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Design and Optimization of Sedimentation Tank Coupled with Inclined Plate Settlers as a Pre-Treatment for Ultra-Filtration

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Abstract
Access to clean and safe drinking water is difficult in most rural areas of Sub-Saharan Africa. In most places, the water is generally available during the rainy season, but it is muddy and full of sediments. But in Karatu, regardless of the season, the 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 or indeed drink water that is no doubt contaminated by sediment and livestock/human feces. Unsafe drinking water is a major cause of water-related diseases that predominantly affect people living in developing countries. Today there are many technologies available to treat unsafe water. However, most of such technologies are suited for use with low turbidity source water. Ultra- Filtration (UF) is one technology which is limited to treating high turbidity water. 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 Nelson Mandela African Institution of Science and Technology (NM-AIST), to see if, given the local particle sizes and distribution in the earthen dam water of Karatu, 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).
Keywords: High turbidity water; Sedimentation tank; Inclined Plate Settler; Ultra-Filtration; Water supply

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 [1]. Fouling results into increased operation and maintenance costs [2] 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 [3]. 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 [4]. 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 [5]. Therefore, in order to meet the prescribed design consideration water quality standards for ultrafiltration, low cost, low maintenance technologies are needed which reduce tank footprint and improve the quality of the pre-treated water.

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 [6]. Most of the studies have dealt with the design and manufacture aspects of these inclined plate sedimentation tanks [7-9] 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 [10]. 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 [11]. 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 [12]. 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 [13] 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. Thus, the variables that can influence the sedimentation efficiency may be expressed as a functional relationship for a given shape of sedimentation tank as

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

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, SOR 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:

$$SLR = \frac{Q}{A_{st}}$$

Where *Q* the discharge into the settling is tank and S_{st} is the surface area available for settling. However, as pointed out by Huisman in [14], 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;

$$SLR = \frac{Q}{n\,A_p \cos\theta + A_{st}}$$

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. The main objective of this work was to pre-treat high turbidity 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.

Materials and Method

The source water used in this study was obtained from an earthen dam located in Basoldawish, Karatu. 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):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	Copper (mg/L)	0.0004
EC (µS.cm-1)	203	Lead (mg/L)	0.0003
TDS (mg/L)	100	COD (mg/L)	70

Perspex glass of 5mm thickness was used for the lab scale sedimentation tank model and Aluminum 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 fiber 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 was sieved through 150 and 300 µm meshes respectively. 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

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variables were studied simultaneously. A peristaltic pump allowed the calibration of the influent by using a beaker and a stop watch.

Experimentation

The schematic diagram and picture of the experimental setup used in this study is shown in Fig.1 below.

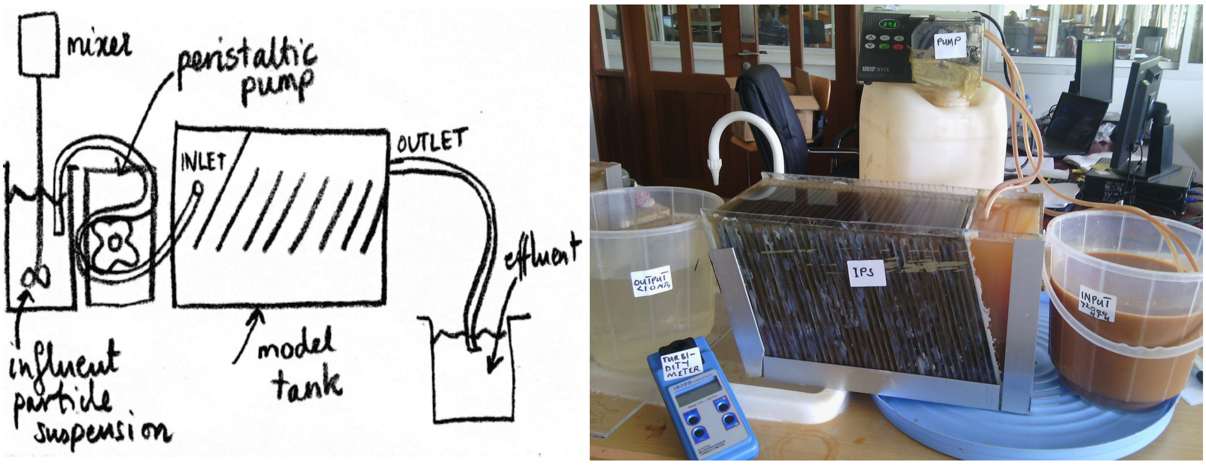

Fig 1: Schematic diagram (left) and a picture (right) of the lab-scale IPS experimentation set-up.

