filters and coagulation and flocculation technologies (Chintokoma *et al.*, 2015; Tchobanoglous *et al.*, 2003). Though in rural communities' coagulation and flocculation technologies are not common due to the chemical accessibility and the purchasing expenses involved (Chintokoma *et al.*, 2015). Therefore appropriate cost-effective treatment technologies are required, especially for higher turbidity waters.

2.2.1 Inclined plates settler (IPS)

The unit operation designed to concentrate and remove suspended solids from water and wastewater is known as sedimentation or clarification tank. These sedimentation tanks occur in either long rectangular or circular shapes (Arcil, 2009)**.** The process of separation of suspended solids and colloidal matter that are heavier than water by gravitation settling or any other body force is referred to as sedimentation (Arcil, 2009; Metcalf *et al.*, 1979). Even though sedimentation tanks eliminate suspended solids and colloidal particulates from water, a large area of land and high capital cost is involved due to the need for a large sedimentation area (Tchobanoglous *et al.*, 2003).

Inclined plates settlers are high-rate sedimentation equipment consisting of an array of inclined parallel plates forming channels of plate stacks. A particle-containing solution can be fed in the plate stack channels for separation, thereby offering a more significant settling area without increasing the area covered by the system (Wisniewski, 2013). Plate stacks usually are stuck in the middle of a parallel inlet and outlet of the sedimentation channel (Leung & Probstein, 1983). The plates effectively split the sedimentation tank into several small settling tanks, and reduces settling time by shortening the vertical distance a particle has to travel to settle, instead of travelling the entire length of the sedimentation tank (Murray & Hanna, 2009). Owing to an increase in surface area and reduced settling distance of the plates, settling tanks with inclined plates can separate particles faster than conventional tanks (Chintokoma *et al.*, 2015). IPS are habitually used in water treatment to make rectangular tanks cost-effective. The IPS reduces the unstable flow patterns and mixing tides which hinders the settling of suspended solids by directing the flow of fluids though inclined plates (Tarpagkou & Pantokratoras, 2014). As soon as the particles reaches the surface of inclined plates, they begin to accumulate to form flocs, which settles to the bottom of the sedimentation tank faster than the finer particles (Chintokoma *et al.*, 2015; Laskovski *et al.*, 2006).

The 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). Solid particles separated from the suspension slip down to the inclined plate's surface by gravitation force and settle at the sedimentation tank's foot, where there being removed at a set time interval to prevent anaerobic conditions and resuspension. Then water without suspended solids rises and leaves the unit through the set structure to other treatment units as shown in Fig. 1 (Murray & Hanna, 2009).

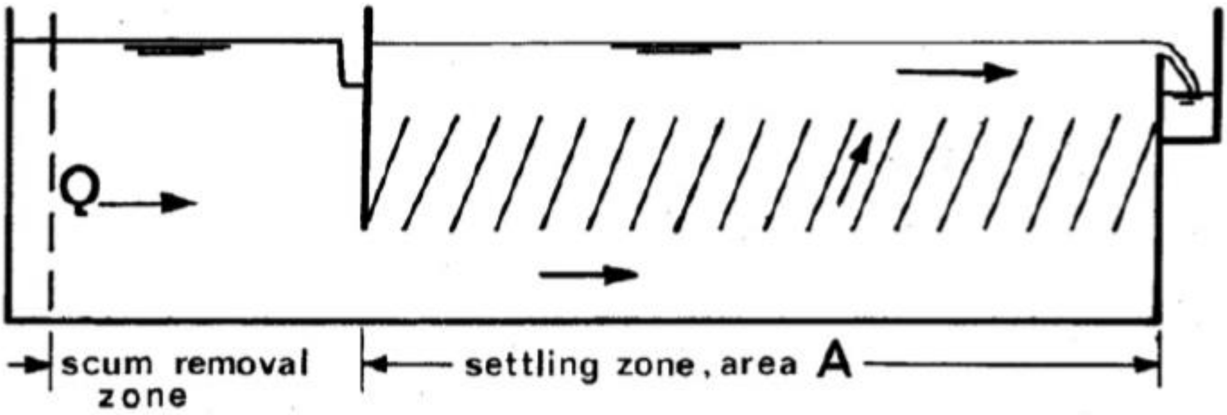


Figure 1: Cross-section view of IPS. Source: Wisniewski (2013)

2.2.2 Constructed wetlands (CWs)

Constructed wetlands are artificially planned, designed and built systems to simulate processes that take place in natural wetlands in a more controlled environment (Njau *et al.*, 2011; Vymazal, 2007). Constructed wetlands can be classified as either surface flow or subsurface flow wetlands which are further subdivided into vertical flow, horizontal flow, submerged plants, floating plants and emergent plants wetlands (Vymazal, 2011). These systems consists of water, plants and certain media (gravel, sand or soil) (Caselles-Osorio *et al.*, 2017). In horizontal subsurface flow constructed wetland the treated wastewaters stays below the surface of the media, as a result the risk of harmful pathogenic organisms to humans and animals is minimized (Kadlec & Wallace, 2008). The CWs are mostly used as secondary or tertiary wastewater treatment systems for agricultural wastewaters, urban runoff, animal wastes, industrial effluents, mining sites effluent water, ground and surface water remediation. The CWs are capable of reducing the levels of the following pollutants in water: organic constituents, suspended solids, nutrients, pathogens, oil and grease, heavy metals, pesticides and other toxic or hazardous pollutants (Kipasika *et al.*, 2014; Lema *et al.*, 2014).

The CW are biological treatment units that has been adopted globally as secondary treatment unit for water and wastewater due to their higher efficiency in the targeted pollutant removal (Garcia *et al.*, 2010). Also, CW are simple to design and operate, and cost-effective as they use locally available materials in construction (Garcia *et al.*, 2010).

Horizontal Subsurface Flow Constructed Wetlands (HSSFCWs) are beneath the surface water and wastewater treatment wetlands, whereby the water flows horizontally below the surface of the media used, from the inlet to the outlet of the treatment unit (Kadlec & Wallace, 2008). The treatment processes occurs in the root zone of the plants (Caselles-Osorio *et al.*, 2017). The HSSFCWS consists of a bed filled with media (gravel, sand or soil), and planted with emergent macrophytes plant. This system is capable of removing particulate matters, organic matters, Pesticides and Herbicides, nutrients, heavy metals and harmful pathogenic organisms (Garcia *et al.*, 2010; Kipasika *et al.*, 2014; Vymazal, 2011). The pollutants removal process in HSSFCWS involves different physical, chemical and biological processes such as: sedimentation, filtration, precipitation, adsorption, volatilization, nitrification, denitrification, fermentation, plant and microbial uptake, predation and natural die off (Garcia *et al.*, 2010; Mtavangu *et al.*, 2017).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

This research was conducted in Monduli District, Arusha, Tanzania. Monduli district is located in the northeastern section of the country and it lies between latitudes 3^o and 4^o South and longitude 36^o to 37^o East of the Greenwich. Figure 2 shows five earth dams studied, whereby Enguiki (Monduli Juu), Nadosoito, Naiti (Eluwai), Nanja, and Shakape are permanent earth dams which are used for domestic water supply purposes and livestock drinking, some images of the dams are presented in Appendices 1 and 2. At Nadosoito earth dam, a pilot community water treatment plant was set and studied on the treatment of the earth dam water. The pilot treatment plant is located on latitude 3^0 24’ 57’’ S and longitude 36^0 22’ 48’’ E.

3.1.1 Site selection criteria

Monduli district is a semi-arid area occupied by the Maasai community, with approximately 158 929 people and large number of livestock (URT, 2013). It is an agro-pastoralist community (Eliakimu *et al.*, 2018). The community has adopted earth dams and borrow pit as the source of domestic water supply and livestock drinking, due to water shortage challenges, whereby average annual rainfall is 650 mm (MoW, 2014; Msoffe *et al.*, 2011). A total number of 26 earth dams were recorded in Monduli District (Ministry of Water Database, 2020), and the number of these structures is still increasing due to population growth. However, different studies have identified turbidity as a common challenge within the earth dams in the Monduli district (Eliakimu *et al.*, 2018; Mtavangu *et al.*, 2016). Therefore, a pilot-scale treatment plant was set at Nadosoito earth dam for community water treatment. Also, five permanent earth dams were selected for water quality analysis, to determine the treatment system’s feasibility on the other earth dams which are used by the community throughout the year. Criteria’s considered in selecting these earth dams was the availability of water throughout the year and the use of such water for domestic purposes and livestock keeping. These data were obtained from Monduli Rural Water Supply and Sanitation Authority. The size of the dam was not considered in the selection as our main aim was on the water quality status of the earth dams.

3.2 Pilot scale IPS-CW design and setup

The installed water treatment system 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) as presented in Appendix 3.

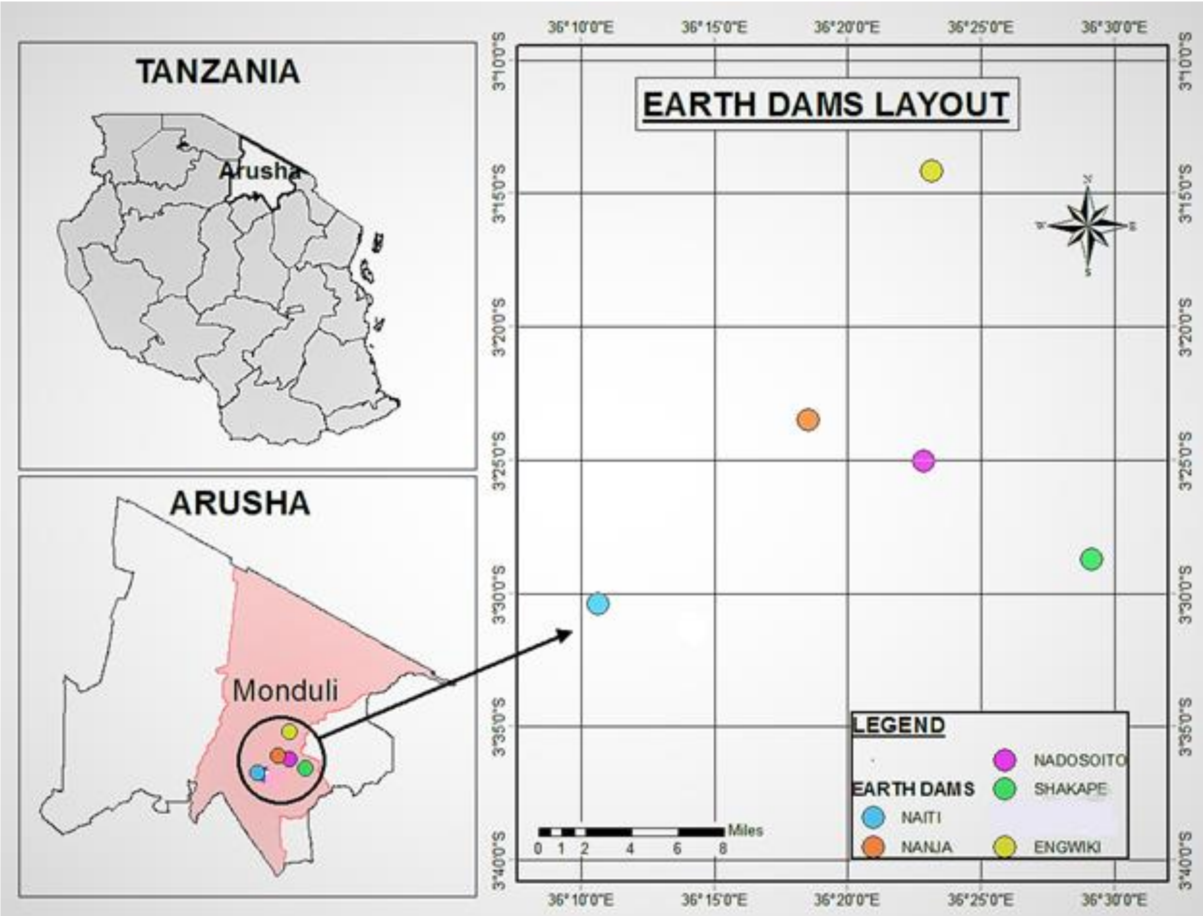


Figure 2: Map of Tanzania showing permanent earth dams which are used for domestic purposes in Monduli District

3.2.1 Sedimentation tank coupled with inclined plates settler (IPS)

The sedimentation tank coupled with IPS was constructed by 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 45^0 inclination angle as represented in Fig.3. 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 constructed wetland.

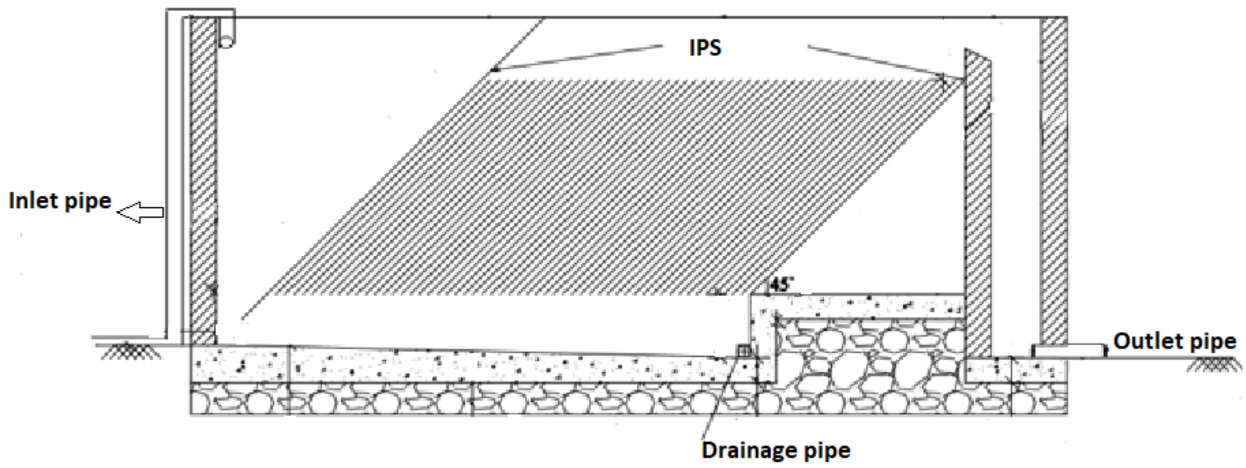


Figure 3: Section view of the sedimentation tank coupled with inclined plates settler (Njau *et al.*, 2016)

3.2.2 Horizontal subsurface flow constructed wetland (HSSFCW)

The HSSFCW was constructed by solid concrete blocks with an internal cement lining to avoid seepage, with dimensions of 12 m length, 4 m width and 1 m depth. The constructed wetland 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 average porosity of 0.4. The wetland was planted with *cyperus alternifolius* plants as shown in Fig. 4.

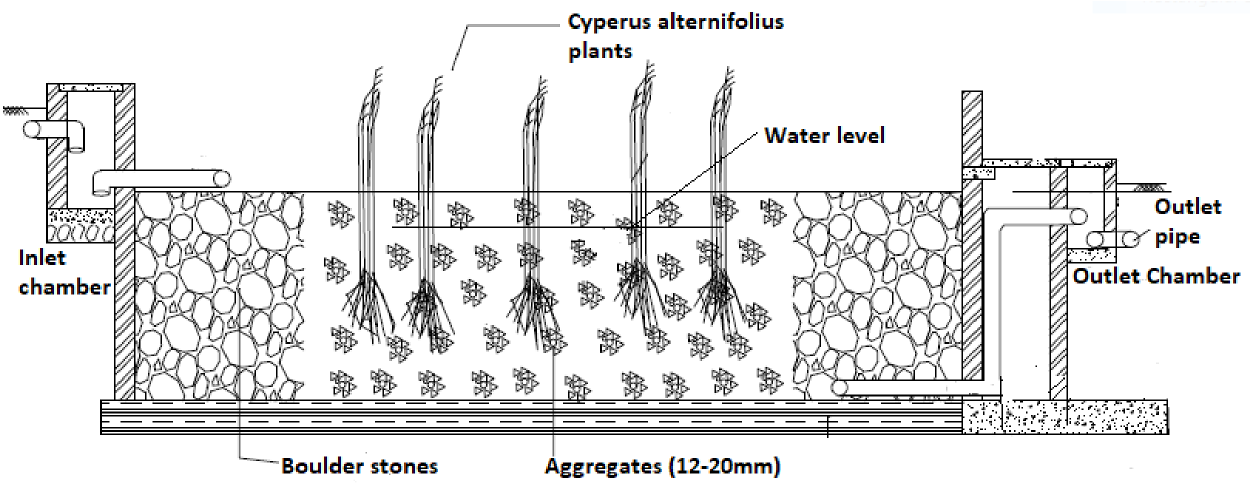


Figure 4: Cross-section area of a horizontal subsurface flow constructed wetland (Njau *et al.*, 2016)

3.2.3 Process flow diagram

The process flow diagram for treating turbid water >1000 NTU from Nadosoito earth dam found in Monduli district is shown in Fig. 5. The water from the earth dam is first collected at the water collection sump and pumped to elevated feed tanks at about 3 m high. Then the water from elevated tanks flows by gravity to the sedimentation tank coupled with inclined plates settler, whereby the flow rate that entered the system was controlled by the water flow meter installed at the IPS inlet pipe. Thereafter effluent water from the IPS feeds the constructed wetland. The treated water from constructed wetland is discharged into an underground storage tank which is installed with a hand pump for drawing water by the communities.

