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Research Article

Design and Economic Evaluation of a Proposed Water Treatment Facility in Trinidad and Tobago

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Abstract

Trinidad and Tobago (TT), a small island developing stateface the challenge of supplying a steady potable water supply to its population. This paper proposed a processing method for a supplemental source intended to supply anew housing development in East Trinidad. Different supply strategies such as surface water, desalination and wastewater treatment were considered and assessedusing SWOT analysis and surface water treatment was chosen as the most suitable option utilizing the nearby Lopinot River as the raw water source.The flowrate of the Lopinot River was estimated to be 0.083 m3/s. and snapshot analysis of thewater quality indicated that the pH was neutral (7.62), Total Dissolved Solids was 2.60x10-1 mg/l, conductivity was 253 uS/cm, turbidity was 4 NTU, an absent coliform count; values within the accepted range outlined by the World Health Organization.These parameters were utilized in the Superpro Simulation software used forthe water treatment plant design. Equipment sizing, economic and consumer health and environmental safety considerations were factored into the design of the proposed water processing plant.The proposed design has the capacity to produce approximately 2,555,000 m3on an annual basis, in excess of the amount for the Trestrail Lands development by 84%. Despite the economic indicators of Net Present Value (NPV), Internal Rate of Return (IRR) and payback time being unfavourable, the water distribution company in TT is a non-profit organization with highly subsided tariffs. It is expected that the economics would be significantly improved if the excess treated water is sold on the national distribution grid.

Keywords Water treatment, Plant design, Economic evaluation, water quality

1. Introduction

The Cabinet Appointed Technical Steering Committee for The Review and Revision of the National IWRM Policy(2017) states that Trinidad and Tobago's (TT) National Water Resources Management Policy is

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committed to "the management of the water resources of the country, to provide not only a reliable water supply to meet present demands of all, but to ensure sustainability of supply and the available water resources of the country to meet the needs of future generations." Through the adoption and implementation Integrated Water Resources Management (IWRM) approach, an international best practice for management of the water sector, TT embarks on achieving this goal [1]. A growing population linked to a concomitant increase in housing developments is one of the challenges TT is faced with in managing its water resource. The objectives of the IWRM policy linked to this challenge is to ensure a fair and efficient allocation of water to the population at an equitable and affordable cost.

In TT, water for both industrial and domestic consumption is supplied by the Water and Sewerage Authority of Trinidad and Tobago (WASA) in conjunction with the Desalination Company of Trinidad and Tobago (DESALCOTT). The raw water supply is drawn from rivers, lakes and/or wells and treated at WASA's facilities via surface or ground water treatment processes (Figure 1)[2]. The treatment process begins with passing the raw water through screens and trash racks to remove large debris followed by uniformed mixing with a coagulant (Alum or Aluminum Sulphate), a flocculant (liquid polymer) and disinfectant (Chlorine) in the headworks chamber.Flocculation is further promoted in the flocculation basins after which the large flocs are removed through gravity settling in the sedimentation stage and a final filtration through gravity sand filter system to remove smaller suspended material[2]. The water is then disinfected via Chlorine addition to remove any pathogens present and in some cases pH adjustment is required before distribution[2].

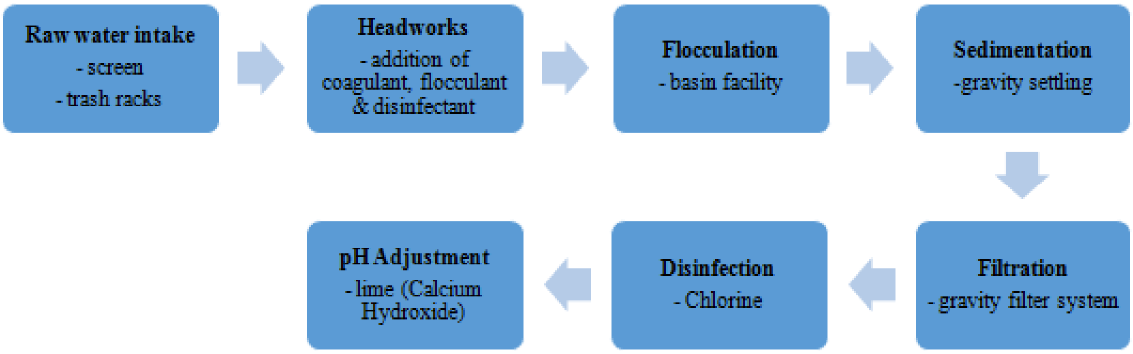

Figure 1: Flow diagram of water treatment process at WASA.[2]

