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Optimization of Sedimentation Tank Coupled with Inclined Plate Settlers as a Pre-treatment for High Turbidity Water

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Abstract:
Access to clean and safe drinking water is a challenge in most rural areas of Tanzania. Unsafe drinking water is a major cause of water-related diseases that predominantly affect people living in developing countries. In most places, water is readily available during the rainy season, but it is muddy and full of sediments. But in Karatu, regardless of the season, water is always highly turbid with suspended particles. High turbidity water is a great challenge to water treatment works as it can be hard to remove and also harbors pathogens. Because of a lack of cost-effective purifying agents, communities suffer from water scarcity and use water that is no doubt contaminated by sediment and livestock/human feces. Today there are many technologies available to treat unsafe water. However, most of such technologies are suited for use with low or no turbidity source water. Ultra-Filtration (UF) is very effective in making unsafe water safe through removal of chemical species and pathogens. UF, however, like many other treatment techniques, is limited to treating water with high turbidity. Pre-treatment is needed. The pre-treatment of high turbidity water (>1000 NTU) is a challenge that was investigated in this research. This paper describes a laboratory scale sedimentation tank coupled with Inclined Plate Settlers (IPS) tested and optimized at NM-AIST, to see if IPS can pre-treat the raw water to remove enough turbidity to make UF a feasible option. The results of this work show that IPS is not only a feasible option in pre-treating highly turbid water for the UF (< 50 NTU) but also a viable technology in treating water with very high turbidities to within the Tanzania drinking water standards (< 25 NTU). The design is ready for pilot testing in field environment.
Keywords: High turbidity water, Sedimentation tank, Inclined Plate Settler, Ultra-Filtration.

2.1 Introduction

Even though a number of large-scale UF plants for drinking water production have been installed around the world the main limitation of the UF process identified in drinking water treatment is membrane fouling (Meier-Haack *et al.*, 2003; Wray and Andrews, 2014). Fouling results into increased operation and maintenance costs (Boyd and Duranceau, 2013) and hence limits the widespread application of membrane processes. Fouling mainly stems from three sources, namely particles in the feed water, buildup of sparsely soluble minerals and byproducts of microorganism growth. Needless to say that membrane is not regarded feasible to treat high-turbidity raw water for apparently easy fouling accompanied with drinking water production (Lin *et al.*, 2012). Hence the use of membrane technology is limited in developing world, especially in sub Saharan countries because of the high turbidity water in such countries and Tanzania, especially Karatu is no exception. The fine sediments observed in high concentrations in Karatu earth dams and the high water volume to be handled are the two major problems for using the conventional wastewater treatment process for drinking water pre-treatment prior to UF (El-Din and Smith, 2002). Although sedimentation tanks are most effective in removing suspended particles from water, high capital cost involved in constructing large sedimentation tanks occupying considerable amount of land and its less effectiveness in removing fine particles limit their use in pre-treating high turbid water with fine particles (Cripps and Bergheim, 2000). Therefore, in order to meet the prescribed design consideration water quality standards for ultrafiltration (Kim *et al.*, 2013), low cost, low maintenance and high efficient technologies are needed which reduce tank footprint and improve the quality of the pre-treated water.

2.2 Literature review

Sedimentation tanks coupled with inclined plate Settlers (IPS) are being used for separation of particles from various types of solid–liquid suspension. Owing to their increased surface area and decreased settling distance, sedimentation tanks with inclined walls are able to separate particles more rapidly than conventional tanks (Sarkar *et al.*, 2007). Most of the studies have dealt with the design and manufacture aspects of these inclined plate sedimentation tanks (Doroodchi *et al.*, 2004, 2006; Galvin, 2009) however such studies have also pointed out that the design and hence the efficiency of the IPS largely depends on the raw water characteristics.

These sedimentation tanks with IPS need to be optimized in order to increase their efficiency depending on the characteristics of the water to be pre-treated. Such studies have not been carried out with the high turbid Karatu earth dams' waters. Difficulties arise in the treatment of highly turbid water because particulate matter can enhance microbial growth, mask detection of microorganisms during water quality testing, interfere and make disinfection processes more expensive (Canada *et al.*, 2001). Inclined plate settlers are high rate sedimentation devices that consist of a series of inclined parallel plates forming channels (plate stack) into which a particle containing solution can be fed for separation (Concha Arcil, 2009). The plate stack is normally installed between a parallel inlet and outlet channel. As the water flows through the plate stack channels, the particles settle onto the downward facing walls of the inclined plates and slide down to the bottom of the settler where they are collected (Guazzelli, 2006). Inclined plate settlers are used in treating water due to their low space requirement and high removal rates. Settling efficiency of the IPS is increased due to the Boycott effect (Davis, 2010) which explains that the presence of inclined plates reduces the settling distance and increases the settling area of the particles thereby increasing the efficiency of the sedimentation tank with IPS. The process of sedimentation depends on many factors such as volume of tank, number of plates, inclination of the plates, length of the plates, particle characteristics, etc. More specifically, the effectiveness of sedimentation tank is dependent upon the physical properties of solids and water, the flow parameters and the geometric parameters of the sedimentation tank (Sarkar *et al.*, 2007). Thus, the variables that can influence the sedimentation efficiency may be expressed as a functional relationship for a given shape of sedimentation tank as

$$E = f_1\left(l_p, V_p, A_p, \propto_p, \omega_p, \eta_p, \varepsilon_p, \rho_w, d_s, v_w, v_f, c_i, g\right) \quad (1)$$