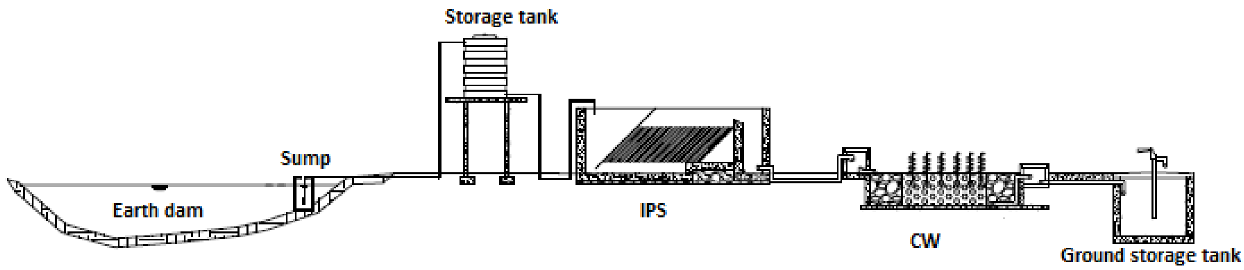


Figure 5: Process flow diagram of the pilot scale IPS-CW treatment system setup at Nadosoito earth dam

3.3 Sample collection

To establish the temporal and spatial variation of water quality within the selected permanent earth dams, sampling was conducted twice a year in the five earth dams; that is in March (as a wet month) and July, 2020 (as a dry month). Two representative composite samples were collected in each earth dam during the wet and dry seasons, making a total of twenty composite samples from the five earth dams.

In the pilot-scale IPS-CW treatment system, three points were selected for water sample collection: the inlet of the IPS, the IPS outlet (an inlet of the CW), and the CW outlet. The treatment 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. In each test six samples were collected at three sampling point making a total number of 150 water samples analyzed.

Water samples for physicochemical analysis were collected in 1000 mL polyethylene bottles while the water samples for microbial analysis were collected in a 400 mL glass bottles. All polyethylene sampling bottles were washed and rinsed with distilled water and then re-rinsed with the sampled water in the integrated system and the earth dams. Simultaneously, the glass bottles were washed, rinsed and sterilized by an autoclave machine. The collected water samples were stored in a cool box at $4^{o}C$ and transported to the NM-AIST laboratory for analysis. The entire sample collection process followed the standard methods for examining water and wastewater (APHA, 2012).

3.4 Sample analysis

The physicochemical parameters analyzed on site include: dissolved oxygen (DO), electrical conductivity (EC), pH, total dissolved solids (TDS), temperature and turbidity using a HANNA multiparameter (HI 9829) and turbidity meter (HI 93703) 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 examining water and wastewater at the NM-AIST laboratory (APHA, 2012). Bacteriological water quality was examined by analyzing faecal coliform indicator bacteria (FC). The membrane filtration method was used to analyze FC, whereby water samples were filtered through membrane filters of 0.45-micron pore size and 47 mm diameter. The filter papers containing the samples were placed on petri dishes containing the MFC-agar medium and incubated at $44.5^{o}C$ for 24 hours to allow the growth of faecal bacteria indicator (Tchobanoglous *et al.*, 2003).

3.5 Data analysis

Research data were analyzed by Origin Pro 9 of 2019 and excel software's. Descriptive statistics were carried out to summarize the results obtained from laboratory analysis, the efficiency formula established the treatment systems' pollutant removal efficiency as shown in Equation 1 below. The representative graphs showing spatial variation in the water quality within the earth dams and the treatment system performance were drawn by Origin Pro 9 software. A T-Test analysis was carried to identify if the rainfall seasons had a significant contribution on the change in the water quality parameters observed in the study.

A Pearson correlation analysis was also carried out to get the water quality relationship between the earth dams and seasonal water quality association. Pearson's correlation coefficient is a statistical test that determines statistical relationship between two variables. It gives information about the magnitude of association together with the direction of the relationship (Kothari, 2004). It indicates that as one variable changes in value, the other variable lean towards a specific direction (Kothari, 2004). Correlational analysis is useful because the value of one variable can predict the value of the other variable. Correlation coefficient values (r) are classified such that value in range of 0.9 to 1.0 indicates very high correlation, 0.7 to 0.89 indicates high correlation, 0.5 to 0.69 moderate correlation, 0.3 to 0.49 low degree correlations and 0 to 0.29 little correlation. (Eliakimu *et al.*, 2018; Obilor & Amadi, 2018).

$$\text{Parameter removal efficiency} = \frac{\text{Mean influent parameter} - \text{Mean effluent parameter}}{\text{Mean influent parameter}} * 100\% \quad (1)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Variation of physicochemical and microbial water quality in the selected permanent earth dams in Monduli district

4.1.1 pH

pH values from the five earth dams ranged from 8.3 to 9 and 7.8 to 8.4 during the dry and wet seasons, respectively as presented in Tables 2 and 3. The results show that during the wet season pH values were low compared to the dry season's pH value in all of the tested earth dams. All values were within the allowable TBS and WHO standards for drinking water of pH range 6.5 to 8.5, except for Nadosoito's pH value during the dry season which was greater than the allowable standards. The low pH values in wet season might be due to the dilution of earth dam water by low pH rain water and the deposition of partly decomposed organic matter, capable of producing organic acid that lowers the pH levels of water (Joseah, 2019). The paired sample t- test at the 0.05 level shows that, the mean values of pH during the wet and dry season from all of the earth dams were not statistically significant different (t (4) = 2.1, p = 0.1).

4.1.2 Temperature

Tables 2 and 3 show temperature values relatively high during the wet season compared to the dry season; this variation depended on the location weather, time of the day and the sample collection period. Temperature values for all five earth dams ranged from 22.8 to 23.9 ^{0}C and 21.6 to 26.7 ^{0}C during the dry and wet seasons, respectively. The water temperature affects the amount of dissolved oxygen in water, whereby as temperature increases the solubility of oxygen decreases and hence, the amount of dissolved oxygen in water decreases (Eliakimu *et al.*, 2018). Also, higher temperatures ranges of 25 to 50 ^{0}C microorganisms multiply easily and may lead to an increase or change in odor, color and taste of water (Irenosen *et al.*, 2012; WHO, 2011). Paired sample t-test at 95% confidence interval showed that there was no statistically significant difference between mean seasonal temperature values (t (4) = 1.5, p = 0.2).

4.1.3 Dissolved oxygen (DO)

The DO concentration assessed in the earth dams ranged from 4.2 to 5 mg/L during the dry season and 3.9 to 4.3 mg/L during the wet season. Minimum DO concentration was observed at Nanja earth dam with the maximum value detected at Nadosoito earth dam as presented in Appendix 6. All of the studied earth dams showed low values of dissolved oxygen in water, this is associated with the higher values of turbidity, TSS and organic matter observed from these water sources. Dissolved oxygen is an important parameter in evaluating drinking water quality as it may predict the level of pollution in water bodies and reflect different processes prevailing in water (Mader *et al.*, 2017). High pollutant loads into water lowers the level of DO because the organic matter from sewage disposal and agricultural waste runoff transformation processes depletes oxygen in water (Jantzen, 1978). Also DO concentration is affected by other water quality parameters such as temperature and turbidity (Kumar & Puri, 2012; Mader *et al.*, 2017). In this study, paired samples t-test at 95% confidence interval showed a statistically significant difference between mean values of dissolved oxygen during the dry and wet seasons for all the earth dams ($t(4) = -3.1$, $p = 0.04$).

4.1.4 Electrical conductivity (EC) and total dissolved solids (TDS)

Electrical conductivity and total dissolved solids are directly related such that an increase in TDS results to an increase in EC (Mtavangu *et al.*, 2017). The EC is an important parameter that indicates the presence of dissolved cation and anions in water, and it reflects the TDS and salinity concentration in a particular water source (Mumtazuddin *et al.*, 2012). The TDS includes organic and inorganic contaminations in water sources that lead to EC rise (Singh *et al.*, 2015). Results from Tables 2 and 3 shows that EC and TDS ranged from 260 to 570 µS/cm and 131 to 286 mg/L during the dry season respectively, and 180 to 302 µS/cm and 90.5 to 151 mg/L during the wet season respectively. The EC and TDS value from all earth dams were within the acceptable drinking standards according to WHO and TBS of 1500 to 2000 µS/cm and 1000 to 1500 mg/L for EC and TDS respectively (TBS, 2005). Paired samples t-test at 95% confidence interval showed that both means of EC and TDS during the dry and wet season were not statistically different at ($p > 0.05$). Dilution of the dam water by rainfall during the wet season might be the cause of low EC and TDS values. Low values of EC and TDS in the earth dam during the wet season were also reported by Eliakimu *et al.*

(2018) who studied seasonal dynamics of Nadosoito Earth Dam water quality in Monduli district.

4.1.5 Turbidity

Turbidity is a cloudiness characteristic of water that reflects the presence of suspended particulate matters. It is an essential physical parameter that requires regular monitoring in water bodies as it decreases oxygen diffusion, harbors pathogens and stimulates bacterial growth (WHO, 2011). In water treatment turbidity affects disinfection processes, and it sometimes inhibit UV disinfection processes (Chintokoma *et al.*, 2015). Besides, turbidity might be associated with taste and odor challenges in water sources (Irenosen *et al.*, 2012). The result from this study revealed that turbidity is a major common challenge in all of the sampled earth dams as its values were above the acceptable standards of drinking water according to TBS and WHO of turbidity ≤ 25 NTU.

Turbidities within the earth dams ranged from 64 to 452 NTU during the dry season and 448 to 3230 NTU during the wet season. A paired samples t-test at 95% confidence interval of the results showed that the mean values of turbidity during the dry and wet seasons were significantly different ($t(4) = 2.9$, $p = 0.04$). Such that the wet season had the highest values of turbidity in all earth dams compared to the dry season. The Nadosoito earth dam had the highest value of turbidity compared to the other earth dams as shown in Fig 6. This explain the fact that although few years ago Nadosoito was a permanent dam, recently it seems to be rapidly filling with silt and thus has become a seasonal dam. The reasons for these rather higher turbidities could not be explained but may be due to increased erosion in the catchment of this dam. Higher turbidity values during the wet season in all earth dams are due to the deposition of organic and inorganic matters from surface runoff. The dry season's lower turbidity values are due to the absence of input turbidity and particle settling resulting from reduced water waves. Different studies have also reported high levels of turbidity throughout the year in earth dams found in Monduli and Karatu districts, Tanzania (Chintokoma *et al.*, 2015; Eliakimu *et al.*, 2018; Mtavangu *et al.*, 2016).

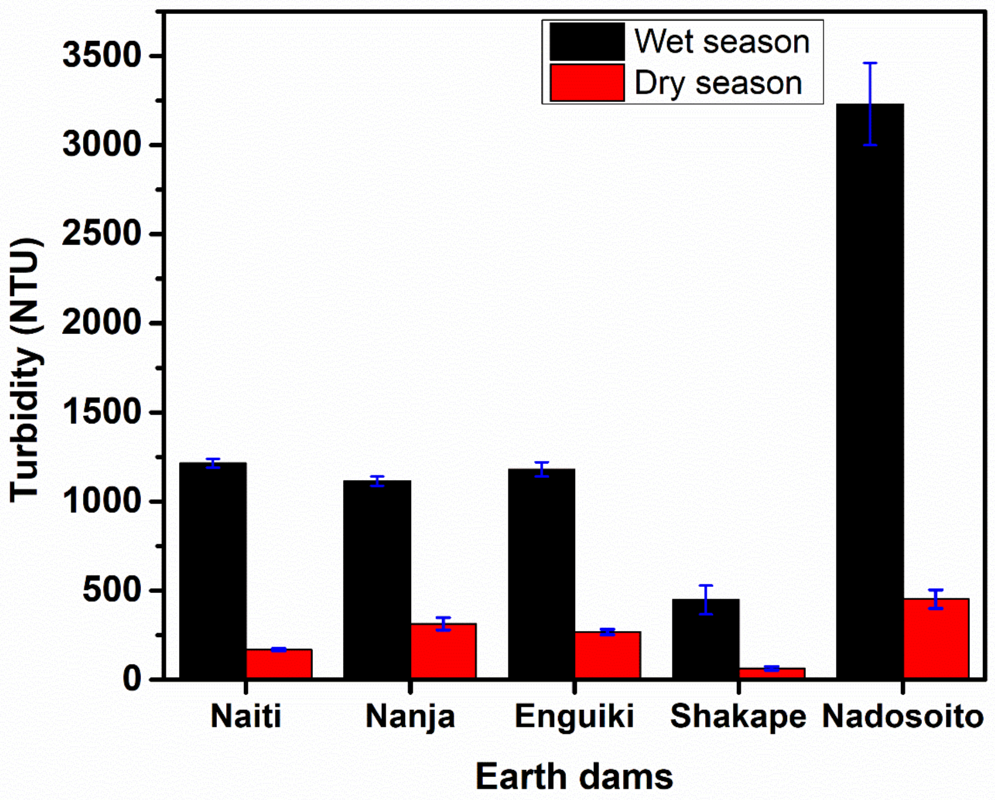


Figure 6: Seasonal variation in turbidity within the earth dams in the Monduli district

4.1.6 Total suspended solids (TSS)

The TSS are smaller suspended solid particles in water resulting from storm water runoff, erosion of reservoir or river banks, dead plants and the discharge of wastewater in water bodies (Joseah, 2019; Raut *et al.*, 2011). In the earth dams TSS value ranged from 153 to 810 mg/L and 878.5 to 5780 mg/L during the dry and wet seasons, respectively. Paired samples t-test at 95% confidence interval results, showed that the mean values of TSS during the dry and wet season were significantly different (t (4) = 3.4, $p = 0.02$). Higher values of suspended solids were experienced in the wet season than in the dry season as shown in Fig. 7 and this could be highly contributed by the storm water runoff from the nearby farms and the animal grazing areas as well as erosion of the banks of the earth dams (Yasin *et al.*, 2015).

