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Research article

Design and feasibility analysis of a low-cost water treatment plant for rural regions of Bangladesh

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Abstract: In this paper, a decentralized low-cost water treatment plant is designed using empirical equations. From the analysis of water quality of Bangladesh, it is seen that the standard level of water quality is not maintained in Bangladesh. First, the primary treatment plant is designed including septic tank and anaerobic pond design. But only primary plant is not enough for the removal of impurities, for this reason secondary treatment plant is designed considering facultative pond, wetland and sand filter. Wetland and facultative pond can remove almost 70% of N and 55–60% of P. The designed plant has an efficiency of 65% in both N and P removal and the effluent amount will be 8.1 mg/L and 1.5 mg/L respectively. The other parameters like arsenic and BOD are also discussed in this paper. Finally, a detailed feasibility analysis of the plant is discussed including environmental impact, technical analysis and installation and running cost. The installation cost of the plant is around 650–700 dollar, whereas a conventional water treatment plant of the same capacity costs 2000–3000 dollar approximately. The designed plant is very much compatible for a big family or two–three small families. Finally, some recommendations are provided which may be considered as future research work.

Keywords: water treatment; waste water; low cost treatment plant; clean water; Bangladesh

Abbreviations: BOD: Biochemical Oxygen Demand; COD: Chemical Oxygen Demand; WHO: World Health Organization; BOD_5: 5-day Biochemical Oxygen Demand; ECA: Environment Conservation Amendment; DO: Demand for Oxygen; DWASA: Dhaka Water Supply & Sewerage Authority; TSS: Toxic Shock Syndrome; A_S: Surface Area; N: Nitrogen; P: Phosphorus; EPA: Environmental Protection Agency; KWASA: Khulna Water Supply & Sewerage Authority;

LGED: Local Govt. Engineering Department; TN: Tri-nitro Toluene

1. Introduction

Municipal wastewater is the conveyed wastes from homes, business offices or modern industries, notwithstanding any groundwater, surface water, and tempest water that might be available. Untreated wastewater, for the most part, contains elevated amounts of natural material, various pathogenic micro-organisms, and in addition supplements and dangerous mixes. It along these lines involves ecological dangers and thus should promptly be passed on far from its sources and treated properly before definite transfer. An objective of wastewater treatment is the security of the earth water, they say is life, to say the truth they are correct. But the accessibility of water is becoming a great concern nowadays in the globalized world, both in developing and developed countries. A sustainable employ of water sources could result in the search of supplementary water sources or even in recycling wastewater treatment plant effluents [1,2]. Waste water treatment is a process which is used to turn waste water into an effluent, that can be returned to the water cycle with no or minimal impact to the environment. This treated waste water can be used for many other purposes. Figure 1 shows a typical configuration of waste water treatment process. Wastewater from home must be treated in an environmentally friendly manner so that it can be reused. In the system, screening is considered as the very first process where wastewater is cleaned (removal of course particles i.e. cotton buds, sanitary items, face wipes, glass particles and etc.); in this process, no heavy machinery is employed. After this, the primary treatment is applied, where organic/solid materials are separated from the water. It is generally done by putting the screened water into settlement tanks so that the solids can sink at the bottom of the tank. The rest of the process is termed secondary treatment; high removal of BOD, COD and toxic materials are ensured at this stage. Primary treated water is stored in rectangular shaped tanks (Aeration Lane) and the air is pumped inside to meet the DO. Lastly, sludge is all over again cleaned and scrapped by sand filter bed resulting in edible water to be reused.

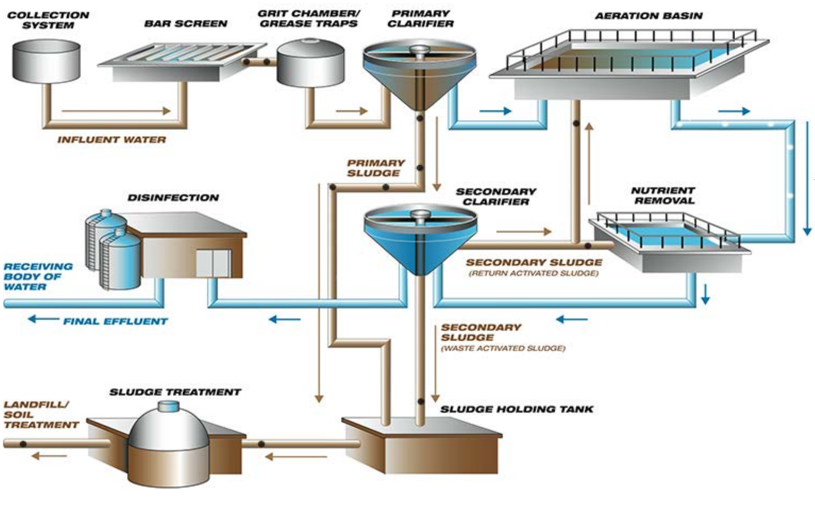

Figure 1. Typical waste water treatment process.

Bangladesh is a developing country, where water treatment and sanitation are currently facing tremendous challenges. Bangladesh has developed in water accessibility and arsenic reduction from various sources of water even though having various internal problems. Responsiveness about sanitation and hygiene has been enhanced considerably in recent times. A number of local and international organizations are trying to lessen the water-related issues. Many initiatives have been taken to set up tube wells for safe water sources. But the quality of water from those tube wells is now and then contaminated. Around 11% of death by diarrhea is associated with the use of unprocessed groundwater [3]. Pollution is more severe in areas with clay and slit layers. In accumulation, indecent placement of latrines and discharge of unprocessed effluent in the surface water are creating more severe infectivity.