Results and Discussion

Raw water physio-chemical characteristics

As can be seen from Table 1 above, 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. As such it was imperative to find out the main cause of this ever all seasonal turbidity. As [15, 16] reported, waters containing iron and manganese in solution are clear and colorless. 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 in [17] 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 figure 2. 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. Again turbidity was chosen as it was the only parameter that was not meeting the design criteria of the sampled water for UF. Other measures of the system performance included pH, EC, COD and TSS removal as shown in Table 2.

Table 2: IPS influent and effluent water quality compared with the UF water requirement and Tanzania drinking water standard.

		UF Design Maximum		IPS water quality		Tanzania Drinking Water Standards
Parameter	**Unit**	**Acceptable**	**Allowable**	**Raw/Influent**	**Product/ Effluent**	
Turbidity	NTU	< 50	100	1500 ± 100	10 ± 2	5 - 25
Temperature	°C	25	40	23 ± 3	23 ± 5	
pH		6-9	2-11	7.2 – 8.5	6.6-8.8	6.5 – 9.2
TSS	mg/L	50	100	500	15	
COD	mg/L	< 20	60	100	10	

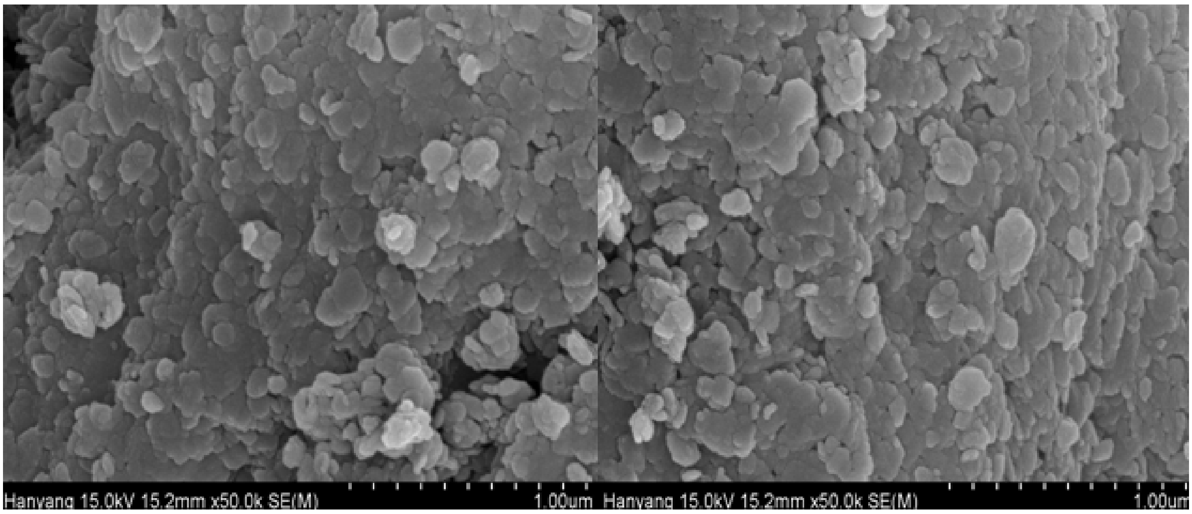

Fig. 2: SEM analysis images of the sediments of the sampled water.

Settling Characteristics of the soil particles

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 figure 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. 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.

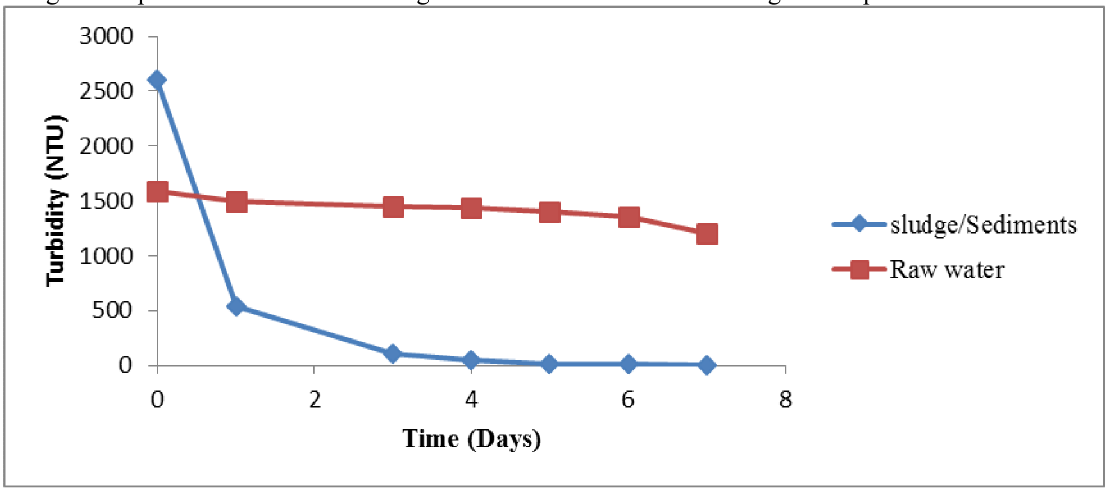

Fig 3: Graph showing the difference in particle settling rate between the soil water sediments and raw water