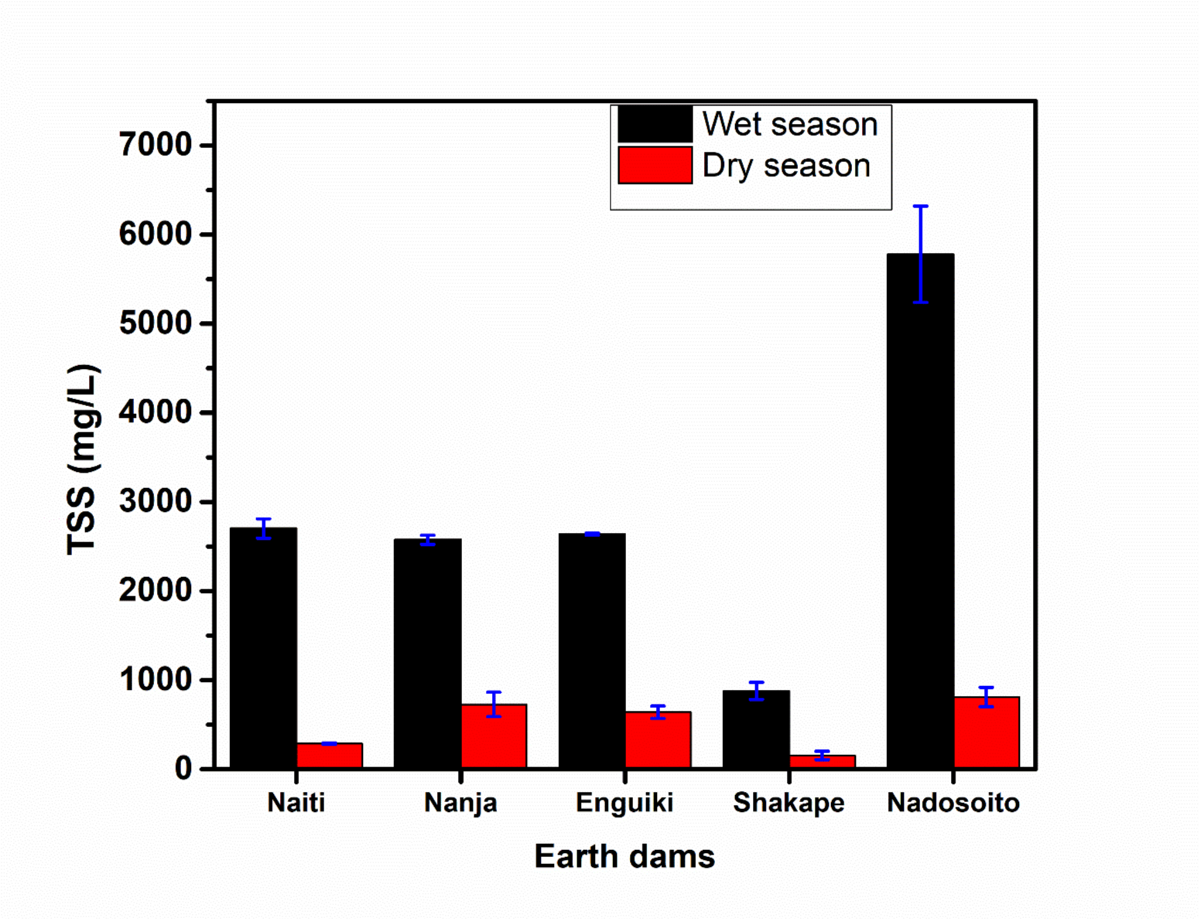


Figure 7: Seasonal variation in TSS within the earth dams in Monduli district

4.1.7 Nitrate (NO_3^-)

Nitrate concentration in the dam ranged from 1.7 to 15.6 mg/L and 7.5 to 65.3 mg/L in the dry and wet seasons respectively. The values of nitrate in the four earth dams were within the allowable standards of drinking water of 50 mg/L by WHO and 10 to 75 mg/L by TBS (EWURA, 2020; TBS, 2005), except for the Nadosoito dam whose nitrate value during the wet season exceeded the WHO standard, but it was within the TBS drinking water standards values as shown in Fig. 8. The cause of higher nitrate value in Nadosito dam might be due to the deposition of livestock wastes, dead plants, and human wastes from the surrounding environment through storm water runoff (Sahoo *et al.*, 2016; Yasin *et al.*, 2015). In this study values of nitrate were higher in the wet season compared to the dry season's value, similar trends were reported by Eliakimu *et al.* (2018); Mtavangu *et al.* (2016), who studied the water quality of earth dams in Monduli district. Paired samples t-test at 95% confidence interval results showed that there was no significant difference between the mean values of NO_3^- in the dry and wet season (t (4) = 2.7, p = 0.06).

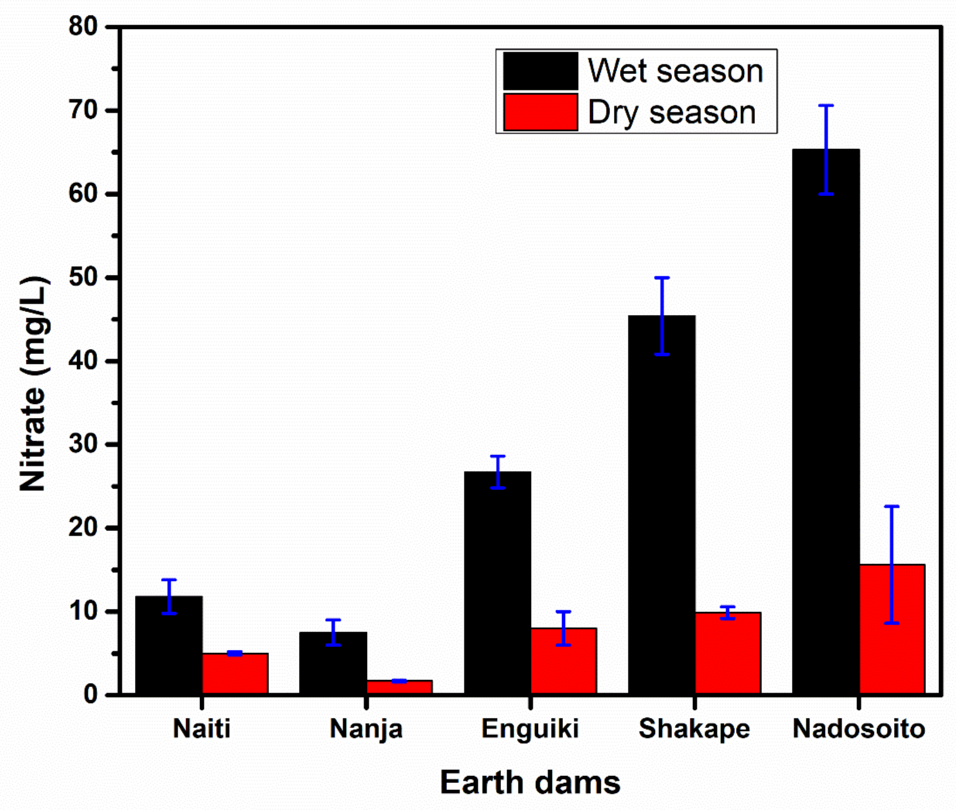


Figure 8: Season variation of nitrate within the earth dams in Monduli district

4.1.8 Ammonium (NH_4^+)

Due to the fact that Monduli district is a pastoral community and all of the sampled earth dams were used for both domestic purposes and livestock drinking, ammonium level monitoring was necessary. Livestock wastes are among the significant sources of ammonia in water sources (Eliakimu *et al.*, 2018). Ammonium concentration within the earth dams ranged from 0.3 to 1.1 mg/L and 0.7 to 5.2 mg/L in the dry and wet season respectively as shown in Fig. 9. Paired samples t-test at 95% confidence interval results showed that there was no significant difference between the mean values of NH_4^+ in the dry and wet season (t (4) = 1.8, p = 0.14). The highest values of ammonium was observed in the Nadosoito earth dam during the wet season, similar results were reported by Eliakimu *et al.* (2018). These values might have been contributed by the large number of animals drinking from the earth dam and the deposition of organic matter from the surrounding areas and human excreta due to the tendency of open defecation within the catchment area (Karavoltsos *et al.*, 2008; Mshida *et al.*, 2017).

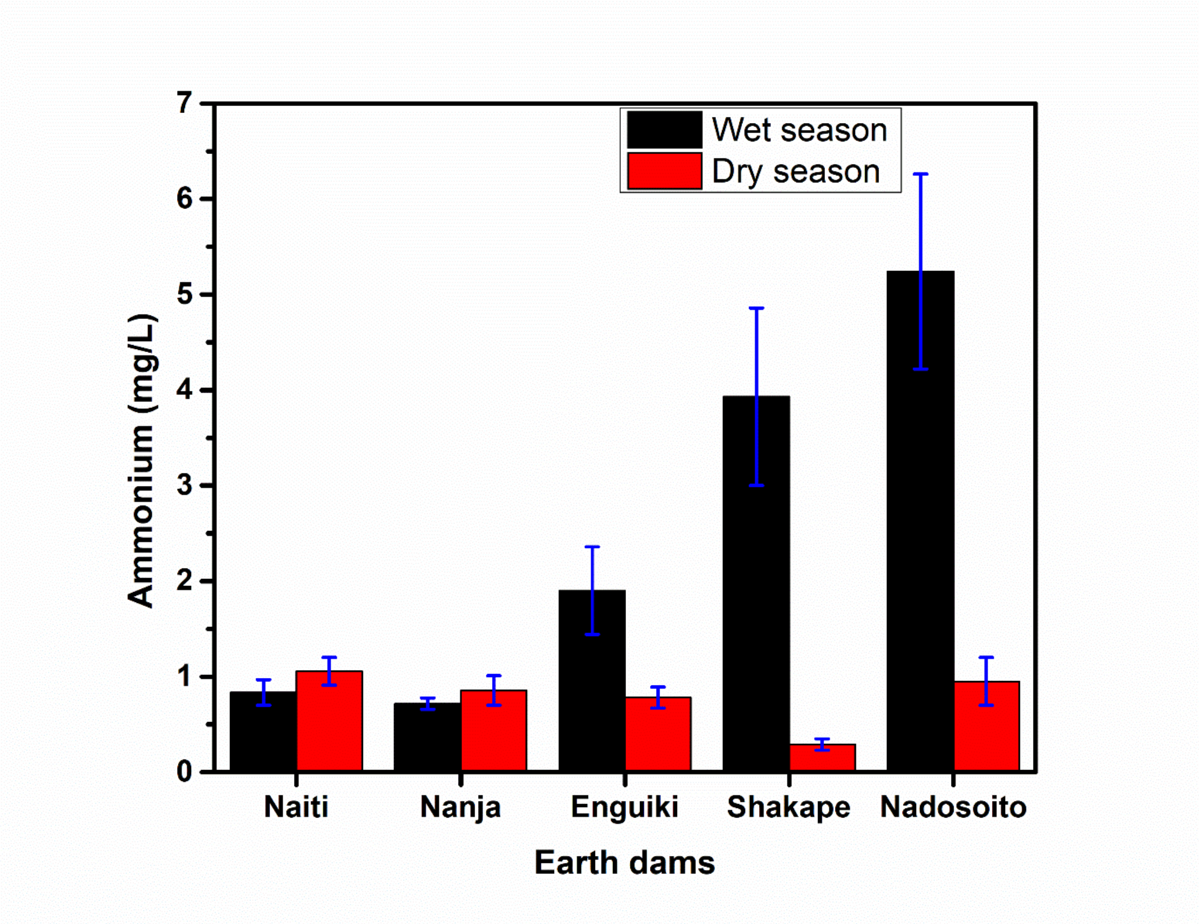


Figure 9: Seasonal variation of ammonium within the earth dams in Monduli district

4.1.9 Phosphate (PO_4^{3-})

Phosphate occurs naturally in animal wastes, microorganisms, plants, and in water sources the concentration > 0.3 mg/L (Chigor *et al.*, 2012). As presented in Fig. 10, the phosphate concentration levels in the earth dams were higher than the water's expected natural levels. They ranged between 0.5 and 1.3 mg/L and 1.6 and 3.6 mg/L during the dry and wet seasons respectively. Paired samples t-test at 95% confidence interval results, showed that there was a significant difference between the mean values of PO_4^{3-} in the dry and wet season (t (4) = 5.5, p = 0.005). The higher values in the wet season for Engwiki, Nait and Nadosoito earth dams might have been due to the deposition of inorganic nutrients, animal wastes and dead plants from the surrounding environment through surface runoff (Irenosen *et al.*, 2012).

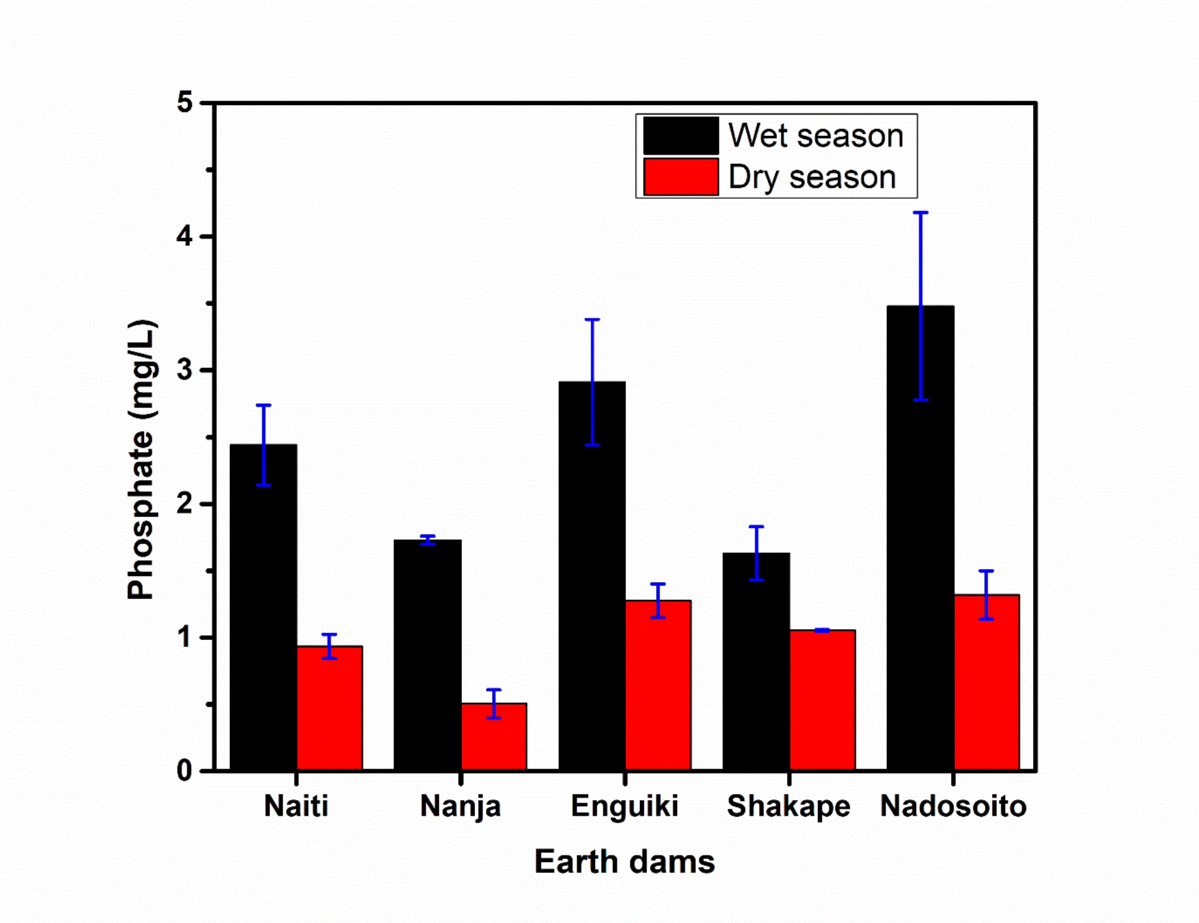


Figure 10: Seasonal variation of phosphate within the earth dams in Monduli district

4.1.10 Biological oxygen demand (BOD_5)

The BOD_5 is an important indicator of water quality used in determining the degree of organic pollution in water sources. The BOD_5 values within the earth dams ranged between 2 to 5 mg/L and 8 to 15 mg/L in the dry and wet season respectively as shown in Fig. 11. Paired samples t-test at 95% confidence interval results showed that there was a significant difference between the mean values of BOD in the dry and wet season ($t(4) = 7.6$, $p = 0.001$). The BOD_5 values for Naiti, Nanja, Engwiki and Shakape exceeded the standard value of drinking water by TBS of $BOD_5 < 6$ mg/L during the wet season indicating high levels of biodegradable matters which might have been caused by the deposition of organic wastes within the earth dams through runoff (Irenosen *et al.*, 2012; Lalparmawii & Mishra, 2012).

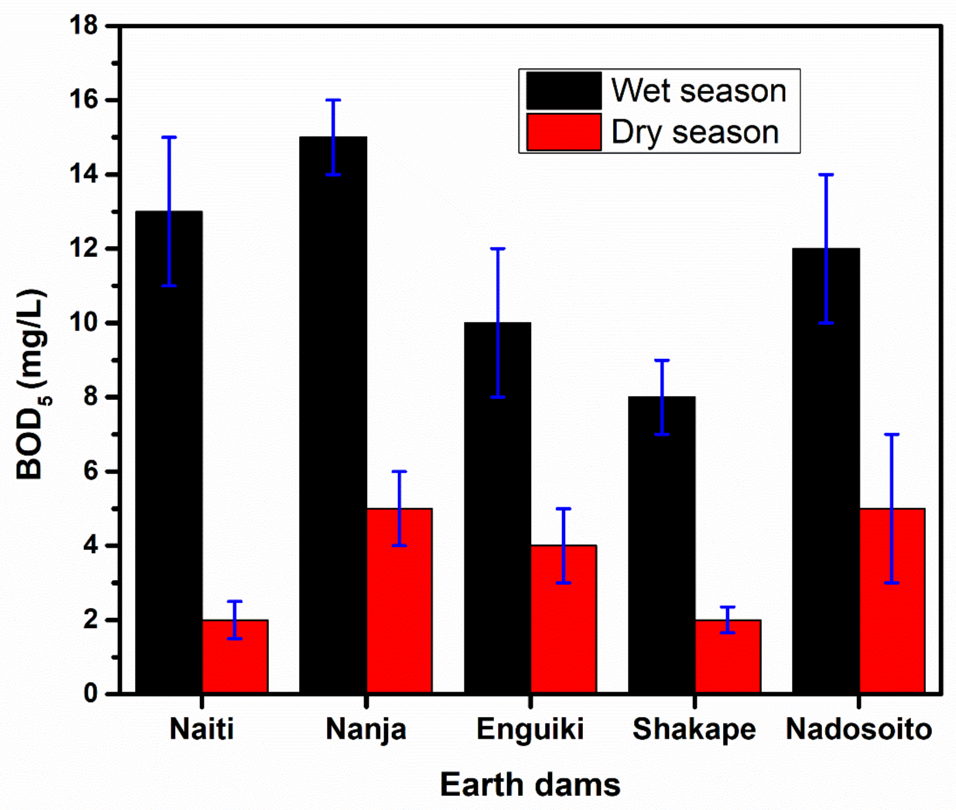


Figure 11: Seasonal variation of BOD within the earth dam in Monduli district

4.1.11 Faecal coliforms (FC)

The FC is a water quality parameter that determines water contamination with pathogens; it shows the hygienic state of water and waterborne diseases' risk (WHO, 2011). Figure 12 indicates that FC levels in the dam ranged from 100 to 650 CFU/ 100 mL and 970 to 1720 CFU/100 mL in the dry and wet seasons, respectively. All values were above the acceptable standards by TBS and WHO of 0 CFU/100 mL FC. The difference in the mean values of FC observed between the dry and wet seasons were statistically significant ($t(4) = 4.9$, $p = 0.008$) using the paired samples t-test at 95% confidence interval. The FC contamination is associated with human faeces and warm-blooded animals (cows) waste, which might have been transported by water runoff, especially in the rainy seasons leading to significant difference in values between the dry and wet seasons. Different studies reported similar results of higher values of FC in the Monduli and Karatu earth dams compared to the allowable standards (Chigor *et al.*, 2012; Eliakimu *et al.*, 2018; Mtavangu *et al.*, 2016).