In Bangladesh, underground water layer diminution is one of the most significant issues. A research of 2011 shows that in Bangladesh, diminution of groundwater was around 0.01–0.05 m/year. Over the last 50 years, the growth of extraction of groundwater was 20–260 km^3/year [4]. Water extraction for cultivation by deep tube wells are the main sector of groundwater pollution. The condition of water infectivity is quite different in urban and rural areas. Water scarcity is a serious issue in urban areas; as on-ground water is infected by toxic effluent discharge. In rural areas, relatively more people have user-friendliness to water sources. In the past few years, arsenic was a major issue for the people of Bangladesh. Somehow, this condition is overcome by making significant efforts to decrease this problem. Rural areas still lag in treatment conveniences of wastewater. Village residents discharge wastewater is almost untreated to the nearest water bodies, though there is an enormous potential of this wastewater to be reused in agricultural fields. Such initiative will not only reduce groundwater demand but can also serve as a healthier environment if accurate treatment is provided.

Several works have been done on waste water treatment in the last few years. Deborah Panepinto et al. anticipated a research presents a multi-step methodology for the assessment of the energetic aspects of wastewater treatment, which was implemented on the largest city in Italy (2.7 M population equivalents as organic load), managed by Società Metropolitana Acque Torino (SMAT) [5]. Waste water treatment high rate algal ponds (WWT HRAPs) are a gifted technology that could help to solve water pollution challenges concomitantly where climate condition is favorable. Generally, 800–1400 GJ/ha/year energy (average biomass energy content: 20 GJ/ton; HRAP biomass productivity: 40–70 tons/ha/year) can be generated in the form of harvestable biomass from WWT HRAP, which eventually can be used to fulfill community-level energy demand [6]. Chen et al. showed different electrochemical techniques for treating wastewater. Though all the systems were effective all of them had very high initial cost and there was a huge chance of chemical exposure [7]. Crini et al. reviewed 4 types of the treatment system and researched on the absorbent based biological treatment process. The system was only applicable for industries and high scale treatment process; cost is moderate but high risk of contamination via absorbents [8]. Liu et al. worked on three types of chemical system to purify industrial wastewater and did a development plant to produce electricity in the meantime of purification by using a single microbial fuel cell. The researchers mainly focused to produce electricity and systems had the low effectiveness of treatment process [9]. Le-Clech et al. did a research on membrane utilized treatment system via bio-reactor; used osmosis and reverse osmosis process to treat wastewater. Bio-reactors are very tough to settle and only applicable for the non-tropical region [10]. Kampschreur et al. conducted a research project on water treatment plants and determined the adverse effects of different centralized treatment processes. The system was effective but a huge amount of NOx was produced while implementing [11].

Singh et al. did a compact review on treating water using microbial fuel cells along with electricity generation, showed various drawbacks of this process. It has higher efficiency, but it hampers the normal living of micro-organisms of the pond [12]. Fu et al. reviewed various treatment process and found zero-valence iron to be an effective treatment effluent. Only natural treatment processes can use zero-valence iron. High risk of iron ion contamination in groundwater was the major deficiency of the plant [13]. Yuan et al. did a research on urban areas on waste water treatment processes using a decentralized technique. This process is also applicable for urban areas where the underwater level is good enough [14]. Seto et al. did a case study on centralized treatment process on San Francisco and found that centralized systems the higher possibility of micro-organism contamination [15]. Ms. Ayesha Sharmin did a master thesis about introducing de-centralized treatment technology on Bangladesh on 2016 at Lund University where she described the pros and cons about that technology very clearly [16].

All the above electrochemical processes are very much costly and the other processes were invented for industrial and urban wastewater treatment and a large population. These plants are not very much effective while Bangladesh is a poor country and most of the people live under the poverty line. For Khulna district of Bangladesh, it is necessary to find or invent a method to treat water which would be efficient and can be implemented at low cost. In April, 2018, Avijit Mallik and Md. Arman Arefin published a research about introducing and design of a de-centralize treatment plant for southern Bangladesh [17]. This research is the extended part of the previous one. In this paper, a new technique is designed and discussed for decentralized wastewater treatment with primary and secondary treatment processes which has high efficiency and plant initial and running cost is low. This plant is very much effective for a big family or three-four small families. All the designed sections are discussed and their advantages and disadvantages are evaluated from the perspective of rural areas of Bangladesh. Detailed feasibility analysis of the designed plant is conducted including installation cost and payback period.

2. Quality & present treatment of drinking water in Bangladesh

According to Bangladesh national drinking water survey 2009, "22 million people are still drinking water that does not meet the standard level for arsenic of 0.05 mg/L and 5.6 million are in high risk of having water with more than 0.2 mg/L arsenic" [18]. Table 1 shows the standard values of different elements in water according to Department of Public Health Engineering and World Health Organization. Some common elements have been selected in this table. In recent few years, arsenic was a very big issue of concern for Bangladesh. BOD, COD, nitrate, phosphate, and chloride are very important elements for drinking water. An excessive amount of these elements can cause a health hazard. Drinking water should contain the following elements according to the standard stated in Table 1 [19].

The survey also stated that "*98% of the tested samples meet the Bangladesh standard of 600 mg/L for chloride concentration*". Fluoride concentration was not so high according to this survey. Six samples (1%) exceeded the Bangladesh standard of 1.1–1.5 mg/L. But, iron concentration seems to be a little bit concerning in the edible water. Throughout the country, only 60% of the tested samples meet the national standard of 1 mg/L iron. The other 40% is below the standard. The amount of phosphorus in almost 93% of the sample meet the standard value 1.96 mg/L, which is equivalent to 6 mg/L phosphate.

Table 1. Water quality parameters.