In 2013, DESALCOTT signed an agreement with WASA, the water distribution company, to expand its facilities to produce 40 MIGD (Million Imperial Gallons per Day) of water where the excess amount after catering to the industry demand would further feed into the supply for consumers in the southern part of Trinidad [3]. Desalination is the process of removing salt from sea or brackish water bringing the water to a usable level[4]. DESALCOTT's desalination process utilizes a reverse osmosis system with the raw seawater source being the Gulf of Paria; after pretreatment of the raw water, which minimizes the occurrence of fouling, bio-fouling, scaling and membrane degradation, the water undergoes the coagulation, flocculation and sedimentation processes to remove solid particles, followed by post-treatment (Chlorination and pH adjustment) before distribution[5]. A visual presentation of this process is seen in Figure 2.

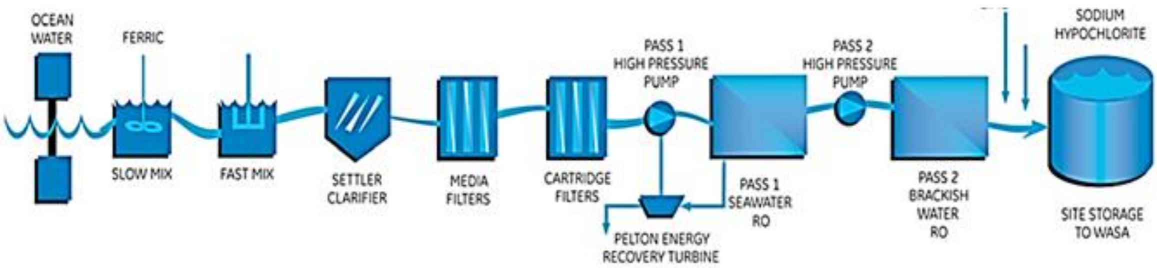

Figure 2: Diagram of water treatment process at DESALCOTT. (Desalcott, Process Description, n.d.)

Along with surface and ground water treatment and desalination,wastewater treatment is another pertinent water treatment method that can be applied toTT. Wastewater or recycle plants are typically used to treat wastewater, ensuring its safe release back into the environment. In additionto being reused for industrial purposes, treated water has been utilized for irrigation purposes. In Italy, a case study conducted on the reuse of industrial effluent from a vegetable canning factory for irritation purposes[6]. Vergine et al. (2017) found that treatment technologies adopted was effective in removing suspended matter and bacteria from the wastewater; no traces of contamination or growth inhibitory effects were observed in the irrigated plants[6].

Despite its effectiveness, wastewater plants may not be suitable for usage as potable water, in particular municipal wastewater treatment plants; as there are limited studies showing success in this field. These types of plants are generally not consumer friendly as consumers are cautious about consuming water that was once chemical wastewater or sewage. Treating wastewater is a risky procedure as the water is heavily contaminated; trace amounts of pathogens or other contaminants such as metals and organic compounds poses a threat to general health if consumed and the water is improperly treated. Studies have shown the successful reuse of treated municipal wastewater for industrial purposes[7]and irrigation applications[8, 9]. However, due to health and consumer preference, the reuse is restricted to non-potable practices such as car washing and toilet flushing[10].It would require thorough and precise disinfection of this water depending on the magnitude of the contamination, which impacts on the financial aspects of implementing this process, to ensure the water is of WHO drinking water standards. For these reasons, this was not considered as a potential supply source in this analysis.