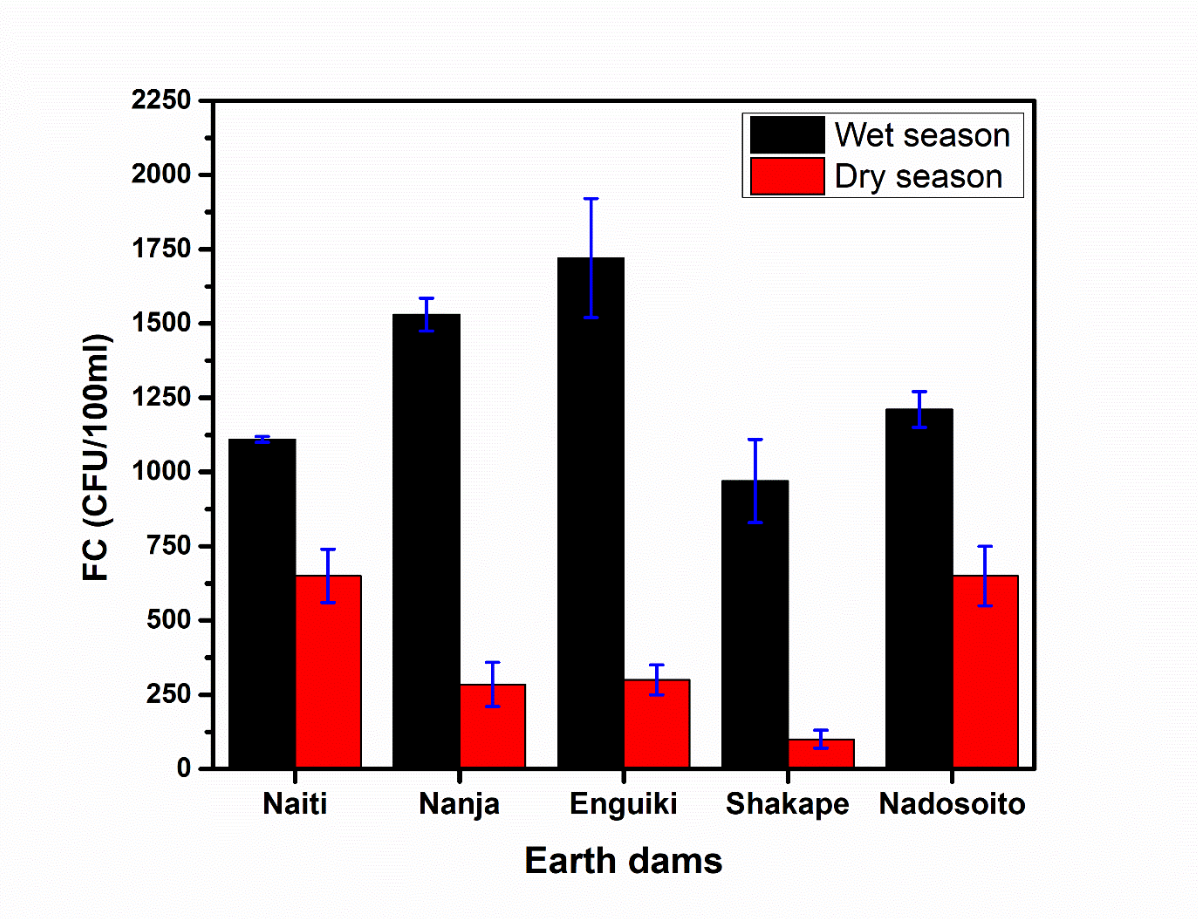


Figure 12: Seasonal variation of FC within the earth dams in Monduli district

Table 2: Summary statistics of the sampled parameters within the earth dams in the dry season

Parameters	Units	Mean	SD	Min	Max
pH	-	8.5	0.2	8.3	9.0
Temperature	℃	23.3	0.4	22.8	23.9
DO	Mg/L	4.5	0.3	4.2	5.0
EC	µS/cm	375.8	116.4	260.0	570.0
TDS	Mg/L	178.6	62.6	131.0	286.0
Turbidity	NTU	253.2	146.9	64.0	452.0
TSS	Mg/L	523.5	287.1	153.0	810.0
NO_3^-	Mg/L	8.0	5.2	1.7	15.6
NH_4^+	Mg/L	0.8	0.3	0.3	1.1
PO_4^{3-}	Mg/L	1.0	0.3	0.5	1.3
BOD	Mg/L	3.6	1.5	2.0	5.0
FC	CFU/100mL	396.9	244.1	100.0	650.0

4.1.12 Correlational analysis

Pearson correlation test conducted on the five earth dams within Monduli district during the wet and dry seasons showed very high correlation for all the tested parameters. That is very high positive correlation in water samples of Nadosoito and Naiti (r = 0.97, $p < 0.01$), Nadosoito and Nanja (r = 0.93, $p < 0.01$), Nadosoito and Engwiki (r = 0.92, $p < 0.01$) and high positive correlation between Nadosoito and Shakape (r = 0.77, $p < 0.01$). This association indicates that the earth dams had nearly similar water quality which might have been influenced by the lithology of the basin and the activities conducted in the areas around the dams (livestock keeping and small scale farming). Result of the correlation between the earth dams is presented in Table 4.

During the dry season very high positive correlation existed between pH and EC (r = 0.97, $p < 0.05$), pH and TDS (r = 0.97, $p < 0.05$), EC and TDS (r = 0.94, $p < 0.05$), turbidity and TSS (r = 0.95, $p < 0.05$), turbidity and BOD (r = 0.91, $p < 0.05$) and TSS and BOD (r = 0.98, $p < 0.05$). High correlation existed between pH and DO (r = 0.88, $p = 0.051$), pH and NO_3^- (r = 0.74, $p = 0.15$), EC and DO (r = 0.82 $p = 0.09$), DO and TDS (r = 0.75, $p = 0.14$), DO and NO_3^- (r = 0.84, $p = 0.07$), EC and NO_3^- (r = 0.73, $p = 0.16$), TDS and turbidity (r = 0.79, $p = 0.11$), NO_3 and PO_4^{3-} (r = 0.85, $p = 0.07$) and NH_4^+ and FC (r = 0.86, $p = 0.59$).

In the wet season very high negative correlation existed between pH and turbidity (r = -0.92, $p < 0.05$), and pH and TSS (r = -0.92, $p < 0.05$), these results reflects that as TSS and turbidity values were increasing due to surface runoff and pH values were decreasing due to dilution by storm water. While very high positive correlation existed between temperature and EC (r = 0.95, $p < 0.05$), temperature and TDS (r = 0.94, $p < 0.05$), EC and TDS (r = 0.99, $p < 0.05$), turbidity and TSS (r = 0.99, $p < 0.05$), and NO_3^- and NH_4^+ (r = 0.99 $p < 0.05$). High positive correlation existed between, turbidity and PO_4^- (r = 0.84, $p = 0.07$) TSS and PO_4^- (r = 0.85, $p < 0.05$), while high negative correlation existed between pH and PO_4^- (r = 0.87, $p = 0.07$), TDS and NO_3^- (r = -0.76 $p = 0.14$), TDS and NH_4^+ (r = -0.7, $p = 0.19$), TDS and PO_4^- (r = -0.72, $p = 0.17$). The very high correlation values exhibited between turbidity and TSS in both season shows a positive relationship or association between TSS and turbidity that is one value might be used to predict the other. Also EC and TDS have shown higher positive correlation in both seasons, reflecting the ability of predicting TDS value from EC. Also the results from correlation analysis have shown that most of the parameters in both season are related either positively or negatively as presented in Appendices 7 and 8.

Table 3: Summary statistics on the sampled parameters within the earth dams in the wet season

Parameters	Units	Mean	SD	Min	Max
pH	-	8.1	0.2	7.8	8.4
Temperature	℃	24.7	2.2	21.6	26.7
DO	Mg/L	4.1	0.2	3.9	4.3
EC	µS/cm	242.2	52.8	180.0	302.0
TDS	Mg/L	119.2	28.7	90.5	151.0
Turbidity	NTU	1437.5	1050.3	448.0	3230.0
TSS	Mg/L	2914.7	1774.4	878.5	5780.0
NO_3^-	Mg/L	31.3	24.1	7.5	65.3
NH_4^+	Mg/L	2.5	2.0	0.7	5.2
PO_4^{3-}	Mg/L	2.4	0.8	1.6	3.5
BOD	Mg/L	11.6	2.7	8.0	15.0
FC	CFU/100mL	1308.0	309.1	970.0	1720.0

Table 4: Correlation matrix of earth dam values in both seasons

	Naiti	Nanja	Engwiki	Shakape	Nadosoito
Naiti	1				
Nanja	0.96889*	1			
Engwiki	0.96592*	0.99667*	1		
Shakape	0.86837*	0.9241*	0.93*	1	
Nadosoito	0.96905*	0.92964*	0.92134*	0.77131*	1

2-tailed test of significance is used
***:Correlation is significant at the 0.05 level**

4.2 Integrated IPS-CW treatment system's performance at Nadosoito earth dam

The IPS-CW treatment system's general performance 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.

Inclined plates settler is a treatment unit targeted for suspended solids removal as demonstrated by previous studies(Abou-Elela *et al.*, 2015; Chintokoma *et al.*, 2015; Dorea *et al.*, 2006; Dorea *et al.*, 2014). In this study the system was evaluated for turbidity, TSS, nitrate, ammonium, phosphate and faecal coliform removal and it showed maximum removal efficiency of 66.7%, 80.8%, 73%, 44.7%, 38.1% and 68.2% respectively, at the flow rate of 5 L/min as presented in Table 5. The performance of the IPS was affected by the set flow rates and sludge removal frequencies whereby, at small flow rates (10 and 5 L/min) the removal efficiency of parameters increased and variations on the treated parameter values reduced despite of the great variability in the influent parameters values. The removal efficiency at small flow rate was high because the suspended solids had enough time to settle (increased residency time) and the turbulence in the water flow was reduced hence increasing the sedimentation rate of particles (Chintokoma *et al.*, 2015; Laskovski *et al.*, 2006).

The CW enhances the removal of pollutants retained in the effluent of the IPS treatment unit. The CW showed better performance in the removal of turbidity, FC, TSS and BOD as presented in Table 5. This is thought to have been contributed by different processes such as filtration, sedimentation, predation and microbial metabolism (Kadlec & Wallace, 2008). The removal of pollutants in CW 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).

This study revealed that Inclined plates settler integrated with constructed wetland is a viable turbid water treatment technology which is cost-effective as it uses locally available materials in construction, it is simple to operate as it requires few number of operators, it's simple to repair and maintain but also requires low energy during the water treatment process as water flows by gravity throughout the entire system. Water treatment technologies' applicability is dependent on the nature of pollutants (Sorlini *et al.*, 2015; WHO, 2016) such that turbidity removal in community waters involves the use of sedimentation tanks, sand filters and coagulation and flocculation technologies (Chintokoma *et al.*, 2015; Tchobanoglous *et al.*, 2003). Although in situation of high turbidities as experienced in this study sand filters will experience frequent clogging hence not directly applicable and conventional sedimentation tank would require a large area of land in order to provide a large surface area for particles to settle hence leading to high initial cost, while the use IPS helps to reduce the amount of land and time required in particle settling by providing large surface area and reducing the vertical distance required for a particle to settle. Also in rural community coagulation and flocculation are not common due to the expenses involved and the accessibility of the coagulants.

4.3 Physicochemical and microbial parameters variations within the integrated IPS-CW treatment system

4.3.1 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 6. 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).

4.3.2 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 (Akratos & Tsihrintzis, 2007; Jing & Lin, 2004). Temperature at the IPS-CW treatment system varied greatly due to different weather conditions with maximum temperature of 28.84 ℃ and minimum value of 20.99 ℃ as shown in Table 6.

4.3.3 Dissolved oxygen (DO)

The DO concentration in the IPS treatment system revealed minor differences at the system's inlet and outlet, with the majority of the result showing a decreasing trend from the inlet to the outlet of the system. In contrast, the constructed wetland treatment system showed a generally decreasing trend from the inlet to the CW outlet this might have been caused by the aerobic decomposition of organic matter in the system. The observed DO decreasing trend in Table 6 might have been attributed by the physical, chemical and biological processes taking place in the integrated systems (Martins *et al.*, 2003; WHO, 2006).

4.3.4 Electrical conductivity and total dissolved solids

Results from Table 6 shows 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).

Table 5: Performance of the IPS, CW and the integrated IPS-CW treatment systems in water pollutants removal

Parameters	Treatment unit	Units	Flow rates (L/min)			
			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
NO_3^-	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
NH_4^+	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
PO_4^-	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

Table 6: In situ parameters concentration from the integrated IPS-CW

Parameters	Sampling Points	Units	Flow rates (L/min)			
			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
Temp	IPS Inlet	℃	25.12±0.5	25.17±0.9	22.41±0.5	25.61±0.8
	IPS out/ Inlet CW	℃	25.8±1	24.98±0.8	22.43±0.7	25.64±0.8
	CW Outlet	℃	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

4.3.5 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. The 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 lowering 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).

4.3.6 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 4011 NTU, with mean values of IPS and CW turbidity removal rates presented in Fig. 13. The results in Table 5 indicate that turbidity removal 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 system of IPS-CW 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 matters 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 there being removed at a set time interval (Chintokoma *et al.*, 2015; Xing *et al.*, 2006). Moreover, turbidity deduction by the CW was led by filtration and sedimentation aided by the reduced interspaces between gravel and plant roots hence capable of removing suspended particles (Mtavangu *et al.*, 2017). Also despite of the fluctuation on the amount of turbidity that entered the system, after treatment the effluent parameter deviation was highly reduced especially at lower flow rates reflecting the capacity of the system to handle varied pollutant loading rate.