Sl. No.	Water Quality Parameters	Bangladesh Standards (mg/L)	WHO Guide Line	Methods/Equipment
01	Aluminum	0.2	–	Atomic Absorption Apectro-photometer (AAS)
02	Ammonia	0.5		UV-VIS
03	Arsenic	0.05	0.01	AAS
04	Barium	0.01	0.7	AAS
05	Benzene	0.01	0.01	Gas Chromatograph
06	BOD 5 day, 20 ºC	0.2	–	5 days Incubation
07	Boron	1.0	–	UV-VIS
08	Cadmium	0.005	0.003	AAS
09	Calcium	75	–	AAS
10	Chloride	150–600	–	Titrimetric
11	Chlorinated Alkenes			
11.1	Carbontetrachloride	0.01	0.004	Gas Chromatograph
11.2	1.1 DichloroEthelene	0.001	0.03	Gas Chromatograph
11.3	1.2 DichloroEthelene	0.03	0.03	Gas Chromatograph
11.4	TetrachloroEthelene	0.03	0.04	Gas Chromatograph
11.5	TrichloroEthelene	0.09	0.07	Gas Chromatograph
12.1	Pentachlorophenol	0.03	0.009	Gas Chromatograph
12.2	2,4,6-Trichlorophenol	0.03	0.2	Gas Chromatograph
13	Chlorine (Residual)	0.2	–	Titrimetric
14	Chloroform	0.09	0.2	Gas Chromatograph
15	Chromium (Hexavalent)	0.05	–	Iron Chromatograph
16	Chromium (Total)	0.05	0.05 (P)	AAS
17	COD	4	–	Closed Reflux Method
18	Coli form (Fecal)	0 CFU (N/100 mL)	0	Membrane Filtration Method
19	Coli form (Total)	0 CFU (N/100 mL)	0	Membrane Filtration Method
20	Color	15 Hazen	–	Color Comparator
21	Copper	1	2	AAS
22	Cyanide	0.1	0.07	UV-VIS/Specific Ion Electrode
23	Detergent	0.2	–	UV-VIS
24	DO	6	–	Multimeter
25	Electric Conductivity	–us/cm	–	Multimeter
26	Fluoride	1	1.5	UV-VIS
27	Hardness as $CaCO_3$	200–500	–	Titrimetric
28	Iodine	200–500	–	Titrimetric
29	Iron	0.3–1.0	–	AAS
30	Nitrogen (Total)	1	–	UV-VIS/Digestion

Continued on next page

Sl. No.	Water Quality Parameters	Bangladesh Standards (mg/L)	WHO Guide Line	Methods/Equipment
31	Lead	0.05	0.01	AAS
32	Magnesium	30–35	–	AAS
33	Manganese	0.1	–	AAS
34	Mercury	0.001	0.001	Mercury Analyzer
35	Nickel	0.1	0.02 (P)	AAS
36	Nitrate	10	50.0 as N	UV-VIS
37	Nitrite	<1	3.0 (0.2)	UV-VIS
38	Odor	Odorless	–	Threshold Method
39	ORP (Eh)	–	–	ORP meter
40	Oil and Grease	0.01	–	Oil and Grease meter
41	pH		6.5–8.5	pH Meter
42	Phenolic Compounds	0.002	–	Gas Chromatograph
43	Phosphate	6	–	UV-VIS
44	Phosphorus	0	–	Digestion
45	Potassium	12	–	AAS
46	Radioactive Materials (Gross Alpha Activity)	0.01 Bq/L	0.5 Bq/L	–
47	Radioactive Materials (Gross Beta Activity)	0.1 Bq/L	1.0 Bq/L	–
48	Salinity	–	–	Multimeter
49	Selenium	0.01	0.01	AAS
50	Silver	0.02	–	AAS
51	Sodium	200	–	AAS
52	Suspended Solids	10	–	Filtration and Drying
53	Sulphide	0	–	UV-VIS
54	Sulphate	400	–	UV-VIS
55	Taste	–	–	Threshold Method
56	Total Alkalinity	–	–	Titrimetric
57	Total Dissolved Solid	1000	–	Multimeter
58	Temperature	20–30 C		Thermometer
59	Tin	2	–	AAS
60	Turbidity	10 NTU	–	Turbidity meter
61	Zinc	5	–	AAS

In Dhaka city, normally water is pumped from deep aquifers. However, the quality does not remain similar to the consumers. Along with its transport through the pipe network, a number of sources cause contamination of the water. The negative pressure of the pump, leakage in the pipes, service installation networks under septic tanks etc. are reasons behind water contamination in the pipe network [20]. Bangladesh government has introduced rules and regulations to protect their water and environment. Different governmental organizations, as well as NGOs, work for implementing regulations. The Department of Environment (DoE) is a government organization, it works on that basis. This organization has created a mobile court in order to implement action against environment conservation violator under the ECA Act, 2010. “Polluters pay principal” is mentioned in the ECA, 1995 [21]. Table 2 represents guidelines for different parameters in surface water. Surface water used by different activity should maintain the concentration of various parameters according to the table below [18,19].

Table 2. Standard for surface water.

Parameter	Irrigation	Agriculture	Drinking	Treated Values
pH	6–8.73	6.00–8	6.5–8.5	6–6.5
EC (Us/m)	0–3.00	0.20–0.25	0.25	0.3–0.4
DO (ppm)	4.25–5	5	3.5–5	3–4.8
TDS (ppm)	0–1900	150	450–510	350–420
Total Nitrogen (ppm)	0–32.00	0–0.1	1	4–4.9
Phosphorus (ppm)	0–2	0–0.1	N/A	9.8–10
Cadmium (ppm)	0–0.0125	0.25–1.8	0–0.002	0
Iron (ppm)	3.5–5.00	0.2	0–0.068	1.5–1.75
Manganese (ppm)	0–0.22	0–0.009	0–0.02	0.15

The National Environment Management Action Plan (NEMAP), 1995 includes identification of major environmental issues and action to minimize environmental degradation improving natural environment by conserving biodiversity. The different international organization also helps financially by providing a fund for implementing environmental regulations in Bangladesh namely DANIDA, SIDA, USAID, CIDA etc. [22].