Where ε = Sedimentation efficiency, l_p = length of plates, v_p= volume of tank, A_p =plate surface area, $\propto_p$ = angle of inclination of plates, ω_p = distance between plates, η_p = number of plates, ε_p = plate roughness, ρ_s = density of the particle, ρ_w = density of the water, d_s = particle size, v_f = velocity of flow, v_w = kinematic viscosity water, c_i = initial concentration of solids, g = acceleration due to gravity. In the design of settling tanks, Surface Loading Rate (SLR) is the most important design parameter and solids removal is thought to be a function of this parameter. Traditionally SLR of conventional settling tanks is computed from the following equation:

$$SLR = \frac{Q}{A_{st}} \quad (2)$$

Where Q the discharge into the settling is tank and S_{st} is the surface area available for settling (Davis, 2010). Industrial application of inclined plate settlers has been shown to be very effective in the optimization of particle settling. The operation of the industrial IPS is analogous to the basic description presented above, although typically a variety of patented design features such as a flow control system and sediment thickener allows for the unit to maintain very high reliability and efficiency Nordic Water Products, (2013) cited by Wisniewski (2013). Although IPS are widely used for wastewater treatment, there are a variety of issues that do not allow the direct integration of an industrial IPS for water treatment especially in rural Tanzania including:

- The main materials used for the design (i.e. steel/stainless steel) are costly and are unlikely to be available in rural Tanzania.
- The design is complex and requires extensive expert knowledge and design expertise.
- The construction of the system is unable to be performed using manual unskilled labour.
- The design of the system often incorporates the use of electricity, particularly in the case of pumps, flow control units and stirrers for thickening sludge etc.
- The plates included in the IPS are usually very thin and spaced very close together. They are also fixed to the walls of the system. As such the system need to be cleaned with high-pressure water or air systems which are not readily available in rural Tanzania and hence poses a construction difficultly.
- The system is designed as a parallelepiped in order to minimize any area loss and minimize footprint. This necessitates the construction of rigorous reinforcement to stabilize the unit and makes it less conducive to construction and operation on sloped gradients.

Hence, there is a need to construct a sedimentation unit and innovatively couple it with IPS. As pointed out by Huisman in Saady (2011) and Noori and Cata (2011), in the case where a conventional settling tank is modified by inserting inclined plates in the upper zone, the surface area of the basin itself has a great significance relative to the projected area of the plates. Consequently the equation governing the Surface Loading Rate (SLR) is given by the following equation;

$$SLR = \frac{Q}{n\ A_p \cos\theta + A_{st}} \quad (3)$$

Where n is number of plates, A_p is the area of the individual plate, and Q is the inclination angle of the plates above the horizontal. Hence the main objective of this work was to pre-treat high turbidity prior to UF through the use of inclined plate settler tanks, which was optimized using an integrative approach. Removal efficiencies of both overflow turbidity and recovery efficiency of clean water were chosen as the dependent output variables.

2.3 Materials and Methods

2.3.1 Study area

The source water used in this study was obtained from an earthen dam located in Basoldawish, Karatu (Figure 1).

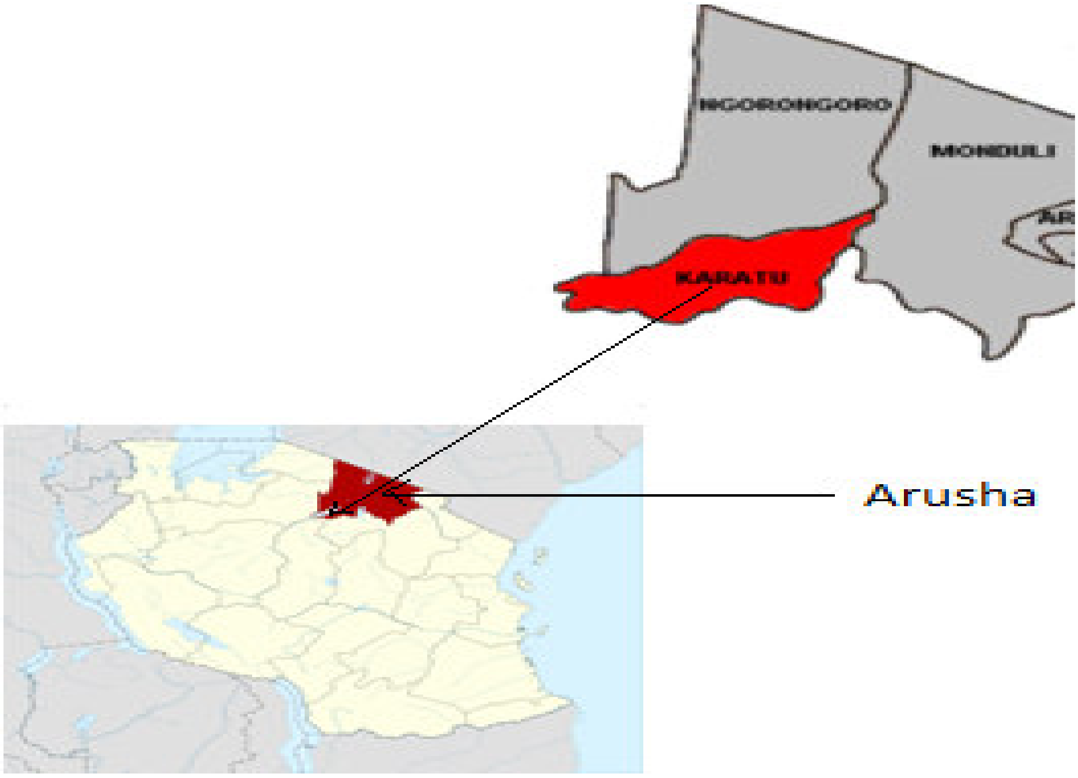

Figure 1: Map of Tanzania showing Karatu, the sampling area.

2.3.2 Analytical methods

The water qualities are shown in Table 1. The turbidity was determined using a turbidity meter (HI 93703). Particle size diameter was estimated using Scanning Electron Microscopy (SEM) analysis. A direct reading spectrophotometer (DR/200) and Fluoride meter (Mettler Toledo) were used to measure Chemical Oxygen Demand (COD) and Fluoride concentration respectively. Heavy metal analysis (e.g. Fe, Mn, Pb and Cu) was done using Energy Dispersive X-ray Fluorescence Spectrometry (EDXRF) at the Tanzania Atomic Energy Commission. Total Suspended Solids (TSS) analysis was done by following the Gravimetric method (TZS 861(Part 1):2005) (TBS, 2005).