2. Motivation

With the growth in population, the demand for this necessity is increasing. On average, the consumption of water per capita in TT was calculated to be 0.93 m3/day. Compared to the usage in the UK, with unmetered consumers utilizing 0.166 m3/day verses metered consumers using 0.126 m3/day [11], we see a large water consumption discrepancy between both countries. The majority of TT's population are unmetered consumers which has led to the over consumption of this commodity as persons are charged fixed amounts based on their property size, leading to possible poor conservation and usage practicesThe water distribution company has initiated implementing water meters where they would be able to measure the amount of water used so that consumers are billed accordingly with one of the benefits being a resulting improved water conservation awareness and practice[12].

In conjunction with increased metering,the water distribution company's target is to achieve 24/7 water supply for all its customers[12]. Residents of D'Abadie receive water from the Caroni-Arena reservoir through the Arouca Highlift Station. In 2018, 82 families moved into the Trestrail Lands housing development, D'Abadie which has the capacity to house 936 households[13].This additional housing development in this area adds an additional strain on the Arouca Highlift Station to supply water for residents in this area with an additional 1,387,000 m3/year increase

3. Objectives

This study will propose a potable water processing strategy as a supplemental source intended to supply a new housing development in East Trinidad. The study will use SWOT analysis for the selection of an appropriate supply strategy from available options including surface water, desalination and wastewater treatment.Estimation of the flowrate and snapshot analysis of key water quality parameters of the Lopinot River will be conducted to supplement the water treatment plant design process which will be achieved using in the Superpro Simulation software. Equipment sizing, economic and consumer health and environmental safety will be factored into the design of the proposed water processing plant.

4. Methodology

A literature survey was conducted to determine the different types of water treatment methods available and their requirements for operation (ground water treatment, desalination, wastewater treatment and surface water treatment).

Water samples from the nearby Lopinot River were collected for water quality testing.Random samples from upstream, midstream and downstream collected and stored consistent with WHO water sampling protocols[14]. These samples were analyzed at the University of Trinidad and Tobago (UTT)'s Materials Characterization Laboratory Facilities. pH and temperature readings were quantified using a Thermo Scientific Orion 3 Star benchtop meter[15]; conductivity measured using a Jenway 4520 Conductivity meteraccording to[16]; Turbidity tested using a HACH Hach DR820 Colorimeter, [17]; TDS was analyzed using the [18]; total coliform bacteria using Kem TecT&S, Coliform Test kit (World Health Organization, 2017).The dimensions of the source were measured and the average flowrate calculated using a tracking element.

The water quality and flowrate data obtained were utilized in the SWOT analysis which was conducted for each process stage as outlined by Teece (2017)to select the individualunit operations[19]. The block flow diagram and theprocess flow diagram containing information on volume flowrate and process conditions were developed. The water quality parameterswere used to determine the selection of equipment as shown in Table 1.

Table 1: Operational monitoring parameters for each stage of the water treatment process[14].

Operational parameter	Raw water	Coagulation	Sedimentation/ Clarification	Filtration	Disinfection	Storage/ Distribution system
pH		✓	✓		✓	✓
Turbidity (or particle count)	✓	✓	✓	✓	✓	✓
Conductivity (total dissolved solids)	✓					

Relevant design equations were used to fully design and size equipment using Microsoft Excel and Super Pro simulation[20]. This was followed by construction of a financial operating model in Microsoft Excelto calculate the Net Present Value (NPV), Internal Rate of Return (IRR), and payback period. These factors were used to determine economic feasibility of the water treatment plant and relevant sensitivity analyses conducted.

Hazard and Operability (HAZOP) and Health, Safety, and Environment (HSE) assessments were conducted along with an evaluation of potential site location and plant layout.

5. Results and Discussion

5.1 Process Selection

Water treatment is based on the principle of turbidity removal and disinfection of its raw water source.The process of selecting the appropriate water treatment method is a key step in providing a steady supply of good quality drinking water to consumers[21].Influential factors which were consideredin determining the design of the treatment facility included source water quality and reliability, pre-existing condition of the site, costing and environmental impacts[22].

Different options of water treatment including surface or ground water treatment, desalination and wastewater treatment were considered. Based on the location of the Trestrail Lands development, there were no ground water sources within an accessible range to give consideration to this supply option. The location was also not conducive to construct a desalination plant as additional costing would be required to transport water from the Gulf of Paria or the Caribbean Sea to the treatment site.