2.1. Urban treatment process

In urban areas, DWASA is responsible for treating potable water for the community, in the capital city Dhaka. DWASA is currently running one large and three small water treatment plants with financial assistance from different funding organizations. According to the department of public health and engineering of Bangladesh, most of the treatment facilities include filtration, flocculation, sedimentation, and disinfection. Some also include ion exchange and filtration depending on the quality of collected water. A groundwater rule is developing to specify the appropriate use of disinfection to assure public health protection.

However, to meet the fastest growing water demand and reduce groundwater extraction, DWASA planned to build four large surface water treatment plants until 2021. These plants have been proposed to draw water from less polluted surface water even though they are distant sources such as rivers. The four plants are expected to have a combined capacity of 1.63 million cubic meters surface water per day, whereas in 2010 the supply of groundwater was 2.11 million cubic meters per day [23,24].

2.2. Rural treatment process

Easy availability and no content of pathogenic microorganisms make groundwater so popular that most of the rural population is now dependent on low-cost tube wells. Studies stated that Bangladesh achieved a remarkable success providing 97% of the rural population with bacteriologically safe tube well water. In some regions where tube well’s water is not trusted worthy, people usually boil water for purification. Arsenic contamination is one of the major challenges in the shallow aquifers and many parts of the country have made shallow tube well water unsafe for drinking. Different strategies have been developed to mitigate the arsenic problem. Those are classified as chemical and non-chemical treatment. Pond sand filters dug and ring well, chili water purifiers (CWP) are some nonchemical solution for arsenic contamination. Chulli water purifier is a special type of clay oven with the metal coil. Water is passing through the coil and gets purified from arsenic by heat. Chemical options include different types of filters such as SIDKO, SONO, READ F, and AIKAN [25].

3. Materials and methods

The current research is mainly focused on wastewater treatment. In this paper, a new economical wastewater treatment process for the rural areas has been proposed and designed. The process is mainly a de-centralized water treatment technique. Decentralized wastewater treatment does not mean one specific plant for the whole population in a defined area but it rather defines more than one or an assortment of technologies. The system is mainly designed for a low to moderate population and small-scale treatment [26]. Decentralized wastewater systems are appropriate especially for semi-urban and rural communities, where population density is comparatively low and scattered. In the proposed treatment method, septic tank and anaerobic pond in village area are supposed to be considered. Different parameters (like BOD, COD, weather conditions and etc.) which are primarily considered to design a septic tank and anaerobic pond are first collected and analyzed. In designing the septic tank and anaerobic pond, the influences of these parameters are considered. To make the effluent in quality of an acceptable level, the primary treatment is not enough [22–44], hence a facilitative pond is chosen where the secondary treatment can be conducted. The design method includes empirical equations. Area requirement for various onsite treatment options has been calculated. Nitrogen and phosphorus removal with these systems have also been discussed. In designing process, the required different parameters were taken from different experimental results conducted by different researchers and organizations.

3.1. Design of a wastewater treatment process

To evaluate the recommended decentralized treatment option in rural areas of Bangladesh, a typical village in the middle part of the country has been selected as a case to make a design of the proposed treatment process, which is decentralized wastewater treatment.

3.1.1. Area selected for design

The village named "Sundermahal" is situated in Surkhali union, Batiyaghata Upazila, Khulna District, and Khulna division. The area is mostly flat and the climate is tropical. The average temperature for this area is about 29.9 ºC and the total annual precipitation is about 1812 mm. Precipitation/Rainfall is the lowest in December, with an average of 6 mm; most of the precipitation here falls in July, averaging 357 mm [27]. In 1988, 1992, 1994, 1997, 2005 and 2011 a number of flood damages were recorded [28]. According to Population Census 2011, the total population of this village is 1233 with 236 households [29]. Agriculture is the main occupation in this area. Tube wells are the main sources of drinking water. Almost 93% of the population use tube wells for potable water collection. Also, ponds and other surface water sources are available for collecting water. In this area, almost 36% of the households use sanitary latrines and 58% has unsanitary latrines. Almost 6% has no latrines at all [30]. So, it indicates that this area has a deficiency in sanitation. No information of wastewater treatment facility was found for this area. Figure 2 gives an overview of Southern Bangladesh (South-Bengal).

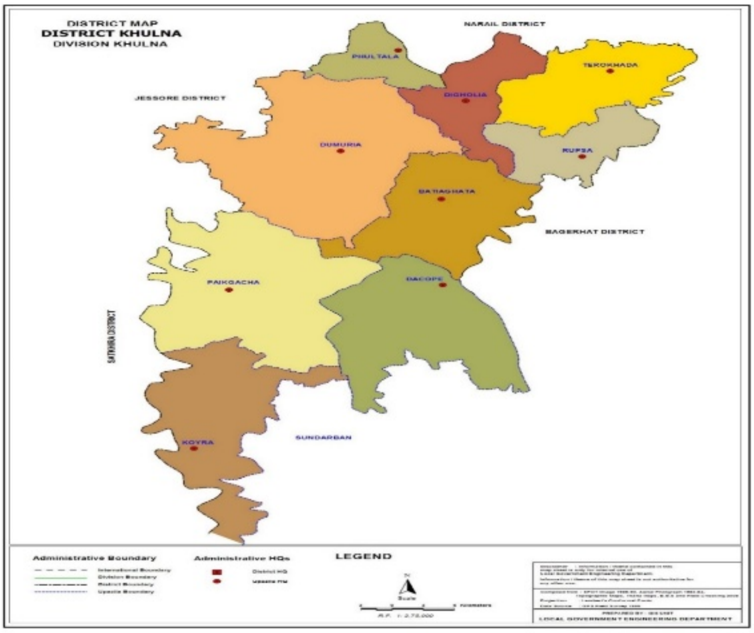

Figure 2. Location of the selected area.