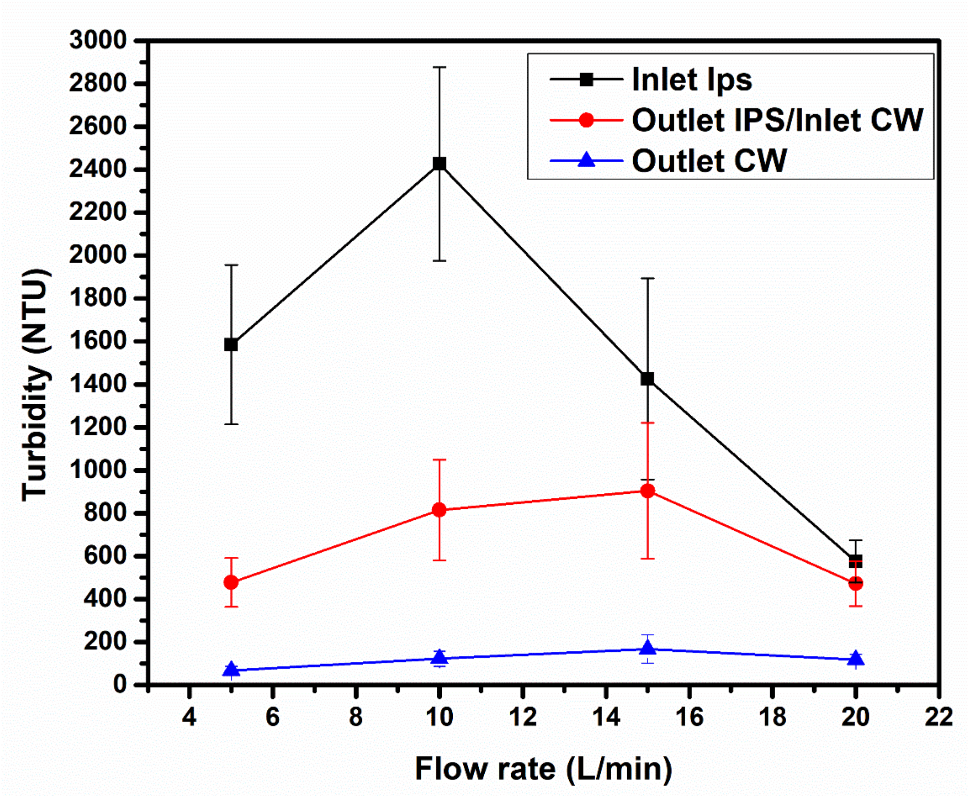


Figure 13: Variation of mean turbidity in the system as a function of water flow rate

4.3.7 Faecal coliform (FC) removal

The FC bacteria present in water may indicate the existence of pathogenic organisms. FC concentration at the inlet of the IPS ranged from 420 to 2880 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 14 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's on solid particles supported by the entrapment by the biofilm developed on the surface of the inclined plates. While in the CW major process is through filtration by the gravels and plant roots, as well as other processes such as natural die off and grazing by larger organism (Ansa *et al.*, 2015; Garcia *et al.*, 2010; Mtavangu *et al.*, 2017; Wu *et al.*, 2016).

4.3.8 Total Suspended Solids removal

Influent TSS concentration at the IPS ranged from 510 to 9780 mg/L and the integrated IPS-CW was able to reduce significant amount of TSS concentration in the water as shown in Fig. 15. The system exhibited mean maximum TSS removal efficiency of 97.4% at the 5 L/min flow rate as presented in Table 5. These results indicates that TSS removal increases with increase in hydraulic residence time through sedimentation process in the IPS and sedimentation and filtration in the CW (Garcia *et al.*, 2010; Xing *et al.*, 2006).

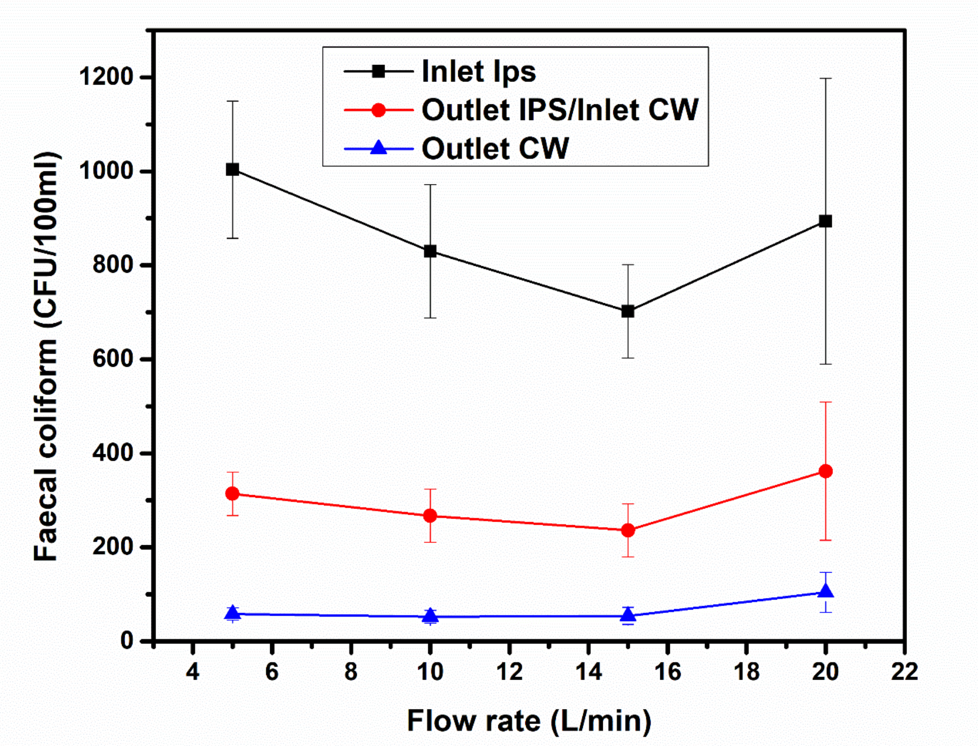


Figure 14: FC removal by the integrated IPS-CW

4.3.9 Nitrate (NO_3^-) removal

Nitrate concentration that entered the system ranged from the 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 was 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 Tanzania (TBS, 2005) and WHO standards of drinking water as shown in Fig. 16a. The IPS and the integrated IPS-CW system mean performance ranged from 52.2% to 73% and 76.8% to 91.7%, respectively as shown in Table 5. The main removal mechanism of organic and inorganic nitrogen in the IPS is through particle settling and denitrification. In the constructed wetland nitrate removal was aided by different physical, biological and chemical processes such as particle settling (sedimentation), sorption, assimilation by plants, algae, and bacteria and transformation processes conducted by microbes (denitrification) (Caselles-Osorio *et al.*, 2017; Garcia *et al.*, 2010).

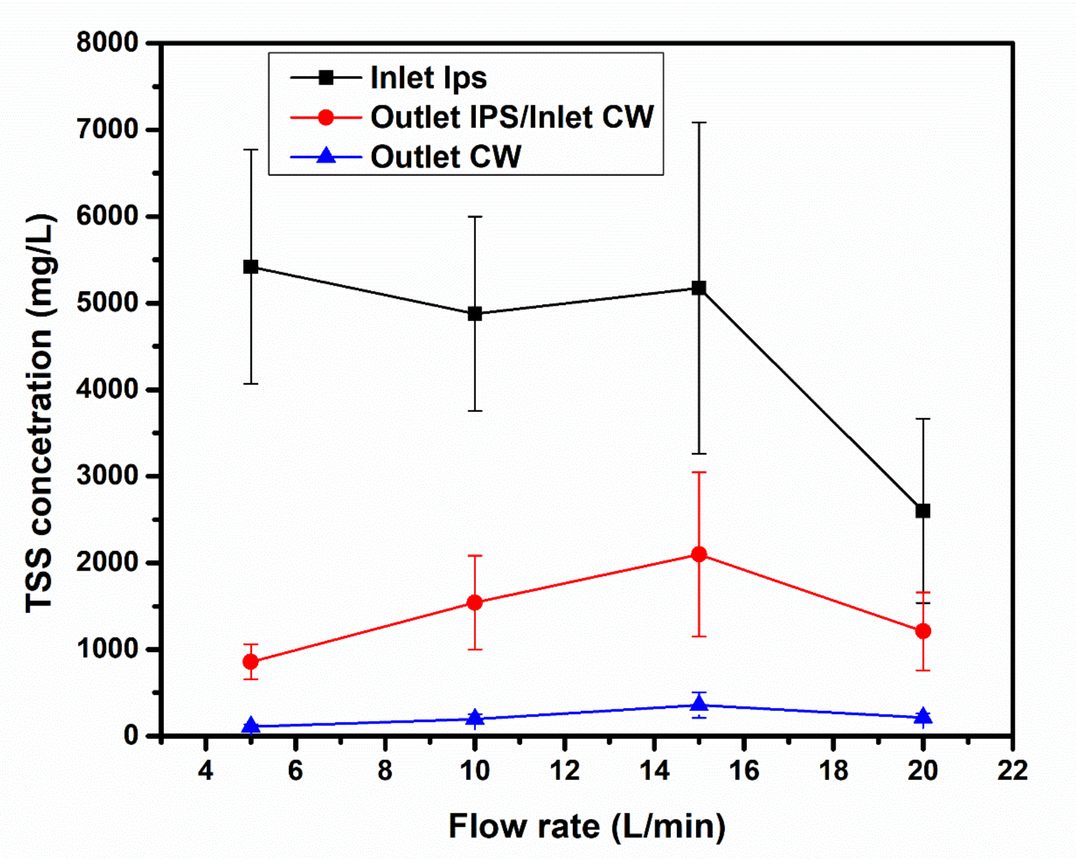


Figure 15: Total Suspended Solids removal by the integrated IPS-CW

4.3.10 Ammonium (NH_4^+) removal

Presence of ammonia in water indicates organic pollution from animal and human wastes and possibility of bacterial contamination (Eliakimu *et al.*, 2018; WHO, 2006) Ammonium concentration that entered in the system at the IPS ranged from 0.55 to 7.29 mg/L. The integrated IPS-CW treatment system was able to reduce significant amount of ammonium concentration in water as presented in Fig. 16c, 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 by sedimentation and nitrification processes due to the presence of dissolved and free oxygen in the system and suspended solids settling (Xing *et al.*, 2006). 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). Although the removal of ammonium in the system was low compared to the other parameter studied. And the lowest removal efficient was observed at the constructed wetland, this might be due to the limited amount of oxygen in the CW as it was being consumed by other processes (Vymazal, 2007).

4.3.11 Biological oxygen demand ($BOD_{5)}$ removal

Influent BOD_5 levels from the earth dams to the treatment system were varying 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 allowable Tanzania standards of drinking water of BOD $\leq$ 6 mg/L as shown in Fig. 16d. Also the system exhibited mean maximum BOD removal efficiency of 91.7% at flow rate of 5 L/min as presented in Table 5. In this system sedimentation, filtration , adsorption, oxygenation and microbial metabolism are considered to be the main mechanisms for BOD removal (Karathanasis *et al.*, 2003).

4.3.12 Phosphate ($PO_4^{3-)}$ removal

Phosphate concentration that entered the system ranged from 0.58 to 9.98 mg/L, and the integrated system was able to remove limited amount of phosphate concentration in water as shown in fig 16b. The integrated system exhibited mean maximum removal efficiency of 49% at 5 L/min flow rate. The removal of phosphate might have been attributed by 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 low removal percent of phosphate by the CW as shown in Table 5.

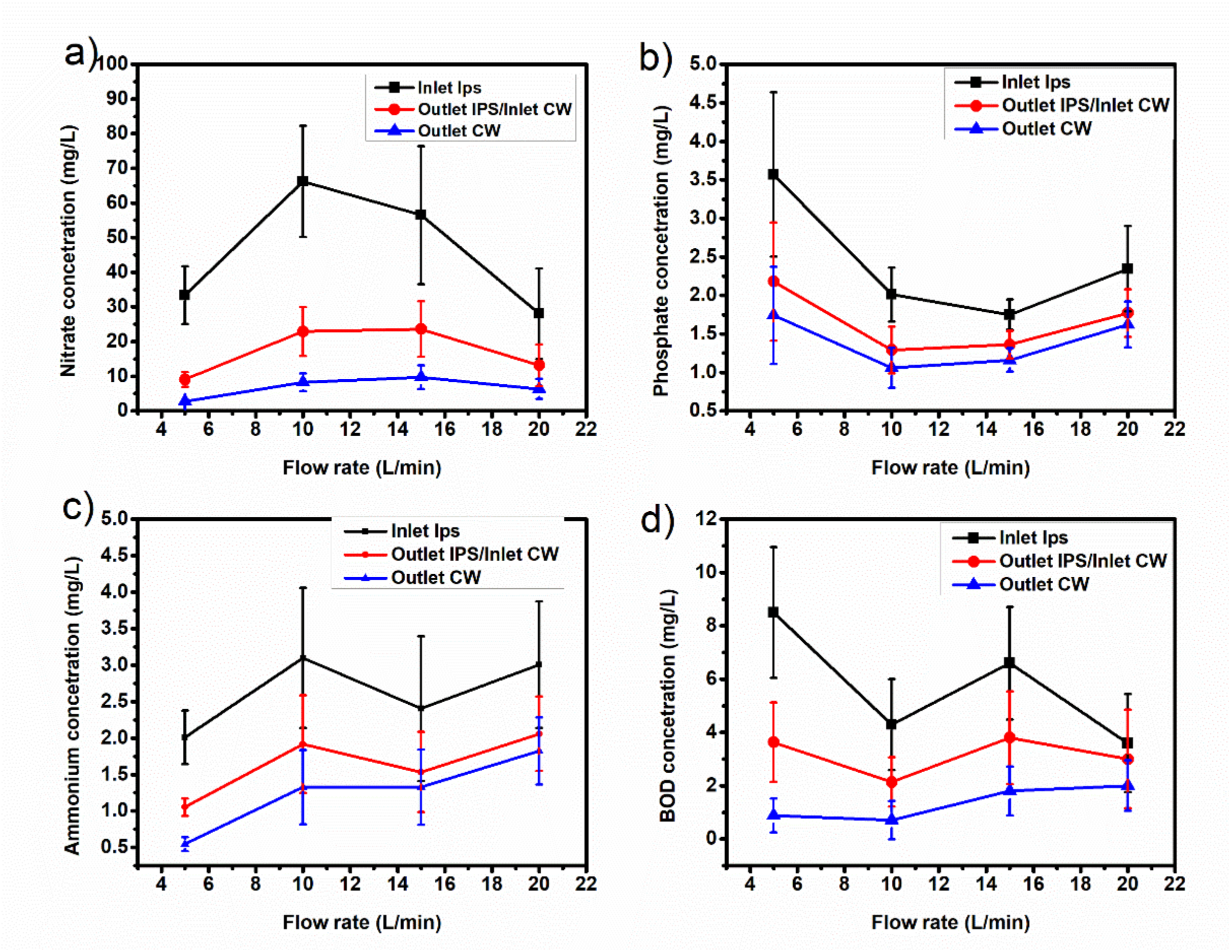


Figure 16: Average nutrients and organic matter removal by the integrated IPS-CW a) Nitrate b) Phosphate c) Ammonium d) BOD$_5$

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

This study revealed that, the physicochemical and microbial characteristics of all of the five tested earth dams in the Monduli District were positively associated and the correlation was significant at $p < 0.05$. Most of the pollutant levels for all of the sampled earth dams were increasing during the wet season and decreasing in the dry season, except for pH, DO, EC and TDS. This might be because the earth dams were rain-fed and open surface water bodies, mostly affected by the deposition of waste from agriculture and livestock through storm water.

Turbidity, faecal coliform and TSS were the major challenging pollutants contributing to the poor water quality within the tested earth dams; with the highest values being detected in the Nadosoito earth dam. These parameters were above the TBS and WHO drinking water standards in all seasons. Also, BOD_5 and NH_4^+ in the wet season exceeded the allowable TBS standards for drinking water. Seasonal variation on the mean values of the most measured water quality parameters was statistically significant, indicating that seasons contributed to the change of concentration of the water quality parameters. The water quality results from the tested water sources pose a high risk of exposure to potential health impact to the water users, this suggests the need for community water treatment systems.

The tested pilot treatment plant, shows that the integrated IPS-CW system is an appropriate pre-treatment combination for water with higher turbidity values typically used in rural areas without water supply systems. It was possible to reduce the turbidities as high as 1585 NTU to acceptable levels of Tanzanian standards. The removal of turbidities at higher flow rates can be improved by the introduction of coagulants at the IPS to improve sedimentation process. This will enable the system to operate well even when the turbidities are above 3000 NTU. Together with turbidity removal, the system was able to remove substantial amount of nutrients and pathogens which are not required in portable water. It was also observed that despite of the high efficiencies for water pollutant removal further treatment is necessary to make the water safe for human consumption. There is a need of 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 in 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.

If portable water is to be available from these earth dams, a community water treatment system is need to remove the unwanted pollutants. According to this research study, Integrated IPS-CW plant is an appropriate water pre-treatment system in the tested dams and any other water sources with higher turbidity values and the associated contaminants.

5.2 Recommendations

In order to ensure the availability of good water quality in the earth dam's different measures have to be taken into consideration including:

(i) The river basins and the water management authorities should be advised to construct structures that will protect the banks of the earth dams from erosion.

(ii) The water authorities together with the communities in the vicinity of theses earth dams should plant trees along the dams which can act as traps for sediment and nutrients.

(iii) Also any activities leading to water quality deterioration within the earth dams' catchment area should be limited, example agricultural activities and animals drinking directly from the dam.

(iv) The IPS-CW system should be adopted as a community water treatment technique in high turbid water sources.

(v) Also in order to simplify the IPS system's application, a simulation study should be carried out using this study results and the previous study results to predict the exact size that will be required in water treatment depending on the pollution status of the water source.

(vi) A disinfection unit should be added to the integrated IPS-CW system to ensure zero pathogens in the system.

(vii) The ministry of water, internal drainage basin and the Monduli rural water authority should make follow up on the number of dams available and do the proper naming of the water sources in order to have a current and reliable database.