For the design of a wastewater plant in this scenario, municipal wastewater would be the closest source available. While studies have shown usage of treated industrial wastewater for irrigation purposes and reuse in other industries, there is limited research on using treated municipal wastewater as potable water. Persons are also skeptical about consuming water that was once their by-product from their daily chores, hence, this method of water treatment was not explored. The surface water treatment process, however, proved a promising option.

5.2 Water Testing and Flow Results

With surface water treatment being the final choice of water treatment, utilizing fresh water from the Lopinot River (which flows in close proximity to the development)was the basis for the design.A visit of the proposed site for the treatment plant and the water source was conducted. Measurements of flow from the river were taken to ensure there was adequate supplyand sample chemical analyses were conducted to ascertain the level of impurities to determine treatment processes necessary. With a flowrate of 0.083 m3/s, the Lopinot River has the potential to supply approximately 7000 m3/day or 2,555,000 m3/year to the treatment facility, surpassing the required 1,387,000 m3/year for the Trestrial Lands Development. Table 2 is a summary of the results from laboratory tests. The parameters tested were all in range with the WHO standards, sanctioning the use of Lopinot River as suitable water source choice.

Table 2: Laboratory analysis results and its comparison with WHO standards[14].

Data Comparison						
Parameter	Unit	World Health Organization	Laboratory Results			
		MCL maximum	Measured Level			
			Upstream	Midstream	Downstream	Calculated Average
Total Dissolved Solids	mg/l	600	$3.62x10^{-1}$	$3.02 x10^{-2}$	$3.88 x10^{-1}$	$2.60x10^{-1}$
pH	-	6.5-8.5	7.61	7.66	7.59	7.62
Conductivity	uS/cm	50-500	251	248	261	253
Turbidity	NTU	5	3	5	5	4
Total Coliform Count	-	Absent	Absent	Present	Absent	n/a

Treatment processes for the plant design were evaluated and chosen with respect to its ability to remove the impurities from the source water, provide accessibility to a sustainable, sufficient and safe drinking water from source to consumer[14]and meet the demand by the Trestrail development.

5.3SWOT Analysis and Process Flow

The results of the SWOT analysis to select the individual unit operations were used to derive a block flow (BFD) and process flow diagram (PFD) as seen in Figures3and 4respectively.From the literature review conducted, different selections of treatment methods, equipment and chemicals were listed and evaluated based on specific parameters (effectiveness, maintenance, cost, land usage, etc.) and ranked where the highest overall rating for each was chosen.The supply potential wascalculated from the flow rate of the surface water source, the Lopinot River, with a value of approximately 7,000 m3/day.

As depicted in Figure 3, water enters the plant by gravitational feed filters through the screen and flows through the valve. The screened water is then pumped into the buffer tank where minor pre-settlement occurs. From the buffer tank the water is pre-Chlorinated and pumped to a rapid mixing tank where Aluminum Sulphate (Alum) is added and mixed. Leaving the mixing tank, the water enters the clarifier where both water and sludge exitsseparately. The exiting sludge is sent for sludge thickener where the sludge settles and the water continuously removed from the top and recycled to the source. The settled sludge goes to the rotary sludge dryer to remove the remaining water; the dried sludge is then safely disposed of. The water leaving the clarifier flows through the rapid sand filters and is then stored in the service tank. Water leaving the service tank is further chlorinated by Sodium Hypochlorous injection and pumped to the onsite storage tank. From the storage tank onsite the fully treated and now potable water is pumped to an uphill distribution tank where it will be distributed to persons of the Trestrail development.