2.3.3 Fabrication of the Model IPS

Calculation of the full scale IPS design was based on the population and water needs of the study area as well as the smallest particle to be removed. This design was downscaled by a factor of 10 so as to fabricate a lab scale model. However some parameters e.g. tank walls couldn't be exactly downscaled by the mentioned factor as doing so could have resulted in unrealistic dimensions of the plate bundle. Nevertheless, Perspex glass of 5mm thickness was used for the lab scale IPS model and Aluminium plates of 0.5 mm thickness were used as the inclined plates. The plates were inserted in the tanks at different adjustable angles by means of prefabricated fibre channels pasted onto the Perspex surface. In order to change the roughness of the plates, sanding was done manually, using silicone sealant and sand which had been sieved through 150 and 300 µm meshes respectively.

2.3.4 IPS experimentation

A laboratory experiment was conducted to test the ability of the scaled model to clarify water with high turbidity. Varying the angle helped in determining the optimum angle for turbidity removal of the IPS. The angle was varied from 30° to 75° with a 15° interval. The number of plates and the distance between them for a particular experiment was maintained by adding or removing extra plates as and when needed. These two variables were studied simultaneously. A peristaltic pump allowed the calibration of the influent by using a beaker and a stop watch. The schematic diagram and photo of the experimental setup used in this study are shown in Fig 2 and plate 1 below.

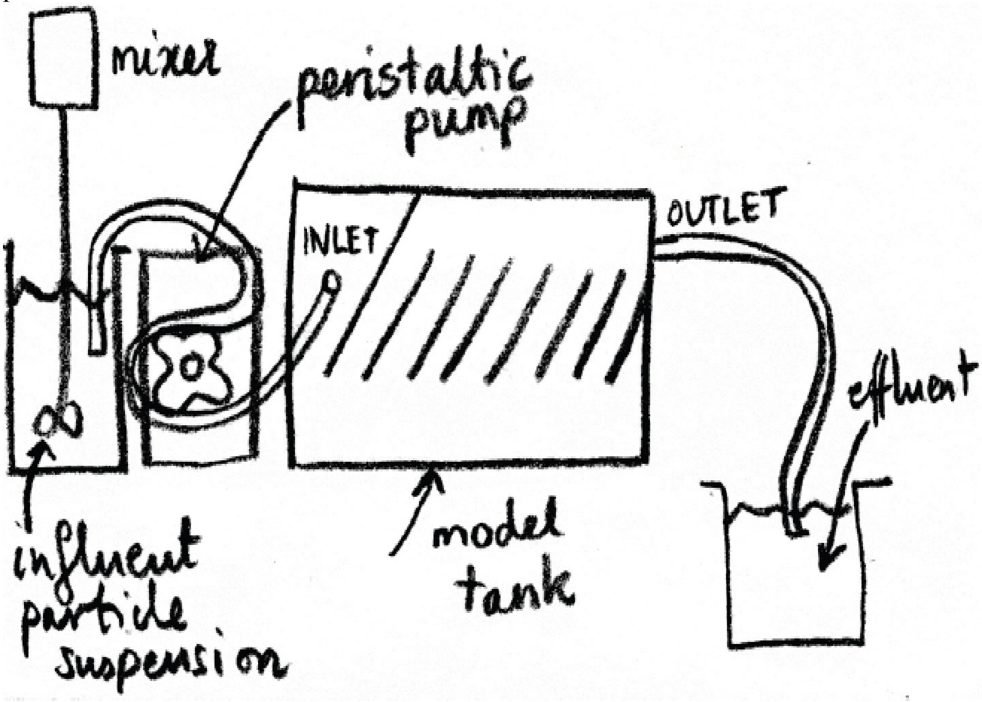

Figure 2: Schematic diagram of the experimental set-up

Plate1: Photo of the lab-scale IPS used in the experiment

2.1.1 Turbidity Removal Efficiency (TRE) calculation

Effluent turbidity and Turbidity Removal Efficiency (TRE) were used as a primary yardstick of the water quality during the laboratory testing of the pre-treatment system. Turbidity removal efficiency was calculated according to equation 4;

$$Efficiecy(\mathrm{E})(\%) = \left[\frac{(Ti - Tf)}{Ti}\right]100 \quad (4)$$

Where Ti is average influent turbidity and Tf is the average effluent turbidity at any time (t).

2.2 Results and Discussion

2.2.1 Raw water physio-chemical characteristics

The raw water quality characteristics are presented in Table 1. Results show that the main problem with the water used in the experiment is turbidity as other parameters are within both the Tanzania and World Health Organization (WHO) drinking water standards (TBS, 2005 and WHO, 2006).

Table 1: Raw water quality parameters

Parameter	Value	Parameter	Value
Turbidity (NTU)	1500 ± 100	Manganese (mg/L)	0.007
pH	7.5 - 8.8	Iron (mg/L)	0.695
Temperature (° C)	23 ± 3	Fluoride (mg/L)	2.41
TSS (mg/L)	500 ± 83	Copper (mg/L)	0.0004
EC (µS.cm-1)	203 ± 24	Lead (mg/L)	0.0003
TDS (mg/L)	100 ± 25	COD (mg/L)	100 ± 10

As such it was imperative to find out the main cause of this ever all seasonal turbidity. As Sarin *et al.* (2004 and Casey (2009) reported, waters containing iron and manganese in solution are clear and colourless. However, on exposure to air or oxygen, such waters become cloudy and turbid due to the oxidation of iron and manganese to the Fe^{3+} and Mn^{4+} states which form colloidal precipitates. This is what was observed in the sampled water.