In the data source used, 30 km^2 areas were given for the total area of the Upazila including 15 other villages. To make the calculation simple, it has been assumed that all the villages are similar in size. Then the area of the selected village has been found about 2 km^2. The condition presented is a typical condition for most of the villages in Bangladesh. There is a significant improvement potential in latrine use and reduction of open defecation but still, people are at risk without any proper wastewater management. The only use of latrines cannot be a single solution, also appropriate wastewater treatment is needed to complete the process and make a healthy environment. In Tables 3 and 4, an approximated estimation of Khulna's water consumption per capita along with source wise consumption has been done using available data provided by KWASA.

A typical survey was done to achieve some important values. The average temperature was 30 ºC. The average pH values ranged approximately 6.5–7.8. The Demand of Oxygen (DO) and ORP results had no such abruptions. Some other very important parameters were noted and those were analyzed with other case reports made on the same topic of interest and our results seemed to be with no significant difference. Table 5 represents the compared results and shows different ranged values of important parameters regarding various types of water based on uses [31].

Table 3. Water source wise population of Khulna.

Calculation of Served Population	Numbers (Approximated)	Remarks
KWASA's Tube Wells		
1. Registered Connections	15000	
2. Inactive	2579	
3. Active	12672	(Registered—Inactive)
4. Consumers per each	13.5	
5. Served Population	171100	(Active X Consumers per each)
Street Hydrant		
6. Total	503	
7. Inactive	403	
8. Active	100	(Total—Inactive)
9. Consumers per each	100	
10. Served Population	10000	(Active X Consumers per each)
KWASA's Hand Pumps		
11. No. of Deep Hand Pumps	3748	
12. No. of Shallow Hand Pumps	5538	
13. Consumers per each	30	
14. Served Population	278600	(Deep Hand Pumps/Shallow Hand Pumps) X Consumers per each
Private Wells		
15. Total	13733	
16. Consumers per each	30	
17. Served Population	412000	(Total X Consumers per each)
18. Uncategorized	85300	

Table 4. Water source wise water use in Khulna.

Water source	Use	Remarks
KWASA's Tube wells	No. of Consumers: 171,100 + 10,000 = 181,100 Water supply: 30,100 m^3/day Loss: 30,100 × 0.40 = 12,040 m^3/day Net supply: 30,100 − 12,040 = 18,060 m^3/day Non-Domestic: 18,060 × 0.2 = 3,610 m^3/day Domestic = 18,060 − 3,610 = 14,450 m^3/d LPCD = 14.45 − 1000/181,100 = 80 L/day/person	Water Loss: 40% (Approximated)
KWASA's Hand Pumps	No. of Consumers: 278,600 Water supply: 39,300 m^3/day Loss: 39300 × 0.10 = 3,930 m^3/day Net supply: 39,300 − 3,930 = 35,370 m^3/day Non-Domestic: 35,370 × 0.2 = 7,070 m^3/day Domestic = 35,370 − 7,070 = 28,300 m^3/d LPCD = 28,300 × 1000/27,8600 = 102 L/day/person	Water Loss: 10% (Approximated)

Continued on next page

Water source	Use	Remarks
Private Pumps	No. of Consumers: 412,000 Water supply: 49,700 m^3/day Loss: 49,700 × 0.10 = 4,970 m^3/day Net supply: 49,700 − 4,970 = 4,4730 m^3/day Non-Domestic: 4,4730 × 0.2 = 8,950 m^3/day Domestic = 44,730 − 8,950 = 35,780 m^3/d LPCD = 35,780 × 1000/412,000 = 87 L/day/person	Water Loss: 10% (Approximated)
Total	No. of Consumers: 957,000 Water supply: 119,100 m^3/day Loss: 20,940 m^3/day Net supply: 98,160 m^3/day Non-Domestic: 19,630 m^3/day Domestic = 78,530 m^3/d LPCD = 78,530 × 1000/957,000 = 87 L/day/person	N/A

Table 5. Pond quality during wet season.

Parameters		Domestic	Wastewater storage	Agriculture	Fisheries	Urban Domestic
SS (mg/L)	Avg.	10–12	14–25	7–13	29–40	20–32
	Max	50	55	21	75	100
	Min	<1	<1	6	6	0.60
TOC (mg/L)	Avg.	7–12	10–19	12–15	12–15.5	10–13
	Max	16	40	20	21	17
	Min	2–2.5	4.4	5.5	5.4	4.3
T-N (mg/L)	Avg.	1–1.56	2–3.56	0.4–0.72	1.61	2.1–3.33
	Max	2.8	13	1.33	4.67	4.3
	Min	0.3	0.4	0.33	1.12	1.113
T-P (mg/L)	Avg.	0.1–0.2	0.7–1.2	0.013–0.05	0.1–0.223	0.65–1
	Max	1.1	2.77	0.122	1.12	1.765
	Min	0.01	<0.03	<0.01	0.01	0.01

3.1.2. Estimation of water flow and BOD_5

Before designing the process, some basic parameters have been collected from various sources. Among them, average water consumption in rural areas of Bangladesh was found to be 83.17 liters/person/day [32]. It is a bit lower than the urban water consumption. This could be due to less water availability or poor economic condition. Average daily water consumption Q = 83.17 liters/person/day = 0.083 m^3/person/day (Appendix 1) will result in an average daily wastewater flow Q_D = 87.17 m^3/day, where, wastewater flow is assumed to be 85% of daily water consumption. Table 6 includes BOD, TN, N as NH_4^+ and TP in the daily wastewater flow. It also includes required an amount of BOD, N, and P in the effluent for water use in irrigation. Average BOD_5 in the influent is calculated in Appendix. The required BOD value in the effluent is found from Table 6. The required values for nitrogen and phosphorus in the effluent are found from a report named Water Quality for Agriculture. The average amount of TN, N, and TP in the influent is estimated as typical content in municipal wastewater with a minor industrial contribution. Calculations are found in Appendix 1. Table 6 shows concentration in effluents and influents [33].