REFERENCES

Abou-Elela, S., Fawzy, M., & El-Gendy, A. (2015). Potential of using biological aerated filter as a post treatment for municipal wastewater. *Ecological Engineering, 84*, 53-57.

Akratos, C. S., & Tsihrintzis, V. A. (2007). Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. *Ecological Engineering, 29*(2), 173-191.

Alparslan, E., Coskun, H. G., & Alganci, U. (2010). An investigation on water quality of Darlik Dam drinking water using satellite images. *Scientific World Journal, 10*, 1293-1306. https://doi.org/10.1100/tsw.2010.125

Amiri, B. J., & Nakane, K. (2009). Modeling the linkage between river water quality and landscape metrics in the Chugoku district of Japan. *Water Resources Management, 23*(5), 931-956.

Ansa, E., Andoh, E., Banu, A., Dorgbetor, R., Lubberding, W., & HJ Gijzen, H. (2015). A review of the mechanisms of faecal coliform removal from algal and duckweed waste stabilization pond systems. *American Journal of Environmental Science, 11*(1), 28-34.

APHA. (2012). *Standard methods for the examination of water and wastewater,* (22nd ed.). American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF), Washington, DC, USA.

Arcil, F. C. (2009). Settling velocities of particulate systems. *Kona Powder and Particle, 27*(0), 18-37.

Boschi-Pinto, C., Lanata, C. F., Mendoza, W., & Habte, D. (2006). Diarrheal diseases. *Disease and Mortality in Sub-Saharan Africa. 2nd edition*.

Carty, G., O'Leary, G., & Crowe, M. (2002). *Water treatment manuals: Coagulation, flocculation and clarification* (Vol. 1840950900). Environmental Protection Agency, Wexford, Ireland.

Caselles-Osorio, A., Vega, H., Lancheros, J. C., Casierra-Martínez, H. A., & Mosquera, J. E. (2017). Horizontal subsurface-flow constructed wetland removal efficiency using Cyperus articulatus L. *Ecological Engineering, 99*, 479-485.

Chigor, V. N., Umoh, V. J., Okuofu, C. A., Ameh, J. B., Igbinosa, E. O., & Okoh, A. I. (2012). Water quality assessment: Surface water sources used for drinking and irrigation in Zaria, Nigeria are a public health hazard. *Environmental Monitoring and Assessments, 184*(5), 3389-3400.

Chintokoma, G., Machunda, R., & Njau, K. (2015). Design and Optimization of sedimentation tank coupled with inclined plate settlers as a pre-treatment for ultra-filtration. *Journal of Environment and Earth Sciences, 5*(17), 140-146.

Deng, H., Ge, L., Xu, T., Zhang, M., Wang, X., Zhang, Y., & Peng, H. (2011). Analysis of the metabolic utilization of carbon sources and potential functional diversity of the bacterial community in lab-scale horizontal subsurface-flow constructed wetlands. *Journal of Environmental Quality, 40*(6), 1730-1736.

Dorea, C., Bertrand, S., & Clarke, B. (2006). Particle separation options for emergency water treatment. *Water Sciences and Technology, 53*(7), 253-260.

Dorea, C. C., Williams, J., Boulay-Côté, F., Bédard, G., & Bouchard, C. (2014). Inclined plate settling for emergency water treatment: towards optimisation. In Shaw, R. J., Anh, N.V., & Dang, T. H. (Eds), *Sustainable water and sanitation services for all in a fast chang-ing world: Proceedings of the 37th WEDC.* International Conference, Hanoi, Vietnam.

Dzimiri, P., Hamza, A., & Marandu, S. (2010). *Tanzania Monduli District Water Supply and Sanitation Project*. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and-Operations/Tanzania-Monduli_District_Water_Supply_and_Sanitation_-24-05-2010_.pdf. Accessed on August 28, 2020.

Eliakimu, N., Machunda, R., & Njau, K. (2018). Water quality in earthen dams and potential health impacts: case of Nadosoito Dam, Tanzania. *Water Practice and Technology, 13*(3), 712-723.

Ewel, K. C. (1997). *Water quality improvement by wetlands (pp 329-344)*. Island Press, Washington, DC, USA.

EWURA. (2020). *Water and wastewater quality guidlines for water supply and sanitation authority- 2nd Edition.* Dar es Salaam, Tanzania., 42pp. https://www.ewura.go.tz/wp-content/uploads/2020/06/Water-and-Wastewater-Quality-Monitoring-Guidelines-2020.pdf. Accessed on October 10, 2020.

Froebrich, J., Ikramova, M., & Razakov, R. (2006). Improved groundwater management strategies at the Amu Darya River. In Baba, A., Howard, K.W. F., Gunduz, O (Eds), *Groundwater and Ecosystems (pp. 153-165).* Springer, Dordrecht. Netherland. https://doi.org/https://doi.org/10.1007/1-4020-4738-X_12

Garcia, J., Rousseau, D. P., Morato, J., Lesage, E., Matamoros, V., & Bayona, J. M. (2010). Contaminant removal processes in subsurface-flow constructed wetlands: A review. *Critical Reviews in Environmental Science and Technology, 40*(7), 561-661.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M. C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., & Noble, I. (2013). Sustainable development goals for people and planet. *Nature*, *495*(7441), 305-307.

Huang, Y. P., Kuo, W. C., Lee, C. H., Ting, C.-S., & Hsieh, H. H. (2007). River water-quality improvement using a large-scale constructed wetland in southern Taiwan. *Environmental Engineering and Management, 17*(4),1-13.

Irenosen, O. G., Festus, A. A., & Coolborn, A. F. (2012). Water quality assessment of the Owena multi-purpose Dam, Ondo State, southwestern Nigeria. *Journal of Environmental Protection, 3*(01), 14-25.

Jantzen, P. G. (1978). Investigating Factors that Affect Dissolved Oxygen Concentration in Water. *American Biology Teacher, 40*(6), 346-352.

Jayaweera, M. W., Kasturiarachchi, J. C., Kularatne, R. K., & Wijeyekoon, S. L. (2007). Removal of aluminium by constructed wetlands with water hyacinth (*Eichhornia crassipes* (Mart.) Solms) grown under different nutritional conditions. *Environtal Science and Health Part A 42*(2), 185-193. https:// doi. org/10. 1080/ 10934520601011361

Jing, S. R., & Lin, Y. F. (2004). Seasonal effect on ammonia nitrogen removal by constructed wetlands treating polluted river water in southern Taiwan. *Environmental Pollution, 127*(2), 291-301.

Joseah, K. C. (2019). *Assessment of Water Quality of Earth Dams in Chepalungu Sub-county, Bomet County, Kenya. [Unpublished Dissertation for Award of MSc Degree at university of Nairobi, Kenya]*.

Kadlec, R. H., & Wallace, S. (2008). *Treatment wetlands*. CRC press, Florida. 1016pp. https://doi.org/10.1201/9781420012514

Karathanasis, A., Potter, C., & Coyne, M. (2003). Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. *Ecological Engineering, 20*(2), 157-169.

Karavoltsos, S., Sakellari, A., Mihopoulos, N., Dassenakis, M., & Scoullos, M. J. (2008). Evaluation of the quality of drinking water in regions of Greece. *Desalination, 224*(1-3), 317-329.

Kessy, F., & Mahali, R. (2017). *Water Sanitation and hygien services in Tanzania; Access, policy trends and financing. ESRF Discussion Paper 72*. https:// thdr. or. tz/ docs/ THDR2017BP-11.pdf. Accessed on November 22, 2020

Kipasika, H., Buza, J., Lyimo, B., Miller, W., & Njau, K. (2014). Efficiency of a constructed wetland in removing microbial contaminants from pre-treated municipal wastewater. *Physics and Chemistry of the Earth, Parts A/B/C, 72*, 68-72.

Kothari, C. R. (2004). *Research methodology: Methods and techniques*. New Age International Publishers, New Delhi.

Kumar, M., & Puri, A. (2012). A review of permissible limits of drinking water. *Indian Journal of Occupational and Environmental Medicines, 16*(1), 40-55.

Kurzbaum, E., Kirzhner, F., & Armon, R. (2012). Improvement of water quality using constructed wetland systems. *Review on Environmental Health, 27*(1), 59-64.

Lalparmawii, S., & Mishra, B. (2012). Seasonal variation in water quality of Tuirial River in vicinity of the hydel project in Mizoram, India. *Science Vision, 12*(4), 159-163.

Laskovski, D., Duncan, P., Stevenson, P., Zhou, J., & Galvin, K. P. (2006). Segregation of hydraulically suspended particles in inclined channels. *Chemical Engineering Science, 61*(22), 7269-7278.

Law, Y., Lant, P., & Yuan, Z. (2011). The effect of pH on N2O production under aerobic conditions in a partial nitritation system. *Water Research, 45*(18), 5934-5944.

Lema, E., Machunda, R., & Njau, K. N. (2014). Influence of Macrophyte Types towards Agrochemical Phytoremediation in a Tropical Environment. *International Journal of Engineering Research and General Science, 2*(5), 441-455.

Leung, W. F., & Probstein, R. F. (1983). Lamella and tube settlers. 1. Model and operation. *Industrial & Engineering Chemistry Process Design and Development, 22*(1), 58-67.

Mader, M., Schmidt, C., van Geldern, R., & Barth, J. A. (2017). Dissolved oxygen in water and its stable isotope effects: a review. *Chemical Geology, 473*, 10-21.

Mandal, H. K. (2014). Influence of wastewater pH on turbidity. *International Journal of Environmental Research and Development, 4*(2), 105-114.

Martins, A., Heijnen, J., & Van Loosdrecht, M. (2003). Effect of dissolved oxygen concentration on sludge settleability. *Applied Microbiology and Biotechnoloy, 62*(5-6), 586-593.

Masbough, A., Frankowski, K., Hall, K. J., & Duff, S. J. (2005). The effectiveness of constructed wetland for treatment of woodwaste leachate. *Ecological Engineering, 25*(5), 552-566.

Megersa, T., & Tullu, T. (2018). Effects of Land Use/Cover Type On Surface Water Quality: In The Case Of Chancho and Sorga Watershed, East Wollega Zone, Oromia, Ethiopia. *International Journal of Environtal Sciences and Natural Resources. IJESNR, 12*(4), 1-12. https://doi.org/10.19080/IJESNR.2018.12.555842.

Metcalf, L., Eddy, H. P., & Tchobanoglous, G. (1979). *Wastewater engineering: Treatment, Disposal, and Reuse*. McGraw-Hill New York.

Mohamed, H., Clasen, T., Njee, R. M., Malebo, H. M., Mbuligwe, S., & Brown, J. (2016). Microbiological effectiveness of household water treatment technologies under field use conditions in rural Tanzania. *Tropical Medicine & International Health, 21*(1), 33-40.

MoW. (2014). *Water sector development programme PHASE II (2014/15 to 2017/2019), United Republic of Tanzania.* https://www. wateraid. org/tz/ sites/g/ iles/jkxoof361/files/wsdp-ii.pdf. Accessed on December 6, 2020.

Mshida, H. A., Kassim, N., Kimanya, M. E., & Mpolya, E. (2017). Influence of Water, Sanitation, and Hygiene Practices on Common Infections among Under-Five Children in Longido and Monduli Districts of Arusha, Tanzania. *Journal of Environmental and Public HEalth*, *2017*, 1-8. Article 9235168. https://doi.org/10.1155/2017/9235168

Msoffe, F. U., Kifugo, S. C., Said, M. Y., Neselle, M. O., Van Gardingen, P., Reid, R. S., Ogutu, J. O., Herero, M., & De Leeuw, J. (2011). Drivers and impacts of land-use change in the Maasai Steppe of northern Tanzania: An ecological, social and political analysis. *Journal of Land Use Science, 6*(4), 261-281.

Mtavangu, S., Rugaika, A. M., Hilonga, A., & Njau, K. N. (2016). *Integrated constructed wetland and sand filter for treatment of community domestic water in rural Tanzania. Unpublished Dissertation for Award of Masters' Degree at Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania, pp 12-33.*

Mtavangu, S., Rugaika, A. M., Hilonga, A., & Njau, K. N. (2017). Performance of constructed wetland integrated with sand filters for treating high turbid water for drinking. *Water Practice and Technology, 12*(1), 25-42.

Mumtazuddin, S., Azad, A., Bharti, P., & Ranjan, R. (2012). Physico-Chemical Analysis of Groundwater of the Budhi Gandak Belt in Muzaffarpur District, India. *International Research Journal of Environment Sciences, 1*, 7-11.

Murray, S., & Hanna, J. (2009). *Guide to Inclined Plate Settlers. Northern Ireland.* https://www.scribd.com/document/367669599/Guide-to-Inclined-Plate-Settlers (accessed 18 February 2021).

Njau, K., Mwegoha, W., Kimwaga, R., & Katima, J. (2011). Use of engineered wetlands for onsite treatment of wastewater by the local communities: Experiences from Tanzania. *Water Practice and Technology, 6*(3), 1-9.

Njau, K. N., Machunda, R., & Chrisogoni, P. (2016). *Validation of inclined plate settlers (IPS) with constructed wetland as treatment technology for community based potable water supply in Nadosaito, Monduli, Tanzania.* www.google.com

Obilor, E. I., & Amadi, E. C. (2018). Test for significance of Pearson's correlation coefficient. *International Journal of Innovative Mathematics, Statistics and Energy Policies*, *6*(1), 11-23.

Raut, K., Shinde, S., Pathan, T., & Sonawane, D. (2011). Seasonal variations in physico-chemical characteristics of Ravivar Peth Lake at Ambajogai District. Beed Marathwada Region, India [paper]. *Journal of Research Biology, 4,* 258-262.

Sahoo, P. K., Kim, K., & Powell, M. (2016). Managing groundwater nitrate contamination from livestock farms: implication for nitrate management guidelines. *Current Pollution Reports*, *2*(3), 178-187.

Senay, G. B., Shafique, N. A., Autrey, B. C., Fulk, F., & Cormier, S. M. (2002). The selection of narrow wavebands for optimizing water quality monitoring on the Great Miami River, Ohio using hyperspectral remote sensor data. *Journal of Spatial Hydrology, 1*(1), 1-5.

Shen, J., Mkongo, G., Abbt-Braun, G., Ceppi, S. L., Richards, B. S., & Schäfer, A. I. (2015). Renewable energy powered membrane technology: Fluoride removal in a rural community in northern Tanzania. *Separation and Purification Technology*, *149*, 349-361.

Singh, P., Chaturvedi, R., Mishra, A., Kumari, L., Singh, R., Pal, D., Giri, D. D., Singh, N. L., Tiwary, D., & Mishra, P. K. (2015). Assessment of ground and surface water quality along the river Varuna, Varanasi, India. *Environmental Monitoring and Assessment, 187*(4), 1-10.

Sorlini, S., Rondi, L., Gomez, A. P., & Collivignarelli, C. (2015). Appropriate technologies for drinking water treatment in Mediterranean countries. *Environmental Engineering and Management Journal, 14*(7), 1-10. https://doi.org/10.30638/eemj.2015.183

Stenstrom, M. K., & Poduska, R. A. (1980). The effect of dissolved oxygen concentration on nitrification. *Water Reseaerch, 14*(6), 643-649.

Tarpagkou, R., & Pantokratoras, A. (2014). The influence of lamellar settler in sedimentation tanks for potable water treatment: A computational fluid dynamic study. *Powder Technology*, *268*, 139-149.

TBS, T. B. O. S. (2005). *National Environmental Standards Compendium: Specification for Drinking Water, Dar es Salaam, (pp23-29*). http://www. tzdpg. or. tz/fileadmin/ documents/ dpg_ internal/ dpg_ working_ groups_ clusters/ ents__ Government_of_ Tanzania/National_Environmental_Standards_Compendium.pdf. Accessed on January 20, 2020

Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2003). *Metcalf & Eddy wastewater engineering: treatment and reuse. International Edition. McGrawHill, 4*, 361-411.

Thiam, S., Diène, A. N., Fuhrimann, S., Winkler, M. S., Sy, I., Ndione, J. A., Schindler, C., Vounatsou, P., Utzinger, J., Faye, O., & Cissé, G. (2017). Prevalence of diarrhoea and risk factors among children under five years old in Mbour, Senegal: a cross-sectional study. *Infectious Diseases of Poverty, 6*(1), 1-17. https://doi.org/10.1186/s40249-017-0323-1

UNICEF. (2018). *Water, sanitation and hygien budget brief Tanzania. Dar es Salaam, Tanzania.* https://www.unicef.org/tanzania/media/1291/file/UNICEF-Tanzania-2018-WASH-Budget-Brief.pdf. Accessed on February 18, 2021.

URT. (2013). *2012 population and housing census.* http: //tanzania. countrystat. org/fileadmin/user_ upload/ countrystat_f enix/congo/ docs/ Census%20 General%20Report- 2012PHC.pdf. Accessed on September 5, 2020.