However, upon analyzing the water sediments for these two chemicals, their concentrations were found to be within the drinking water standards i.e. 0.007 and 0.675 mg/l respectively. Davies - Colley and Smith (2001) reported that the other source of turbidity in water is suspended particles e.g. very small clay particles. As such SEM analysis was conducted to deduce the particle sizes of the suspended particles in the water. The SEM analysis results are presented in plate 2. The details regarding applied voltage, magnification used were implanted on the photograph itself (Plate 2). The SEM provides further insight into the morphology and particle size distribution profile of the water sediments. The data obtained from scanning electron- micrograph showed that the particles were irregular in shape in the range of 0.5~2µm and uniformly distributed.

The results further reveal that the soil sediments are composed of very fine clays with an aspect ratio of 2 and have significant agglomeration. According to Guazzelli (2006) such a particle has a settling velocity of less than 0.011 mm per second and it will take more than 200 days to settle down discretely at 50°C (Beringer *et al.*, 2012). This explains the all year round turbid behaviour of the sampled Karatu earthen dam water.

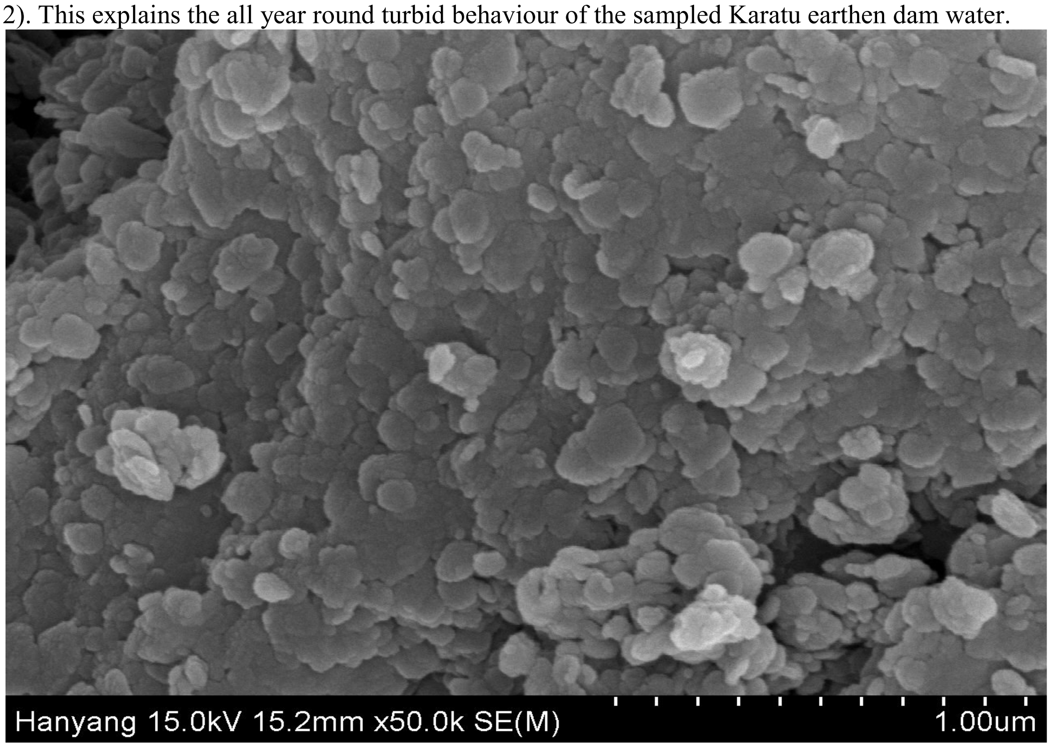

Plate 2: SEM analysis images of the sediments of the sampled water

Effluent and influent turbidity were chosen as the main measure of the performance of the system. This is due to the simplicity of the measurement and how applicable it relates the results to Ultra-filtration requirement. On the other hand, turbidity was chosen as it was the only parameter that was not meeting the design criteria of the sampled water for UF as shown in Table 2. Other measures of the system performance included pH, EC, COD and TSS removal.

Table 2: Raw water quality compared with the Ultra-Filtration design criteria requirement.

		Raw water Quality	Ultra-Filtration Design Criteria	
Parameter	**Unit**		**Acceptable**	**Allowable**
Turbidity	NTU	1500 ± 100	< 50	100
Temperature	°C	23 ± 3	25	40
pH		7.2 – 8.5	6-9	2-11
TSS	mg/L	500 ± 83	50	100
COD	mg/L	100 ± 10	< 20	60

2.2.2 Settling characteristics of the suspended particles

An experiment was conducted to compare the settling characteristics of the raw water with that of the settled sediments or sludge. The sludge was collected from the bottom of the IPS after an experiment. This sludge was put in a 1000 ml measuring cylinder side by side with another similar cylinder containing raw water. It is interesting to note that the rate of particle settling was higher for the soil water sediments or sludge than that of the raw water. This is evidenced in Fig. 3 which shows the turbidity of the undisturbed supernatant of both the sediments and raw water over a one week period. The results show that the particles are able to form flocs which increase their density and then they settle down faster. The major factor influencing settling velocity is the water density. Since density is defined as mass per unit volume, sludge density was increased by higher sediment concentration. This sediment concentration was higher relative to that of water at room temperature which in turn increased the settling velocity of the suspended particles. This phenomenon has a profound effect on the design and operation of an ideal settling tank as it determines the settling rate of particles over time.