Table 6. Concentration of various parameters in influent and effluent.

Sl. No.	Items	Level-1 (A)	Level-1 (B)	Level-2	Level-3
1	COD (mg/L)	50	60	100	120
2	BOD_5 (mg/L)	10	20	30	60
3	SS (mg/L)	10	20	30	50
4	Oil (Animal/vegetable) (mg/L)	1	3	5	20
5	Petroleum (mg/L)	1	3	5	15
6	Ammonia (mg/L)	15	20	−	−
7	TP	0.66	1	3	5
8	pH	6.7	6.5	7.9	8.2
9	Colon Bacillus (p/L)	1000	10000	10000	−

*Note: Levels denotes various stages of wastewater.

BOD in the influent is calculated from an empirical equation (Appendix 1), for influent BOD, C_0 = 1000 B/Q_D, BOD contribution per day (B) is assumed to 40 g/capita/day for medium-sized communities.

3.1.3. Primary-treatment facility

A primary treatment is needed to make the whole treatment process more efficient and to reduce the organic load in the secondary treatment. A septic tank is one of a common type of primary treatment. Also, anaerobic ponds can also act as a primary treatment tool. Septic tank can be installed in each household or one anaerobic pond can be used for the whole community.

4. Results and discussion

4.1. Design of septic tank

An Indian standard code will be used for the design of the septic tank in “Sundermahal” village. Figure 3 represents recommended the size of septic tanks according to the number of users (Bureau of Indian standards, 1993).

If 5 persons in each house are assumed for the selected village, then from Figure 3 the size of a septic tank can be found to be of 1.5 m long and 0.75 m wide. The depth is assumed 1.3 m including 1 m depth from the outlet pipe to the bottom of the tank and 0.3 m distance from roof to liquid. So, a 1.13 m^2 septic tank is recommended for each household in this village.

V (volume of septic tank) = (1.5 × 0.75 × 1.3) = 1.46 m^3 (approximately).

This septic tank can store 1460 L liquid and each of the houses will need a septic tank of approximately 1.46 m^3. Several requirements are stated for installing a septic tank. It should be 60 m away from any community well, 9 m away from any buried water storage tank and 15 m from any source of potable water or natural water body [34–36]. A septic tank can remove BOD, TSS, oil, and grease. Typically, a septic tank can remove 30 to 50% BOD and 60 to 80% TSS.

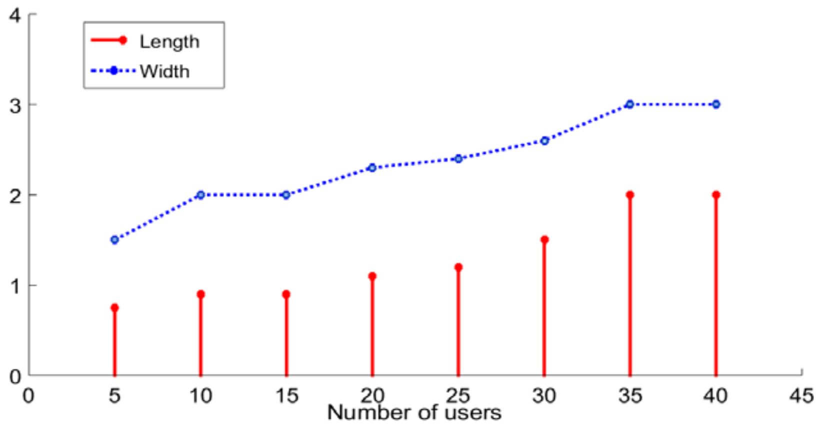

Figure 3. Length and width of septic tank according to the number of users.

4.2. Design of anaerobic pond

Design of an anaerobic pond below has been done using waste stabilization pond and Constructed Wetland Design Manual:

$$\text{Volume of anaerobic pond, } V_A = C_0Q_D/\lambda_v \quad (1)$$

$$\text{Hydraulic retention time, } t_{AN} = V_A/Q_D \quad (2)$$

From Eq 1, V_A = 141 m^3 (Appendix 2); for temperature > 25 °C; λ_v = 350 g/m^3/day [9]. The depth of the anaerobic pond is considered to be 3 m and the area would then be almost 37 m^2. Hydraulic retention time, t_{AN} = 1.6 days (approx.) (Appendix 2). The minimum value of retention time is recommended to be one day. With the designed anaerobic pond almost 70% BOD removal is possible at the temperature above 25 °C [37].

4.3. Secondary treatment

Only a primary treatment is not enough to make the effluent in quality of an acceptable level. With the above design of septic tank and anaerobic pond, 30 to 70% of BOD removal is expected. For secondary treatment different options can be chosen, such as wetland, facultative pond or sand filters. Depending on the geography, landscape and weather condition various options can be adopted.

4.4. Design of facultative pond

$$\text{Area of facultative pond, } A_F = 10C_0Q_D/\lambda \quad (3)$$

In Bangladesh, the average temperature is assumed to be more than 25 °C. Here in the calculation 28 °C have been used. In this design, a primary treatment has already been suggested. In primary treatment, for septic tank almost 30% BOD is removed. So, in further secondary treatment design, a reduced BOD in the secondary influent is assumed.