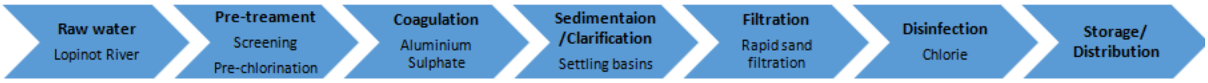

Figure 3: Block Flow Diagram of Proposed Water Treatment Process

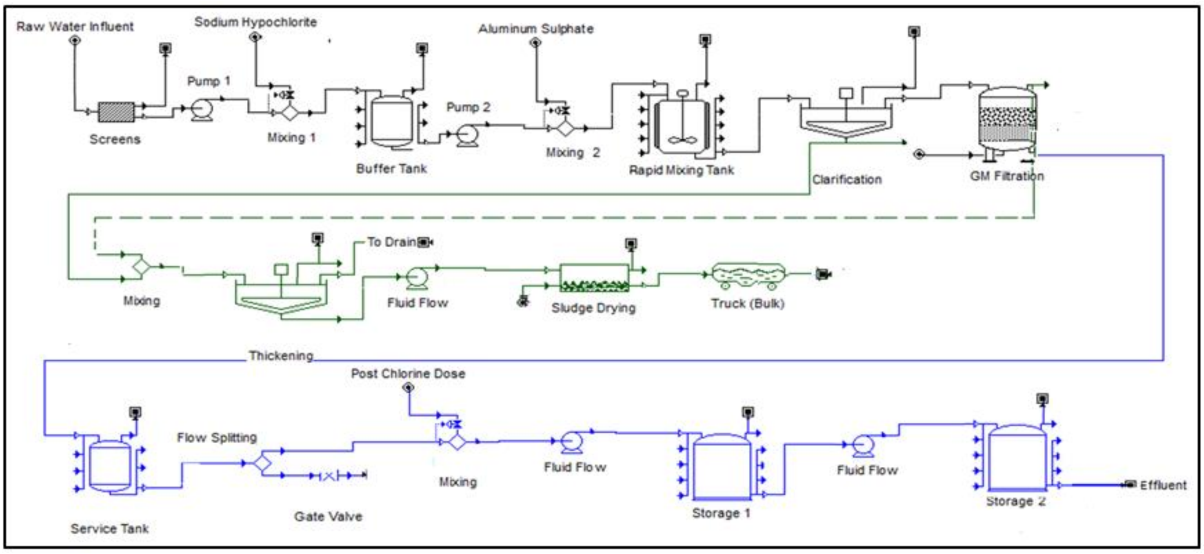

Figure 4: Process Flow Diagram of Water Treatment Process

5.4 Design and Equipment Sizing

In order to appreciate the physical aspects of our model, Microsoft Excelsheets were simulated using calculations for appropriate unit ops to size and design each equipment found on our plant[20]; results summary is capture in Table 3.The designs were compared to a Superpro Simulation model which was generated for the purpose of not only to get the physical but the chemical aspects of our model. The Superpro Simulation model also gave a more in depth design being an incomparable engineering tool.

Table 3: Summary of Specification Sheets used for Microsoft Excel Calculations.

Component	Process Data	Mechanical Data

name	Parameter	Value	Unit	Parameter	Value	Unit
Rapid Sand Filter	*Design Area*	8.48	m^2	*Activated Carbon Volume*	3.05	m^3
	Inlet Volume Flow	42394.8	L/H	*Green Sand Volume*	2.03	m^3
				Length	2.34	m
				Depth of Sand	50-75	cm
				Breath	1.8	m
Screen	*Net Submerged Area*	0.19	m^2	*Gross Width of Screen Chamber*	1.2	m
	Inlet Volume Flow	0.057	m^3/s	*Total Depth*	0.716	m
				Length	2.34	m
				Size of Channel	0.9	m^2
Rapid Mixing Tank	*Detention Time*	30	Seconds	*Volume*	1.894	m^3
	Inlet Volume Flow	500002.578	Uk Gal/Day	*Width of Tank*	1.08	m
				Height of Tank	1.62	m
				Impeller Width	0.0648	m
				Impeller Diameter	0.324	m
Clarifier	*Settling Velocity*	0.0004764	m/s	*Volume*	500	m^3
	Inlet Volume Flow	1200061.877	G/D	*Height*	3	m
				Diameter	14.6	m
				Surface Area	166.7	m^2
Tank	*Volume*	5883.4	m^3	*Height*	13	m
				Radius	12	m
Pump	*Velocity*	2.378	m^2/s	*Diameter of Pipe*	0.15	m
				Length of Suction Line	3	m
				Length of Discharge Line	15	m