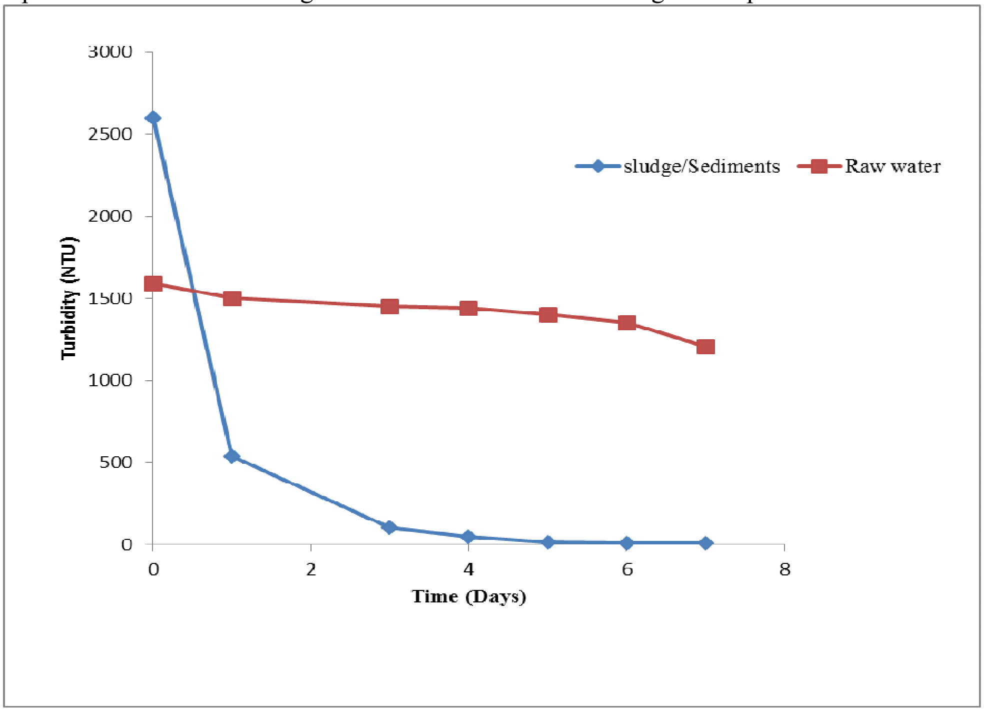

Figure 3: Difference in particle settling rate between the water sediments and raw water

2.2.3 Optimum angle of plate inclination

After obtaining the sedimentation behaviour or characteristics of sediments and raw water, the optimum plate inclination angle (θ) which gave the minimum effluent turbidity i.e. maximum turbidity removal was determined for the various flow rates. The results are shown in Fig 4-6. As it can be seen from the figures, the optimum plate inclination angle, which provided the highest turbidity removal with the optimized flow rate, is 45 °.

This agrees with what Salem *et al.* (2011) found out in a study and also the optimized angle value is within the range as proposed by Davis (2010), Salem *et al.* (2011) and Wisniewski (2013).

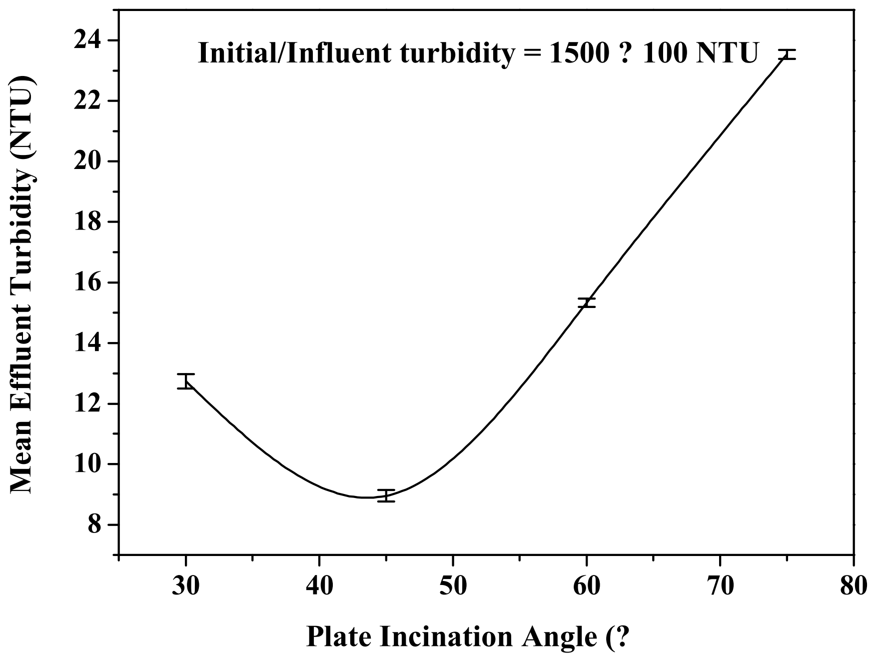

Figure 4: IPS mean effluent at different plate inclination angle at Q = 10 ml/min