From Eq 3, $A_F = 784.692\ m^2$ (Appendix 3):

$$\text{Retention time, } T_F = A_F D/Q_M \quad (4)$$

Where D is the depth of the pond (1.5 m usually) and Q_M is mean flow, Q_I is influent flow, Q_E is effluent flow and "e" is evaporation rate. Evaporation rate for Bangladesh is found from a historical data study and the values vary with temperature during the year. An average monthly evaporation value of 120 mm for 28 °C is considered in this calculation [44]. From this, a daily evaporation rate can be calculated. Average daily evaporation rate (e) = 120/30 = 4 mm/day. Let;

$$Q_M = (Q_I + Q_E)/2 \quad (5)$$

$$Q_E = Q_I - 0.001\ A_F.e \quad (6)$$

From Eqs 5 and 6, $Q_E = 84\ m^3$/day; $Q_M = 85.67\ m^3$/day = 86 m^3/day. Then, putting values of Q_M and Q_E in Eq 4, T_F = 14 days (approx.) (Appendix 3). Again, if an anaerobic pond is considered as a primary treatment, from the above equation the area for facultative pond becomes 260 m^2 and the retention time found 6 days. This variation is because of the high BOD removal in the anaerobic pond, with almost 70% BOD removal in an anaerobic pond.

4.5. Design of wetland

$$\text{Area of reed bed of wetland, } A_W = K.\ Q_D\,(\ln C_0 - \ln C_t) \quad (7)$$

K is a rate constant, the value found for BOD removal K_{20} = 180 m/year = 0.5 m/day for subsurface wetland and θ is constant and the value is 1.1 [22–25].

$$K_T = K_{20} \times \theta^{(T-20)} \quad (8)$$

$K_{28} = (0.5)\times(1.1)^{28-20}$ = 1.08 m/day (for 28 °C)

Using values of K in Eq 7, $A_W = 346.386\ m^2$ (approx.) (Appendix 4).

This area for subsurface wetland is calculated with 30% BOD reduction from the septic tank. The value varies if an anaerobic pond is used as a pretreatment. Then the area needed will be 209 m^2. The depth of the wetland designed above is considered to be 0.6 m. Eqs 7 and 8 have been collected from reference no [38–40].

4.6. Design of sand filter

Using guidelines from Washington State Department of Health (2012) and LGED, Bangladesh (2016) an intermitted sand filter is designed below:

$$\text{The surface area of filter bed, } A_S = Q_D/\text{Loading rate} \quad (9)$$

The maximum loading rate is 2 to 5 gal/day/square feet recommended in the EPA design manual; the depth of media is 46–91 cm [32–38]. Design loading rate is considered 4 gal/day/square feet. $A_S = 534.785\ m^2$ (approx.) (Appendix 5). 420 m^2 sand filters are found to be suitable for loading rate 4 gal/day/square feet.

5. Design summary

The above design shows an overview of the total decentralized system for a typical village. The area of the village is about 2 km^2 (assumed). Primary treatment facilities show, occupying a small area of about 37 m^2 for the anaerobic pond. For secondary treatment, the area of a wetland found was almost half of the facultative pond. To implement a facultative pond of 784.926 m^2 in this small area will not be suitable. In the above design, several systems are discussed with an example size of the treatment facility. Also, a comparison between options has been done to evaluate suitable options according to the situation. To make the effluent reusable; required BOD value has been calculated according to the requirements given by the government in Table 6. As nutrient concentration is important for reusing the effluent water in irrigation, nitrogen and phosphorus removal has been discussed. With a facultative pond, the effluent fulfills requirement given in Table 2. But for the other two systems, N and P concentration was higher than the requirement.

From studies it has been seen that de-centralized wastewater managements have very high potential on nitrogen and phosphorus removal. A normal series of wetland and facultative pond can remove almost 70% of N and 55–60% of P [41,42]. Normally, P removal is proportional to atmospheric temperature. If the designed plant above has an efficiency of 65% (assumed) in both N and P removal then the effluent amount will be 8.1 mg/L and 1.5 mg/L respectively. From Tables 2,4 and 5 the values seem to be effective. Further analysis on N and P removal shows that this system can sustain up to 65% of nominal efficiency and the wetland along with sand filter can totally can remove up to 21.2 mg/L of N and 11.9 mg/L of P.

6. Feasibility of the proposed plant

De-centralized management system for wastewater treatment has been briefly discussed in this paper and a design has been made regarding economy and environment of Bangladesh. Here, a technical and operational feasibility will be discussed. To apply this system on Bangladesh the first hindrance is local acceptability and govt. funding. USA and Sweden have already applied and made great success on this type of wastewater treatment technologies for their urban domestics. Recently, China applied this technology and they also found great after results. Bangladesh and China have almost same type of environment and soil mostly on every part. So, to apply de-centralize wastewater treatment for Bangladesh it is highly recommended to follow China's plan on DWWT implementation [43,44]. Figure 3 shows the tabular schematic about implementing DWWT in Bangladesh.

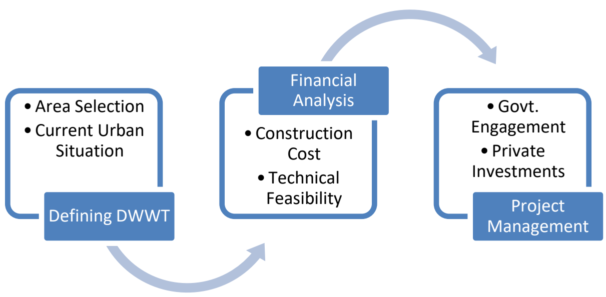

Figure 3. Structure of proposed method.