5.5Financial Model and Sensitivity Analyses

A comprehensive financial operating model was developed using the Microsoft Excel tool to determine the efficiency and feasibility of thisproposed water treatment facility that has the capability of producing2,555,000 m3 of potable water annually. The input feed utilized in the design was the supply demand for the Trestrail Lands Development which was calculated to be 1,387,000 m3/year. A fixed capital investment, total operating expenditure, taxes on profit as well as a cash depreciation of 10% were factored into this model. The fixed capital investment, divided into direct and indirect cost, is the total cost of constructing the plant before start up; the direct cost covers the equipment capital cost inclusive of its installation and other utilities necessary for its operation (electrical, piping, instrumentation and controls infrastructure) while the indirect, calculated as a percentage of the direct cost, accounts for services provided by engineers and contractors, construction expenses as well as a contingency fee. The equipment sizing and costing index were calculated and scaled to the designed dimensions taking to account the time value of money for the current year[20]. The total fixed capital investment was calculated to be $13,555,162.00 USDTable 4.

Table 4: Fixed Capital Investment Analysis

Cost Type	Line Item Breakdown	Percentage	Cost (Usd)
Direct	Capital Cost	1.00	$2,847,125.00
	Purchased-equipment installation	0.47	$1,338,149.00
	Instrumentation and controls installation	0.18	$512,482.00
	Piping installation	0.66	$1,879,102.00
	Electrical installation	0.11	$313,184.00
	Buildings and services	0.18	$512,482.00
	Yard improvements	0.10	$284,712.00
	Service facilities installation	0.70	$1,992,987.00
Indirect	Engineering and supervision	0.33	$939,551.00
	Construction expenses	0.41	$1,167,321.00
	Contractor's Fee	0.05	$589,355.00
	Contingency	0.10	$1,178,710.00
TOTAL FIXED CAPITAL INVESTMENT (FCI)			**$13555,162.00**

The operating expenditure is the total money spent on an annual basis to maintain the operations of the plant. This would include costs for consumables (Alum and Chlorine), utility, sludge treatment and maintenance work and labor; for chemical plants, the annual maintenance cost is typically 5 to 15 % of the installed capital costs[20]. The operational cost was found to be $1,398,608.39 USD (Table 5) where the maintenance fee was calculated on the maximum range (15%).

Table 5: Operating Expenditure Analysis.

Item #	Item	Yearly Throughput / Consumption	Units	Unit Cost	Total Yearly Cost
1	Cost of Alum	50,534	L	$0.89	$44,975.44
2	Cost of Chlorine	22,712	L	$1.50	$34,068.00
3	Cost of Electricity	373,130	kWh	$0.03	$11,193.89
4	Cost of Sludge Treatment	12	m^3	$7,441.86	$89,302.33
5	Cost of supervisor salary	12	Monthly supervisor Salary	$24,000.00	$288,000.00
6	Cost of maintenance	2	Shut down for the year	5-15% of installed capital cost	$427,068.74
7	Cost of Operator Salary	12	Monthly Operator Salary	$42,000.00	$504,000.00
TOTAL OPERATIONAL COST					**$1,398,608.39**

The cash flow into the system is a factor of the rate at whichthe water distribution companysells water to its consumer, the population of the Trestrail Lands housing development. For a period of one year, the total revenue is calculated with an estimated population of 4,097 personsrequiring a total of approximately 3,800 m3 of water daily (1,387,000 m3 per year). With the introduction of the metered system and at a rate of $1.75TTD/m3, the potential annual revenue can amount to $2,427,250 TTD or $374,490 USD.

The quality of water used for consumption is governed by the WHO. When designing this facility, these parameters were used as a benchmark to ensure that the water produced was in accordance with these standards. Sensitivity analysis were conducted for the Total Dissolved Solids (TDS) comparing the WHO maximum contamination level of 500 mg/L[14]with the calculated concentration from the design plant which yielded a value of 0.35 mg/L. In Figure 5we see that the treatment plant has the capacity to treat a maximum raw water concentration of 9918 mg/L TDS and still obtain a WHO standard result.