URT. (2016). *Research priorities for Tanzania (2015 - 2020).* http://tawiri.or.tz/wp-content/uploads/2017/06/Tanzania-Research-Pririties-from-COSTECH.pdf. Accessed on November 23, 2019.

Varol, M., Gökot, B., Bekleyen, A., & Şen, B. (2012). *Spatial and temporal variations in surface water quality of the dam reservoirs in the Tigris River basin, Turkey*. *Catena, 92*, 11-21.

Vymazal, J. (2007). Removal of nutrients in various types of constructed wetlands. *Science of Total Environment, 380*(1), 48-65.

Vymazal, J. (2011). Constructed wetlands for wastewater treatment: Five decades of experience. *Environmental Science & Technology*, *45*(1), 61-69.

Wang, F., Liu, Y., Ma, Y., Wu, X., & Yang, H. (2012a). Characterization of nitrification and microbial community in a shallow moss constructed wetland at cold temperatures. *Ecological Engineering*, *42*, 124-129.

Wang, R., Baldy, V., Périssol, C., & Korboulewsky, N. (2012b). Influence of plants on microbial activity in a vertical-downflow wetland system treating waste activated sludge with high organic matter concentrations. *Journal of Environmental Management, 95*, S158-S164.

WHO. (2006). *Guidelines for drinking-water quality [electronic resource]: 3rd edn. Vol. 1. First addendum to third edition.* World Health Organization press, Geneva Switzerland.

WHO. (2011). *Guidelines for drinking-water quality*. https://www.google.com

WHO. (2016). *Results of round I of the WHO International Scheme to evaluate household water treatment technologies.* World Health Organization press, Geneva Switzerland, 64pp. https:// apps. who. int/iris/ bitstream/ handle/ 10665/ 204284/ 9789241509947_ eng.pdf

Winton, R. S., Calamita, E., & Wehrli, B. (2019). Reviews and syntheses: Dams, water quality and tropical reservoir stratification. *Biogeosciences*, *16*(8), 1657-1671.

Wisniewski, E. (2013). Sedimentation tank design for rural communities in the hilly regions of Nepal. *Journal of Humanitarian Engineering, 2*(1), 43-54.

Wu, S., Carvalho, P. N., Müller, J. A., Manoj, V. R., & Dong, R. (2016). Sanitation in constructed wetlands: A review on the removal of human pathogens and fecal indicators. *Science of the Total Environment*, *541*, 8-22.

Xing, C.-H., Yamamoto, K., & Fukushi, K. (2006). Performance of an inclined-plate membrane bioreactor at zero excess sludge discharge. *Journal of Membrane Science, 275*(1-2), 175-186.

Yasin, M., Ketema, T., & Bacha, K. (2015). Physico-chemical and bacteriological quality of drinking water of different sources, Jimma zone, Southwest Ethiopia. *BMC Research Notes*, *8*(1), 1-8.

Zamani, M., Sadoddin, A., & Garizi, A. Z. (2012). Assessing land-cover/land-use change and its impacts on surface water quality in the Ziarat Catchment, Golestan Province-Iran. *International Congress on Environmental Modelling and Software*, *26*, 1-7. https://scholarsarchive.byu.edu/iemssconference/2012/Stream-B/26

Zhang, T., Xu, D., He, F., Zhang, Y., & Wu, Z. (2012). Application of constructed wetland for water pollution control in China during 1990–2010. *Ecological Engineering*, *47*, 189-197.

APPENDICES

Appendix 1: Nanja and Engwiki Earth dams during the wet season (March, 2020)

Appendix 2: Water usage by both humans and animals for domestic purposes and animal watering at Shakape earth dam

Appendix 3: The IPS-CW treatment system at Nadosoito Earth dam

The earth dam

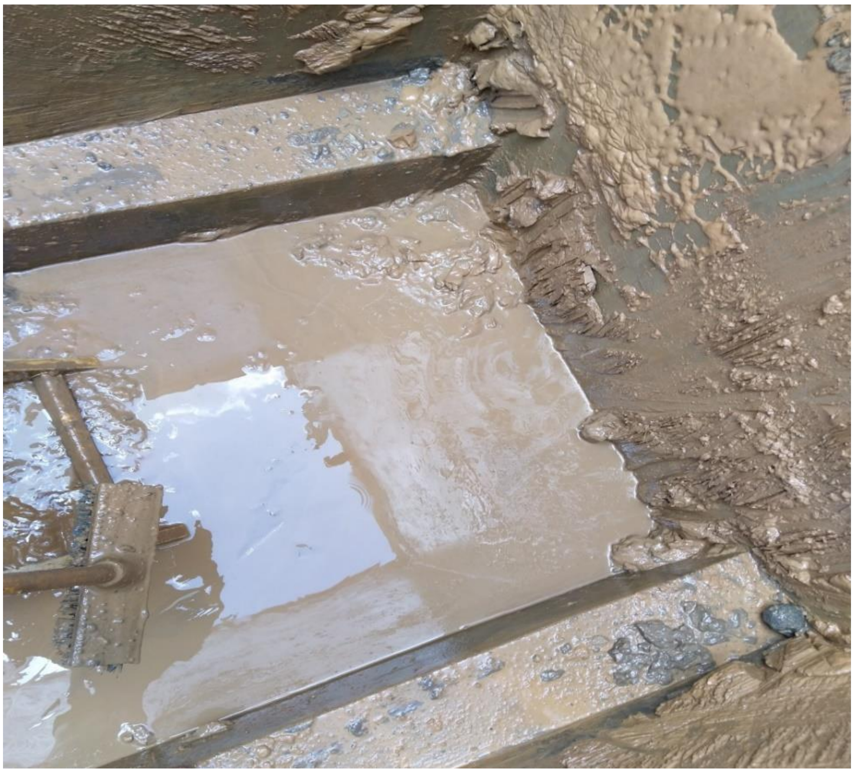
Complete assembly of the integrated system,

The Inclined plates settler

The Constructed wetland

The water reservoir with a hand pump

Appendix 4: Sludge/sediments at the bottom of the inlet of the IPS after two weeks of treatment



Appendix 5: Nadosoito community fetching water from the IPS-CW treatment plant

Appendix 6: Results of the five sampled earth dams in the wet and dry season in comparison with the drinking water standards

Parameters	Standards		Seasons	Earth dams				
	TBS	WHO		Naiti	Nanja	Engwiki	Shakape	Nadosoito
PH	6.5 - 9.2	6.5-8.5	Dry	8.5	8.4	8.3	8.5	9.0
			Wet	8.3	8.2	8.0	8.4	7.8
Temp (^{0}c)			Dry	23.0	23.5	22.8	23.9	23.5
			wet	28.7	26.2	21.6	25.8	23.1
DO (mg/L)			Dry	4.6	4.2	4.3	4.5	5.0
			wet	4.3	3.9	4.2	4.0	4.2
EC (µS/cm)		1600	Dry	328.5	347.5	260.0	373.0	570.0
			wet	289.0	302.0	180.0	236.0	204.0
TDS (mg/l)		1200	Dry	164.5	173.5	131.0	138.0	286.0
			wet	145.0	151.0	90.5	118.5	91.0
Turbidity (FTU)	5 - 25	5	Dry	168.5	313.5	268.0	64.0	452.0
			wet	1215.0	1114.5	1180.0	448.0	3230.0
TSS			Dry	288.0	926.5	640.0	153.0	810.0
			wet	2702.5	2575.0	2637.5	878.5	5780.0
NO_3^- mg/L	10 -75	50	Dry	5.0	1.7	8.0	9.9	15.6
			wet	11.8	7.5	26.7	45.4	65.3
NH_4^+ mg/L	2		Dry	1.1	0.9	0.8	0.3	1.0
			wet	0.8	0.7	1.9	3.9	5.2
PO_4^- mg/l	2.2	2.2	Dry	0.9	0.5	1.3	1.1	1.3
			wet	2.4	1.7	2.9	1.6	3.5
BOD_5	6		Dry	2.0	5.0	4.0	2.0	5.0

			wet	13.0	15.0	10.0	8.0	12.0
FC (CFU/100ml)	0	0	**Dry**	650.0	284.5	300.0	100.0	650.0
			wet	1110.0	1530.0	1720.0	970.0	1210.0

Appendix 7: Correlation matrix for physicochemical and microbial parameters for earth dam water sources during dry season

	pH	**Temp**	**DO**	**EC**	**TDS**	**Turb**	**TSS**	**NO3-**	**NH4+**	**PO43-**	**BOD**	**FC**
pH	1											
Temp	0.72	1										
DO	0.41	0.11	1									
EC	0.57	**0.92***	-0.05	1								
TDS	0.67	**0.92***	0.02	**0.99***	1							
Turb	**-0.92***	-0.44	-0.28	-0.34	-0.48	1						
TSS	**-0.92***	-0.44	-0.28	-0.29	-0.43	**0.99***	1					
NO_3^-	-0.57	-0.47	-0.17	-0.68	-0.76	0.59	0.48	1				
NH_4^+	-0.51	-0.40	-0.21	-0.62	-0.70	0.55	0.43	**0.99***	1			
PO_4^{3-}	-0.87	-0.72	0.10	-0.64	-0.72	0.84	0.85	0.51	0.43	1		
BOD	-0.18	0.35	-0.34	0.66	0.58	0.29	0.39	-0.53	-0.53	0.02	1	
FC	-0.35	-0.57	-0.33	-0.24	-0.19	0.02	0.12	-0.38	-0.43	0.21	0.30	1

2-Tailed test of significance is used

***:Correlation is significant at the 0.05 level**

Appendix 8: Correlation matrix for physicochemical and microbial parameters for earth dam water sources during dry season

	pH	Temp	DO	EC	TDS	Turb	TSS	NO_3^-	NH_4^+	PO_4^{3-}	BOD	FC
pH	1											
Temp	0.28	1.00										
DO	0.88	0.18	1.00									
EC	**0.97***	0.49	0.82	1.00								
TDS	**0.97***	0.22	0.75	**0.94***	1.00							
Turb	0.66	-0.17	0.30	0.58	0.79	1.00						
TSS	0.42	-0.23	0.02	0.36	0.59	**0.95***	1.00					
NO_3^-	0.74	0.18	0.84	0.73	0.62	0.33	0.15	1.00				
NH_4^+	0.33	-0.58	0.17	0.14	0.46	0.62	0.53	-0.15	1.00			
PO_4^{3-}	0.40	-0.29	0.64	0.31	0.27	0.17	0.05	0.85	-0.07	1.00		
BOD	0.38	-0.05	-0.06	0.38	0.56	**0.91***	**0.98***	0.11	0.38	-0.06	1.00	
FC	0.65	-0.38	0.63	0.46	0.67	0.54	0.32	0.26	0.86	0.24	0.15	1

2-Tailed test of significance is used

***:Correlation is significant at the 0.05 level**

RESEARCH OUTPUTS

a) Journal paper

Check for updates

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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

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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).

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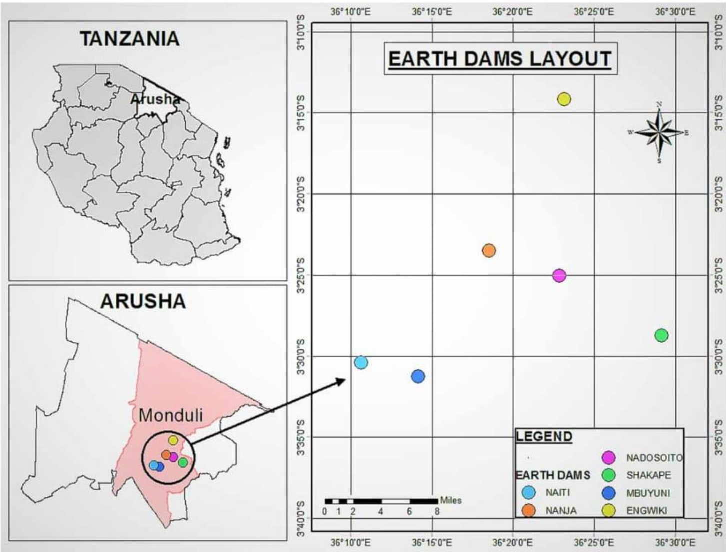

Figure 1 | Map of Tanzania showing permanent earth dams in the vicinity of the study area which are used for domestic purposes.

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.

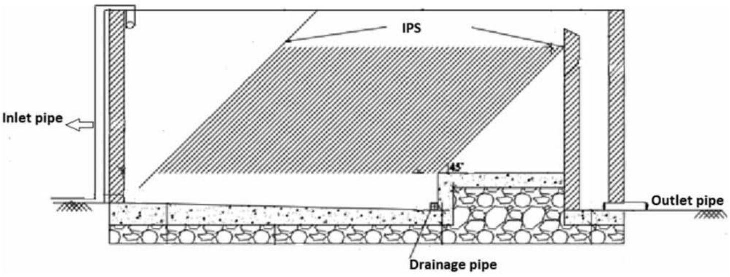

Figure 2 | Section view of Sedimentation tank coupled with inclined plates settler.

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.

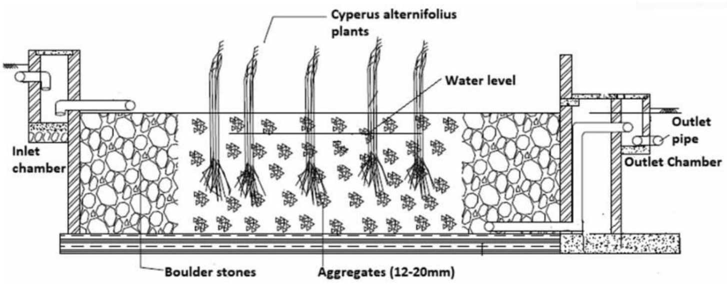

Figure 3 | Cross-section area of a horizontal subsurface flow constructed wetland.

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.

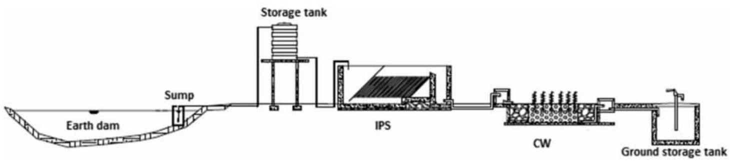

Figure 4 | Process flow diagram of the pilot scale IPS-CW treatment system setup at Nadosoito earth dam.

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

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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

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

Parameters	Sampling points	Units	Flow rates (L/min) 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

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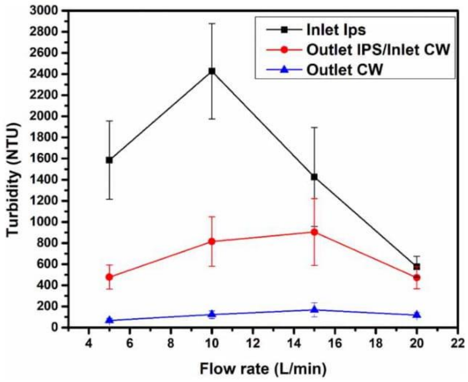

Figure 5 | Variation of mean turbidity in the system as a function of water flow rate.

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.

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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).

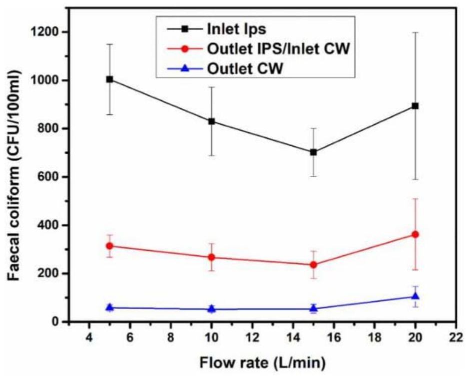

Figure 6 | FC removal by the integrated IPS-CW.

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).

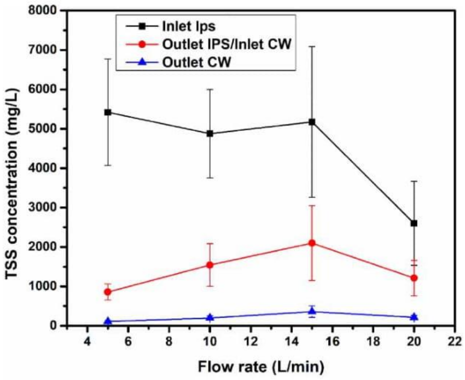

Figure 7 | TSS removal by the integrated IPS-CW.