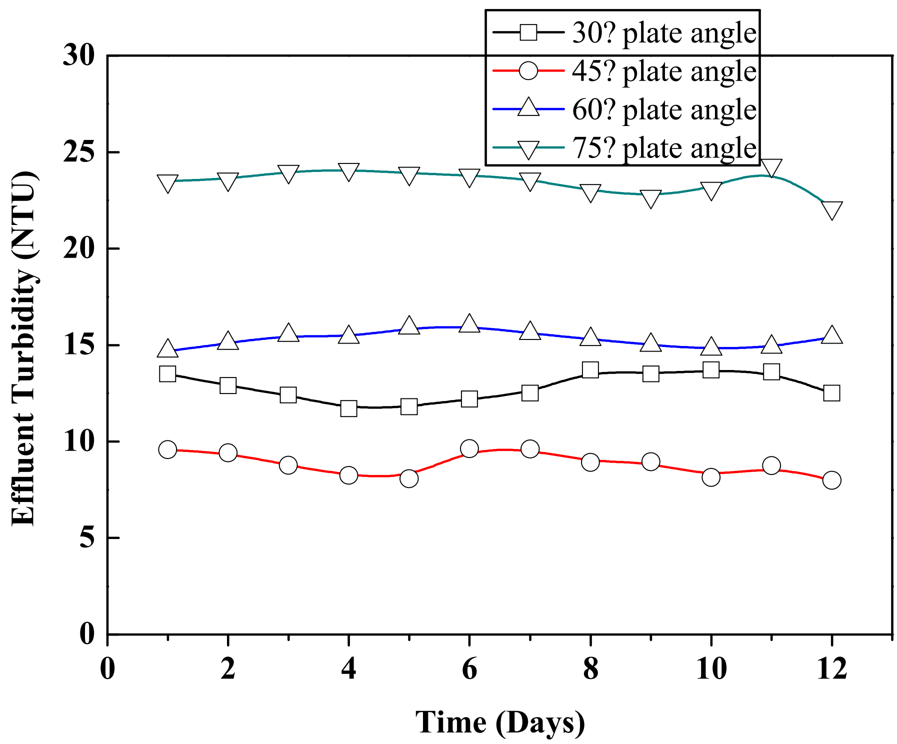

Figure 5: Effect of Plate Inclination on effluent turbidity over time (Q= 10ml/min).

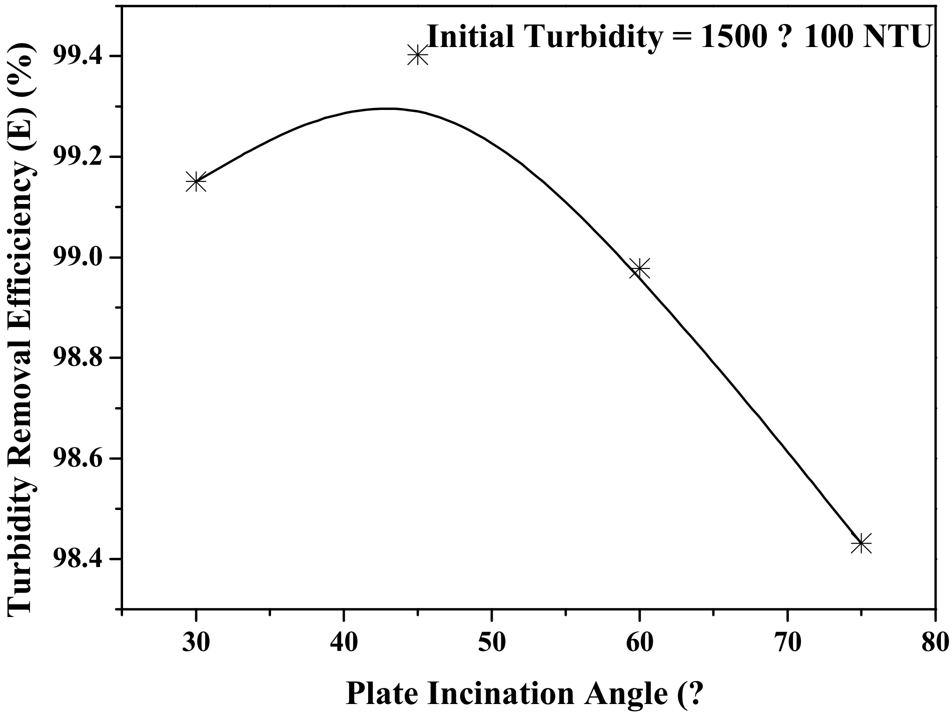

Figure 6: Effect of Plate Inclination (θ) on Turbidity removal efficiency

2.2.4 Plate spacing and roughness

The plate spacing affects the rate of settling. When the plate spacing decreases, the settling distance (height) also decreases and this increases the rate of particle settling. However, if the plate spacing is too small, obstruction of flow increases and results in solids being re-entrained into the flow stream rather than being removed from the flow. The plate spacing affects the rate As Adelman *et al.* (2013) reported in another study, plate spacing of 1 cm has also been found to be optimal in pre-treating the high turbidity water in this experiment. On the other hand, as shown in Fig 7, surfaces along which the settling out material moves down should be smooth as possible (Smith *et al.*, 2013).

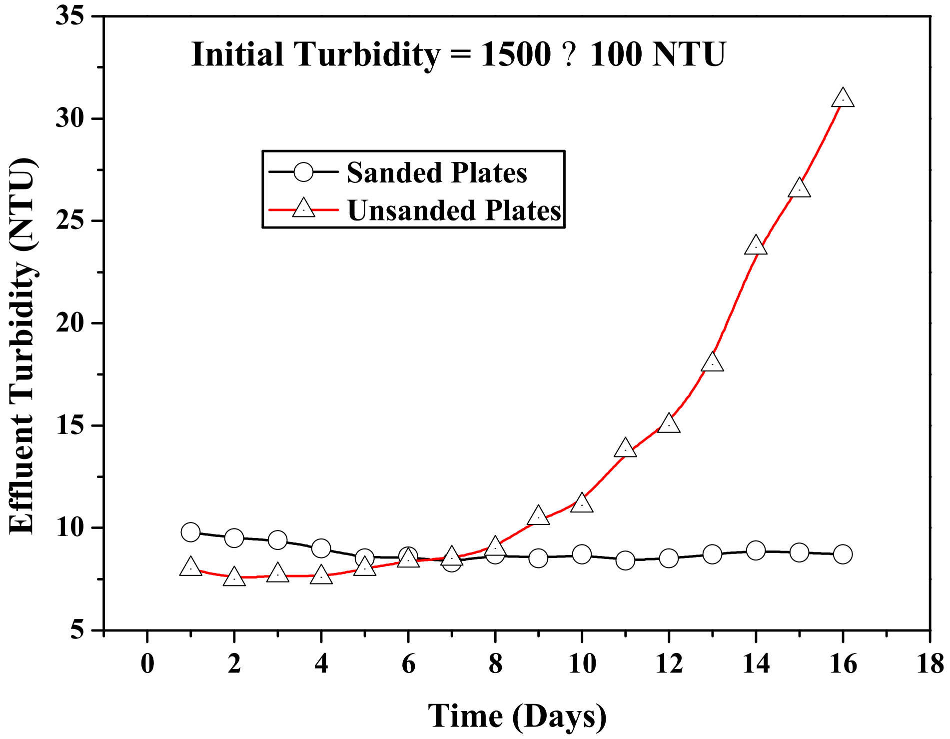

Figure 7: Effect of plate roughness on effluent turbidity over time.