Angle of plate Inclination

After obtaining the relationship between sedimentation efficiency (ε) and plate angles (θ), the optimum plate angle which gave the maximum sedimentation efficiency i.e. turbidity removal was determined for the best flow rate. The results are shown in Figure 4. As it can be seen from the figure, the optimum plate angle, which provided the highest turbidity removal, is 45 °. This agrees with what other studies [14] found out.

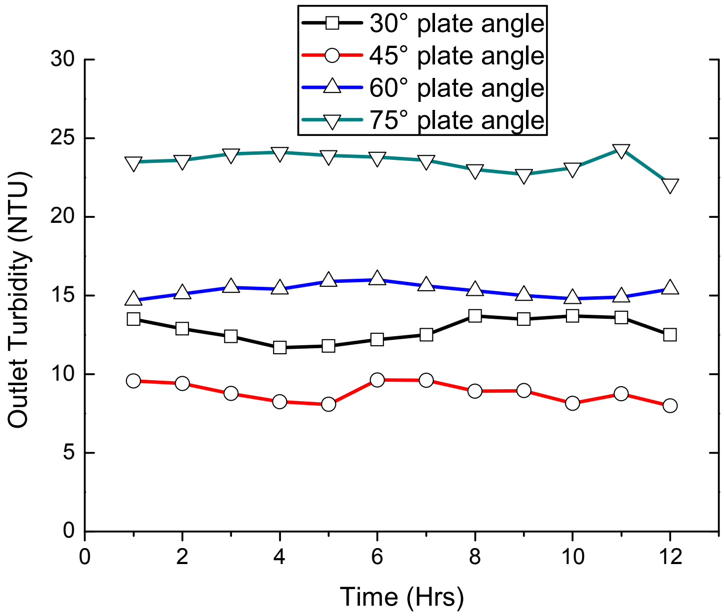

Fig 4: Effect of Plate Inclination on effluent turbidity (Q= 10ml/min).

Plate roughness and spacing

Much as the closer the plate spacing, the greater the available settling per unit of horizontal floor area, the plate spacing becomes critical when the solids deposited on the plates obstructs the flow stream and results in solids being re-entrained rather than being removed from the flow. On the other hand, as shown in figure 5, surfaces along which the settling out material moves down should be smooth as possible. Plate spacing of 1 cm has been found to be optimal.