5.6Economic Summary

An analysis of the results shown in Table 6illustrates that from a financial stand point, this proposal is not economically feasible. Both the IRR and payback period were calculated to give negative results as the revenue generated is not able to compensate for thefixed capital investment and operational cost required to keep the treatment plant running.These results were justified as the water distribution company is a non-profit organization, funded by the government, hence emphasis is not placed on imposing an increased costing for this commodity. The plant has the potential to produce water at an excess of 85%. This additional water could be incorporated into the water distribution company's supply for neighbouring communities to fully benefit from the facilities output. Further calculations on modifying the water rate to achieve a break-even point will also be investigated in an effort to make the design proposal economically attractive.

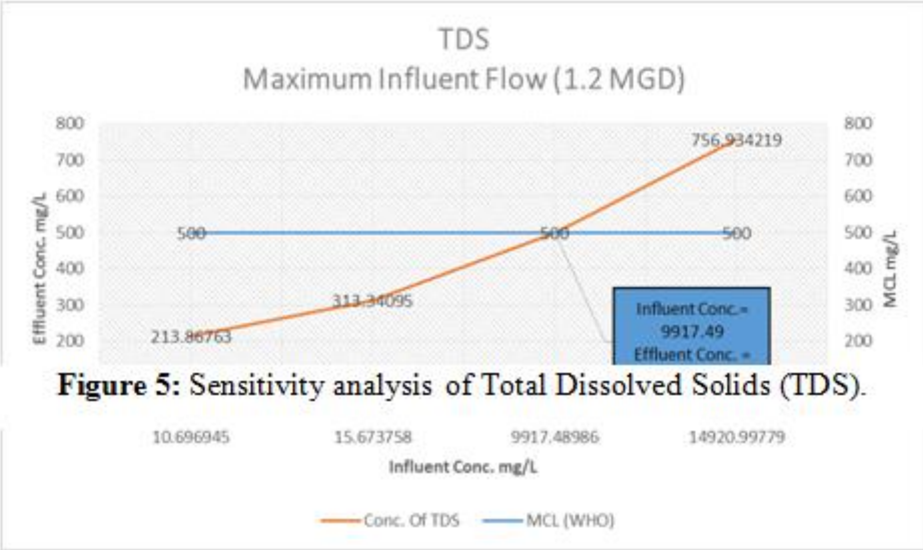

Figure 5: Sensitivity analysis of Total Dissolved Solids (TDS).

Table 6: Economic Summary for Trestrail Lands Water Treatment Facility.

Trestrail Lands Water Treatment Facility	
Net Present Value (USD)	$35,158,749
Internal Rate of Return (%)	No value generated
Payback Period (Years)	No value generated
Fixed Capital Investment (USD)	$13,555,162.00
Total Operating Cost (USD)	$1,398,608.39
Total Revenue per year (USD)	$374,490.00

5.5 HAZOP and HSE

A Hazard and Operability Study (HAZOP) is a systematic approach to investigating a process and identifying all of the possible ways in which parameters can deviate from the intended design conditions, creating hazards or operability problems. An investigation into how the water treatment facility might deviate for its intended design the system was evaluated for disparities in flows, levels and pressures.

A Health Safety and Environment assessment of the proposed water treatment plant was also conducted through an Environmental Impact Assessment (EIA) used toevaluate the possible effects of the proposed facility on the environment in conjunction with an economic evaluation. The EIA was done with an Environmental Health Impact Assessment which incorporates development policies and the potential impacts on the health of the human population. Areas covered in the impact assessment were hazard identification, environmental factors such as sludge disposal and vulnerability to communities and community risk factors.

6. Conclusion

A water treatment plant with the ability of producing potable water of a quality recommended by the World Health Organization's (WHO) drinking water standards to supply the Trestrail Lands housing development at capacity requirement of 3,800 m3/day was designed and evaluated. A surface water treatment plant using raw water from the Lopinot River was selected and designed using SuperPro design software. Key flowrate and water quality parameters such as pH, total dissolved solids, conductivity, 253 uS/cm, turbidity4 NTU and total coliform bacteria count was obtained in the laboratory from water samples collected. Thedesigned plant can produce approximately 7,000 m3/day of potable water in excess of the amount for the Trestrail Lands development by 84%. Despite unfavourable economic indicators, the water distribution company in TT is a non-profit organization with highly subsided tariffs. It is expected that the excess treated water can be sold on the national distribution grid.

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