2.2.5 Lab scale IPS flow rate

Runs were carried out at four different flow rates, with values of 10, 20, 30, and 40 ml/min and graph was plotted between inlet turbidity versus outlet turbidity over time (t). The results are shown in Fig. 8-10. The results show that the minimum flow rate (10ml/min) produced the best effluent as shown in Fig.8. Operation of the system at the maximum flow-rate (40ml/min) resulted in a decrease in both the operational time-frame of the system and also the turbidity removal efficiency as seen in escalation of the effluent turbidity (Fig. 9) and decrease in turbidity removal efficiency (Fig. 10). The effluent turbidity can be seen to rise and the observation of the dense sludge zone cloud confirms this suggestion.

Short circuiting of the concentrated particle flow occurred in the last channel which suggests that an increase in flow-rate to the system results in the scouring of the particles contained within the sludge cloud and the unequal distribution of the flow to the plate bundle allows the easy flow of a more concentrated particle solution up the collecting weir.

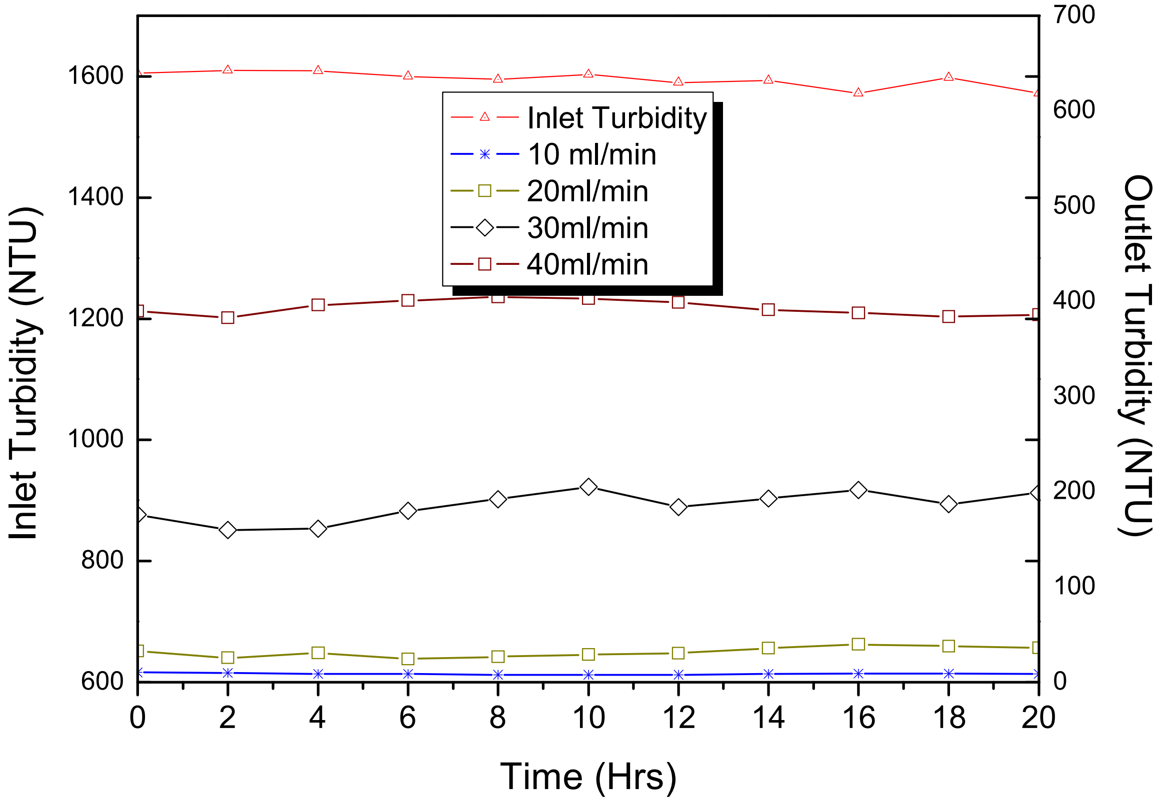

Figure 8: Performance of a 45° laboratory scale IPS with different flow rates (θ= 45°).

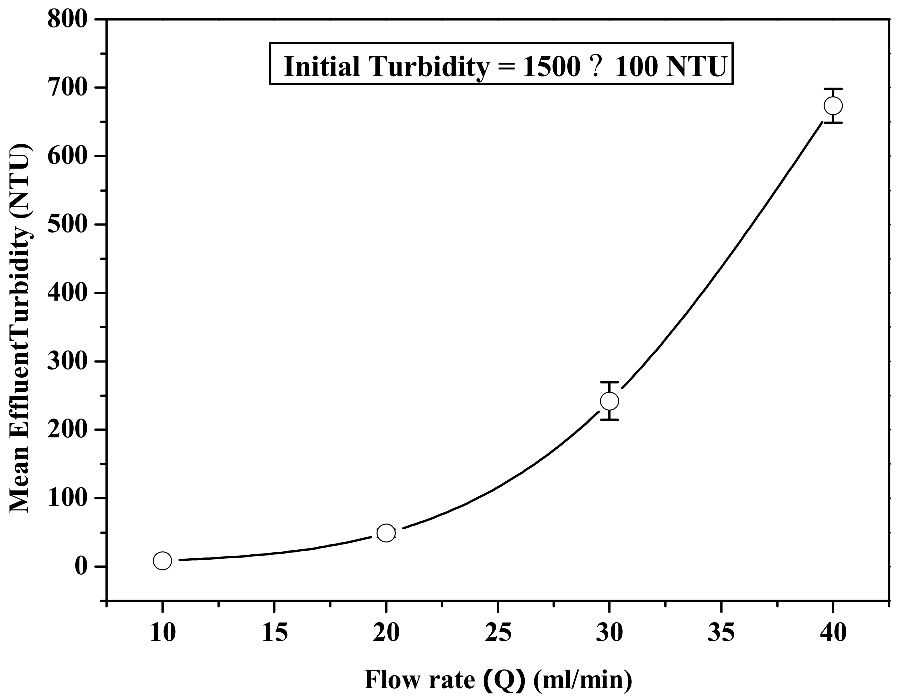

Figure 9: Mean effluent turbidity of the model IPS with different flow rates (θ = 45°).