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

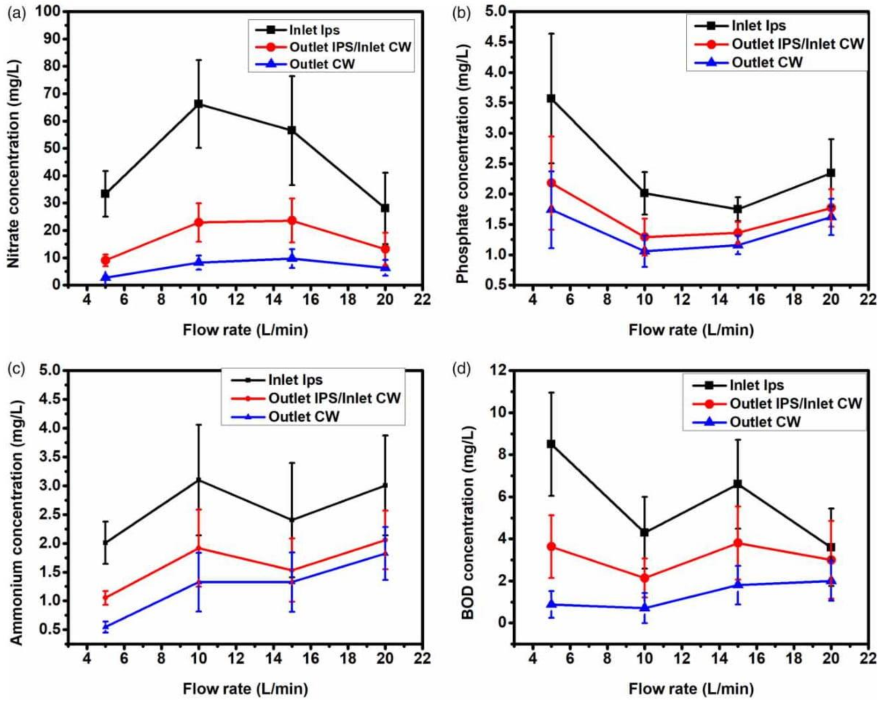

Figure 8 | Average nutrients and organic matter removal by the integrated IPS-CW (a) NO_3^- (b) PO_4^{3-} (c) NH_4^+ (d) BOD_5.

allowable Tanzania standards of drinking water of BOD $\leq$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.

REFERENCES

Abou-Elela, S., Fawzy, M. & El-Gendy, A. 2015 Potential of using biological aerated filter as a post treatment for municipal wastewater. *Ecological Engineering* **84**, 53–57.

Akratos, C. S. & Tsihrintzis, V. A. 2007 Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. *Ecological Engineering* **29**(2), 173–191.

Ansa, E., Andoh, E., Banu, A., Dorgbetor, R., Lubberding, W. & HJ Gijzen, H. 2015 A review of the mechanisms of faecal coliform removal from algal and duckweed waste stabilization pond systems. *American Journal of Environmental Sciences* **11**(1), 28–34.

APHA 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF), Washington, DC, USA.

Arcil, F. C. 2009 Settling velocities of particulate systems. *Kona Powder and Particle Journal* **27**(0), 18–37.

Carty, G., O'Leary, G. & Crowe, M. 2002 *Water Treatment Manuals: Coagulation, Flocculation and Clarification*. Environmental Protection Agency, Wexford, Ireland, p. 85.

Caselles-Osorio, A., Vega, H., Lancheros, J. C., Casierra-Martínez, H. A. & Mosquera, J. E. 2017 Horizontal subsurface-flow constructed wetland removal efficiency using *Cyperus articulatus* L. *Ecological Engineering* **99**, 479–485.

Chintokoma, G., Machunda, R. & Njau, K. 2015 Design and optimization of sedimentation tank coupled with inclined plate settlers as a pre-treatment for ultra-filtration. *Journal of Environment and Earth Sciences* **5**(17), 140–146.

Deng, H., Ge, L., Xu, T., Zhang, M., Wang, X., Zhang, Y. & Peng, H. 2011 Analysis of the metabolic utilization of carbon sources and potential functional diversity of the bacterial community in lab-scale horizontal subsurface-flow constructed wetlands. *Journal of Environmental Quality* **40**(6), 1730–1736.

Dorea, C., Bertrand, S. & Clarke, B. 2006 Particle separation options for emergency water treatment. *Water Science and Technology* **53**(7), 253–260.

Dorea, C. C., Williams, J., Boulay-Côté, F., Bédard, G. & Bouchard, C. 2014 *Inclined Plate Settling for Emergency Water Treatment: Towards Optimisation*. https://repository.lboro.ac.uk/articles/conference_contribution/Inclined_plate_settling_for_emergency_water_treatment_towards_optimisation/9595811.

Dzimiri, P., Hamza, A. & Marandu, S. 2010 Tanzania-Monduli_District_Water_Supply_and_Sanitation Project_-24-05-2010_.pdf.

Eliakimu, N., Machunda, R. & Njau, K. 2018 Water quality in earthen dams and potential health impacts: case of Nadosoito Dam, Tanzania. *Water Practice and Technology* **13**(3), 712–723.

Ewel, K. C. 1997 *Water Quality Improvement by Wetlands*. Island Press, Washington, DC, USA.

EWURA 2020 *Water and Wastewater Quality Guidlines for Water Supply and Sanitation Authority*. Energy and Water Utilities Regulatory Authority (EWURA), Dar es Salaam,Tanzania. https://www.ewura.go.tz/wp-content/uploads/2020/06/Water-and-Wastewater-Quality-Monitoring-Guidelines-2020.pdf.

Froebrich, J., Ikramova, M. & Razakov, R. 2006 Improved groundwater management strategies at the Amu Darya River. In: *Groundwater and Ecosystems* (A. Baba, K. W. F. Howard & O. Gunduz, eds). Springer, Dordrecht, The Netherlands, pp. 153–165.

Garcia, J., Rousseau, D. P., Morato, J., Lesage, E., Matamoros, V. & Bayona, J. M. 2010 Contaminant removal processes in subsurface-flow constructed wetlands: a review. *Critical Reviews in Environmental Science and Technology* **40**(7), 561–661.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M. C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N. & Noble, I. 2013 Sustainable development goals for people and planet. *Nature* **495**(7441), 305–307.

Huang, Y.-P., Kuo, W.-C., Lee, C.-H., Ting, C.-S. & Hsieh, H.-H. 2007 River water-quality improvement using a large-scale constructed wetland in southern Taiwan. *Environmental Engineering and Management* **17**(4), 277.

Jayaweera, M. W., Kasturiarachchi, J. C., Kularatne, R. K. & Wijeyekoon, S. L. 2007 Removal of aluminium by constructed wetlands with water hyacinth (*Eichhornia crassipes* (Mart.) solms) grown under different nutritional conditions. *Environtal Science and Health Part A* **42**(2), 185–193. https://doi.org/10.1080/10934520601011361.

Jing, S.-R. & Lin, Y.-F. 2004 Seasonal effect on ammonia nitrogen removal by constructed wetlands treating polluted river water in southern Taiwan. *Environmental Pollution* **127**(2), 291–301.

Kadlec, R. H. & Wallace, S. 2008 *Treatment Wetlands*. CRC Press, Boca Raton, FL.

Karathanasis, A., Potter, C. & Coyne, M. 2003 Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. *Ecological Engineering* **20**(2), 157–169.

Kipasika, H., Buza, J., Lyimo, B., Miller, W. & Njau, K. 2014 Efficiency of a constructed wetland in removing microbial contaminants from pre-treated municipal wastewater. *Physics and Chemistry of the Earth, Parts A/B/C* **72**, 68–72.

Kurzbaum, E., Kirzhner, F. & Armon, R. 2012 Improvement of water quality using constructed wetland systems. *Review on Environmental Health* **27**(1), 59–64.

Law, Y., Lant, P. & Yuan, Z. 2011 The effect of pH on N_2O production under aerobic conditions in a partial nitritation system. *Water Research* **45**(18), 5934–5944.

Lema, E., Machunda, R. & Njau, K. N. 2014 Influence of macrophyte types towards agrochemical phytoremediation in a tropical environment. *International Journal of Engineering Research and General Science* **2**(5), 441–455.

Leung, W. F. & Probstein, R. F. 1983 Lamella and tube settlers. 1. model and operation. *Industrial & Engineering Chemistry Process Design and Development* **22**(1), 58–67.

Mandal, H. K. 2014 Influence of wastewater pH on turbidity. *International Journal of Environmental Research and Development* **4**(2), 105–114.

Martins, A., Heijnen, J. & Van Loosdrecht, M. 2003 Effect of dissolved oxygen concentration on sludge settleability. *Applied Microbiology and Biotechnoloy* **62**(5–6), 586–593.

Masbough, A., Frankowski, K., Hall, K. J. & Duff, S. J. 2005 The effectiveness of constructed wetland for treatment of woodwaste leachate. *Ecological Engineering* **25**(5), 552–566.

Mshida, H. A., Kassim, N., Kimanya, M. E. & Mpolya, E. 2017 Influence of water, sanitation, and hygiene practices on common infections among under-five children in Longido and Monduli districts of Arusha, Tanzania. *Journal of Environmental and Public Health* **2017**, 9235168. https://doi.org/10.1155/2017/9235168.

Mtavangu, S., Rugaika, A. M., Hilonga, A. & Njau, K. N. 2017 Performance of constructed wetland integrated with sand filters for treating high turbid water for drinking. *Water Practice and Technology* **12**(1), 25–42.

Murray, S. & Hanna, J. 2009 *Guide to Inclined Plate Settlers*. https://www.scribd.com/document/367669599/Guide-to-Inclined-Plate-Settlers (accessed 18 February 2021).

Njau, K., Mwegoha, W., Kimwaga, R. & Katima, J. 2011 Use of engineered wetlands for onsite treatment of wastewater by the local communities: experiences from Tanzania. *Water Practice and Technology* **6**(3), wpt2011047.

Shen, J., Mkongo, G., Abbt-Braun, G., Ceppi, S. L., Richards, B. S. & Schäfer, A. I. 2015 Renewable energy powered membrane technology: fluoride removal in a rural community in northern Tanzania. *Separation and Purification Technology* **149**, 349–361.

Stenstrom, M. K. & Poduska, R. A. 1980 The effect of dissolved oxygen concentration on nitrification. *Water Reseaerch* **14**(6), 643–649.

Takata, K. & Kurose, R. 2017 Influence of density flow on treated water turbidity in a sedimentation basin with inclined plate settler. *Water Science and Technology: Water Supply* **17**(4), 1140–1148.

TBS (Tanzania Bureau of Standards) 2005 National Environmental Standards Compendium: Specification for Drinking Water, Dar es Salaam, pp23-29. Part-1,TZS 574. http://www.tzdpg.or.tz/fileadmin/documents/dpg_internal/dpg_working_groups_clusters/cross_cutting_groups/environment_and_natural_resources/Resources/Sector_Documents_-_Government_of_Tanzania/National_Environmental_Standards_Compendium.pdf.

Tchobanoglous, G., Burton, F. L. & Stensel, H. D. 2003 *Wastewater Engineering: Treatment and Reuse* (Metcalf & Eddy), 4th edn. International Edition. McGraw-Hill, pp. 361–411.

UNICEF 2018 *Water, Sanitation and Hygiene Budget Brief Tanzania*. United National Children's Fund (UNICEF), Dar es Salaam, Tanzania. https://www.unicef.org/tanzania/media/1291/file/UNICEF-Tanzania-2018-WASH-Budget-Brief.pdf.

URT 2016 *Research Priorities for Tanzania (2015 - 2020)*. http://tawiri.or.tz/wp-content/uploads/2017/06/Tanzania-Research-Pririties-from-COSTECH.pdf.

Vymazal, J. 2007 Removal of nutrients in various types of constructed wetlands. *Science of Total Environment* **380**(1), 48–65.

Wang, F., Liu, Y., Ma, Y., Wu, X. & Yang, H. 2012a Characterization of nitrification and microbial community in a shallow moss constructed wetland at cold temperatures. *Ecological Engineering* **42**, 124–129.

Wang, R., Baldy, V., Périssol, C. & Korboulewsky, N. 2012b Influence of plants on microbial activity in a vertical-downflow wetland system treating waste activated sludge with high organic matter concentrations. *Journal of Environmental Management* **95**, S158–S164.

WHO 2006 *Guidelines for Drinking-Water Quality [Electronic Resource]: Incorporating First Addendum*, Vol. 1. Recommendations. World Health Organization, Geneva, Switzerland. https://apps.who.int/iris/bitstream/handle/10665/43428/9241546964_eng.pdf

WHO 2011 Guidelines for drinking-water quality. *WHO Chronicle* **38**(4), 104–108.

WHO 2016 *Results of Round I of the WHO International Scheme to Evaluate Household Water Treatment Technologies*. https://apps.who.int/iris/bitstream/handle/10665/204284/9789241509947_eng.pdf.

Wisniewski, E. 2013 Sedimentation tank design for rural communities in the hilly regions of Nepal. *Journal of Humanitarian Engineering* **2**(1), 43–54.

Wu, S., Carvalho, P. N., Müller, J. A., Manoj, V. R. & Dong, R. 2016 Sanitation in constructed wetlands: a review on the removal of human pathogens and fecal indicators. *Science of the Total Environment* **541**, 8–22.

Xing, C.-H., Yamamoto, K. & Fukushi, K. 2006 Performance of an inclined-plate membrane bioreactor at zero excess sludge discharge. *Journal of Membrane Science* **275**(1–2), 175–186.

Zhang, T., Xu, D., He, F., Zhang, Y. & Wu, Z. 2012 Application of constructed wetland for water pollution control in China during 1990–2010. *Ecological Engineering* **47**, 189–197.

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b) Poster presentation

PERFORMANCE OF INCLINED PLATES SETTLER INTEGRATED WITH CONSTRUCTED WETLAND FOR HIGH TURBIDITY WATER TREATMENT

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Introduction

- Water shortage challenges in semi arid areas of Tanzania has lead to the dependence on dams and borrow pits for domestic use (Shen et al.,2015).
- Monduli district has 26 dams, most of which are shared by human, livestock and wildlife, this sharing is associated with the water quality problem reported in previous studies (Mtavangu et al.,2017).
- Higher turbidity levels and faecal coliform values are the major challenging pollutants in the studied earth dams in Monduli district(Eliakimu et al.,2018; Mtavangu et al.,2016).
- A pilot-scale inclined plates settler integrated with constructed wetland (IPS-CW) system was tested on the treatment of Nadosoito earth dam water with turbidities ranging from 186 to 4011 NTU to meet the allowed drinking water standards

General objective

To evaluate the performance of inclined plates settler integrated with the constructed wetland for highly turbid water treatment

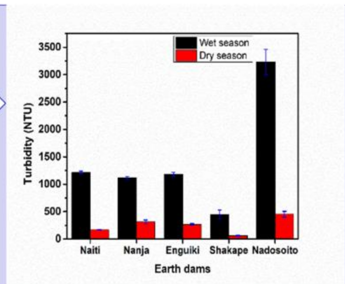
Specific objectives

- To determine the water quality of the selected major permanent earth dams within Monduli district.
- To evaluate the performance and validate the field application of inclined plates settler integrated with the constructed wetland (IPS-CW) in treatment of high turbid water at the Nadosoito dam.

The IPS-CW treatment system at Nadosoito Earth dam

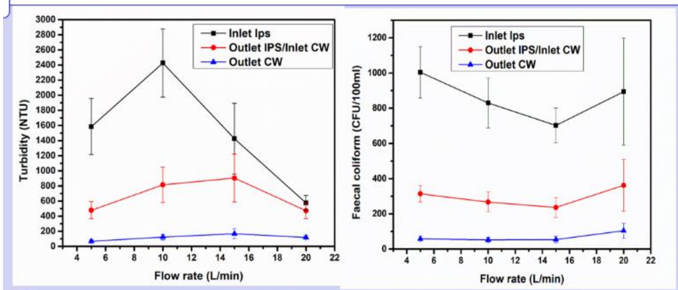
Results and discussion

Seasonal variation in turbidity within the earth dams in the Monduli district



- Most of the pollutant levels for all of the sampled earth dams were increasing during the wet season and decreasing in the dry season.
- The IPS-CW treatment system achieved maximum removal efficiency of 95.7% and 94.2% for turbidity and faecal coliform at 5 L/min flowrate, respectively.

Turbidity and Faecal coliform removal in the integrated IPS-CW



Conclusion

- The integrated IPS-CW plant is a feasible water pre-treatment system for water with higher turbidity values typically used in rural areas without water supply systems.
- Despite of the high efficiencies for water pollutant removal further treatment is necessary to make the water safe for human consumption.

References

APHA. (2012). Standard methods for the examination of water and wastewater 22nd Edition. *American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF), Washington, DC, USA*

Chintokoma, G., Machunda, R., & Njau, K. (2015). Design and Optimization of sedimentation tank coupled with inclined plate settlers as a pre-treatment for ultra-filtration. *Journal of Environment and Earth Sciences, 5*(17), 140-146.