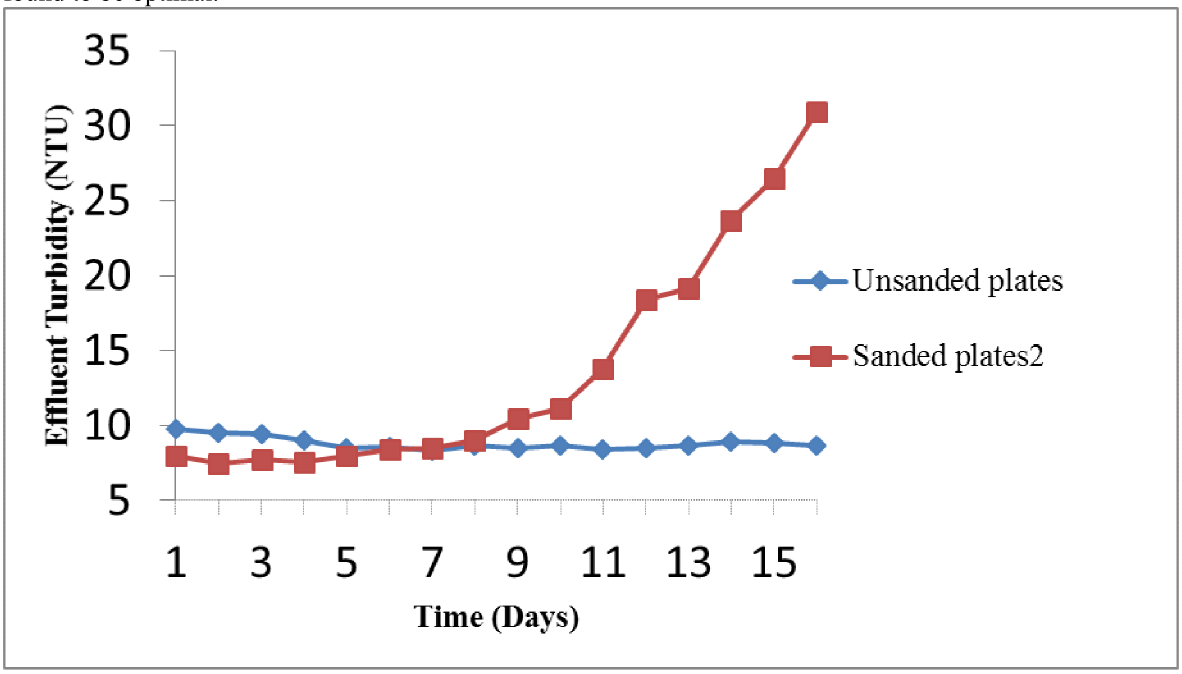

Figure 5: Performance of Sanded and smooth plates in turbidity removal over time.

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 figure 6 below. The results show that the minimum flow rate (10ml/min) produced the best effluent as shown in Figure 6. This is because any 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 which allows the easy flow of a more concentrated particle solution up the collecting weir.

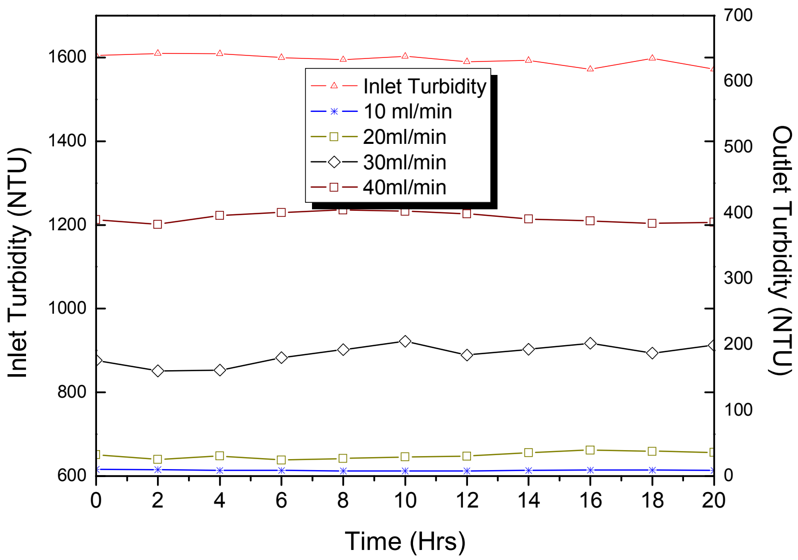

Figure 6: Performance of a 45° laboratory scale IPS with different flow rates

Comparison of the IPS effluent turbidity with Tanzania and UF standards

As shown from figure 7 below, the lab scale IPS effluent turbidity is way below the UF design requirement and the Tanzania drinking water standards. This shows that the sedimentation tank coupled with IPS is feasible in pre-treating water prior to UF.

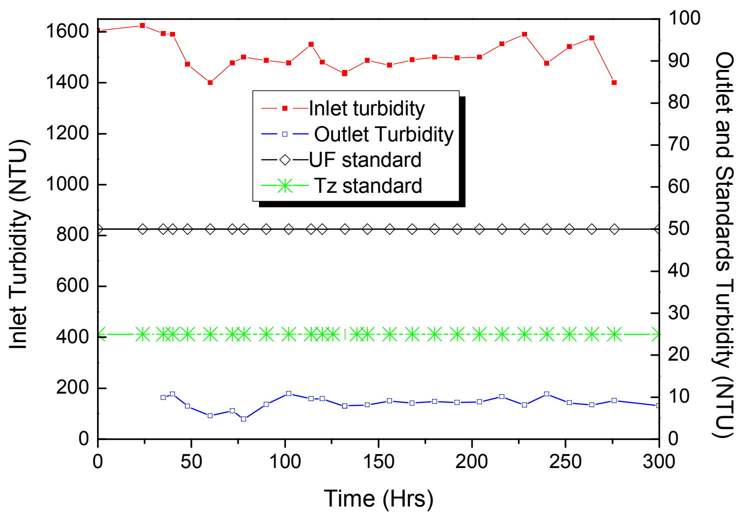

Fig 7: Comparison of IPS effluent turbidity with Tanzania and UF standards

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 portable 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 and safe water in the domestic rural environment through the use of sedimentation tanks coupled with inclined plate settlers that can be adapted and supported by contemporary scientific knowledge. Use of this technology can reduce poverty, decrease excess morbidity and mortality from waterborne-disease infections, and improve overall quality of life in rural Karatu. 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.

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