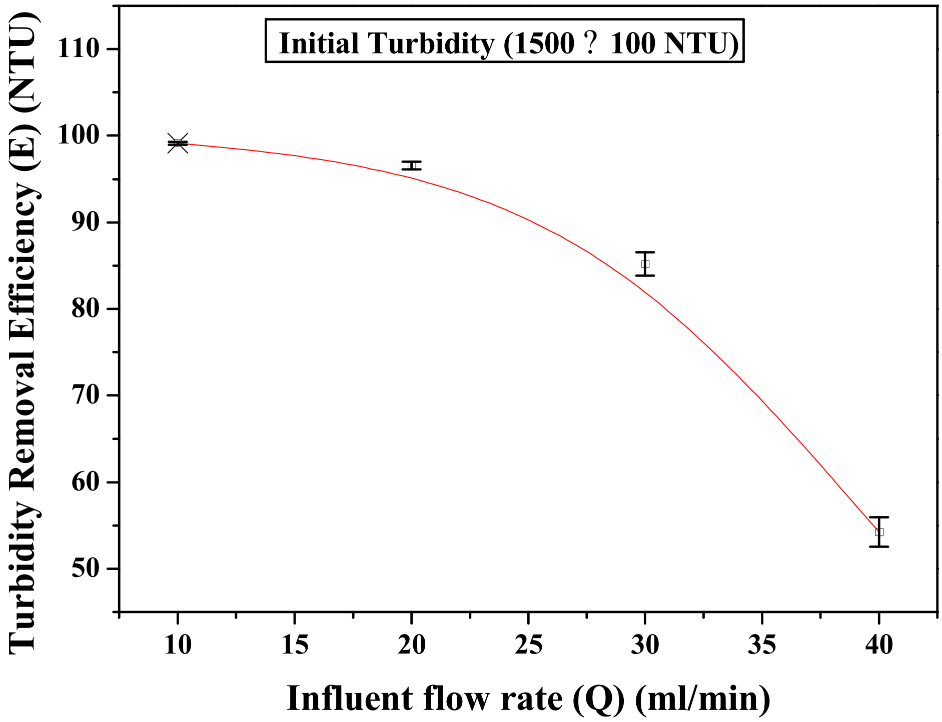

Figure 10: Turbidity Removal Efficiency (E) as a function of flow rate (Q) at θ = 45°.

2.2.6 Comparison of the IPS effluent turbidity with Tanzania and UF standard

As shown from Fig. 6 below, the lab scale IPS effluent turbidity (< 10 NTU) is way below the UF design requirement (50 NTU) and the Tanzania drinking water standards (25 NTU). This shows that the sedimentation tank coupled with IPS is feasible in pre-treating water prior to UF and can be adapted and supported by contemporary scientific knowledge.

Table 3: Raw water quality comparison with IPS effluent, UF and Tanzania standards

		IPS water Influent	UF Design Maximum		IPS Water Effluent	Tanzania Drinking Water Standards
Parameter	**Unit**		**Acceptable**	**Allowable**		
Turbidity	NTU	1500 ± 100	< 50	100	8 ± 2	< 25
Temperature	°C	23 ± 3	25	40	23 ± 5	-
pH		7.5 – 8.8	6-9	2-11	6.6-8.8	6.5 – 9.2
TSS	mg/L	500 ± 83	50	100	15 ± 3.5	500
COD	mg/L	100 ± 10	< 20	60	10 ± 2.3	70

Nevertheless, it should be noted that if the experimental results are somewhat representative of the potential operation of the system at full-scale, it may be suggested that the relatively low flow rates of the design does not allow for enough water to be treated per day. However as the laboratory model was not a perfect representative of the system, this conclusion requires further validation with the construction of a pilot scale model.

2.3 Conclusion

Results showed that turbidity removal is dependent on plate inclination angle and flow rate. The highest turbidity removal efficiency with the optimized tank was 99.2% with the lowest at 97%. The results of the study show that IPS is feasible in pre-treating high turbid water for further treatment (e.g. Ultra-filtration UF) but also gives promising prospects that the design can alternatively be used to both treat the ever high turbidity water of the Basoldawish dam and also provide potable water to the rural community due to its smaller footprint and higher turbidity removals as the effluent water turbidity (≤10 NTU) falls way below the Tanzania standard for drinking water (= 25 NTU).

The findings show that it is possible to provide clean water in the domestic rural environment through the use of sedimentation tanks coupled with inclined plate settlers if a disinfection step is added to the system. So the use of sedimentation tanks in combination with inclined plates, which are durable, provides a solution to the need for clean and safe drinking water in the rural communities of Tanzania.

RECOMMENDATIONS FOR FURTHER RESEARCH

Research tends to open more new questions than it answers. Therefore, at the end of this extensive project, there is a suggestion of list of areas where further research is needed. Firstly the paper recommends the need for a pilot scale of the design in the study area so that the system can be tested and evaluated in real environment settling so as to validate and test the design integrity of the system. Pilot scale experimentation with a wide range of feed flow-rates, particle concentrations and turbidities would be necessary to fully understand system performance. Secondly the paper also recommends the need for a study on the effect of temperature on the settling characteristic or behaviour of the suspended particles.

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