6.1. Technical feasibility

Feasibility analysis is usually done to see if the system is compatible with the environment or not. Installation and running cost is also analyzed in this section. Mathematically:

$$N_k = \sum_i^n \{TP_i \times R_i \times WU_i + TP_i \times (1 - R_i) \times WUN_i\} \times 365 \times C_k \times \alpha \div 10^9 \qquad (10)$$

$$TW = \sum_i^n TPF_i \times WU_i \times \alpha \div 1000 \qquad (11)$$

Here,

N_k = total emission of pollutant "k" in kilo-tons/day (where, k_1 = COD, k_2 = BOD_5);

TW = total domestic wastewater emission from small towns and villages in a year "n" in kilo-tons/day;

R_i = ratio of served population within supply area "I" in %;

WUN_i = per person water consumption within supply area "I" in L/d;

C_k = concentration of pollutant in domestic waste, mg/L;

A = proportion of waste discharge to water consumption;

TPF_i = total population in the area "i" in the year "n" in per thousands.

Here,

$$TPF_i = TP_i \times (1 + R_p)^6 \qquad (12)$$

Where, Rp = Avg. growth of population, %.

Below Table 7 shows the approximated rate of wastewater discharge in Khulna from the equations stated above.

Table 7. Approximated wastewater discharge from Upazila's and Villages of Khulna per day.

Area	Wastewater from Upazila (Small towns) (kilo-tons/day)	Wastewater from villages (kilo-tons/day)	Total (kilo-tons/day)
Phultola	8000.9	200	8200.9
Digholia	1204.33	430	1634.33
Terokhadia	3747.853	124	3871.853
Paikgacha	2300	7200	9500
Dumuria	1366.9	9335.777	10702.677
Rupsha	7300	35	7335
Koyra	22	3750	3772
Dakope	12.5	7400	7412.5
Batiyaghata	1430.3	8337	9767.3
		Total:	62196.56

6.2. Environmental impact analysis of DWWT

To analyze the impact on environment, estimation of pollutant reduction plays a very important role. If establishing a new system cannot control pollutant emission then the system will not be feasible for environment. So, estimating the amount of pollution reduction is very important. Mathematically it can be denoted as:

$$TR_k = {TW_n \times C_k \times 365 \times r}/_{10^6} \quad (13)\ [44]$$

Where, TR_k → total reduction of pollutant "k" in kilo-tons per year;

TW_n → total amount of domestic wastewater in the year "n" in kilo-tons = 62196.56 kilo-tons/day;

R → treatment percentile ratio in "%" = 40% (can be upgraded to 80%) [47];

C_k → concentration of pollutant "k" in mg/L = 20 – 100 mg/L [38,42–44].

If results seem positive and has a satisfactory ration between each then the system can be said to be environment friendly. In our designed system, from Eq 13, the result is approximately 90806.9776 kilo-tons/year, which is a huge reduction rate. Capacity of single unit treatment plant = 10000 tons/day [27–38]. Total needed plants in Khulna district = $TR_k \div (365 \times Capacity\ of\ unit\ treatment\ plant) = 90806977.6/(365 \times 10000)$ = 25 (approx.). So, each upazilla will need 25/9 = 3 treatment plants, which will be of the same unit sized.

6.3. Financial analysis for DWWT construction and operation

In this section, financial issues about DWWT development are discussed. Financial demand and pressure for DWWT construction in each upazila area is estimated below along with recommendations on financial structure are provided. At last, operation cost of DWWT facility and the local residents' payment capacity has been analyzed.

6.3.1. Construction cost of DWWT facilities

The cost demand of DWWT construction in each basin area is calculated by the following formula:

$$M = TW_n \times p \times r/1000 \quad (14)$$

In which:

M → cost for construction of DWWT, million USD;

TW_n → amount of domestic wastewater from small towns and villages in a year "n", kilo tons/day;

p → construction cost of unit treatment capacity, USD/(ton/d);

r → target of treatment rate in year "n", %.

As the DWWT definition is not familiar in Bangladesh so the exact construction and maintenance cost cannot be calculated nor any govt. reports regarding this technology has been found. So, for reference, 17 previous project reports from China, USA and Sweden has been studied with treatment capacities below 10000 tons/d built between 1996 and 2007 and their cost estimation techniques were investigated to make a rough assumption on DWWT establishment costing for Bangladesh [45–47]. Table 8 shows an estimated cost of unit treatment capacity plant.

Based on studied projects and reports, the unit construction will vary from 500–2000 USD based on design and utility structures. Our basic designed will approximately cost around 650 USD for primary setup. Considering a possible pipeline expansion cost this system needs minimum 800 USD for construction.

Table 8. Construction cost of unit treatment capacity plant (in USD).

Capacity Tons/day	Wetlands (constructed)	Infiltration (Rapid)	Filtration (Catalytic)	Filtration (Biological)	Activated Sludge	Aerated Lagoon	Total
400–500	–	–	257.8	120	–	135	420–550
500–1000	145	–	230.55	–	433.62	–	650 (approx.)
1000–1500	–	112	–	–	–	–	n/a
1500–2000	132	–	–	–	–	–	n/a
2000–2500	152	–	–	134	544.4	–	750–1000
2500–3000	–	–	–	144	–	–	800–1400
3000–8000	233	91	267.78	1200	947.5	102	2000 (approx.)

6.3.2. Operation cost

In this section, the operation cost of DWWT facility is estimated according to existing small wastewater treatment projects. Combined with the sewage charge level of urban wastewater treatment and payment capacity of rural residents, the sewage charge policy of DWWT is discussed. Case studies are cited to estimate the operation cost of DWWT [48,49], which includes energy cost (C_1), medical cost (C_2), labor cost (C_3), depreciation cost (C_4), heavy repair cost (C_5), maintenance cost (C_6), management cost (C_7) and interest cost (C_8). According to relevant design standards [50–52]:

$$C_1 = e \times d \times 365 \tag{15}$$

Where, e → daily electricity consumption, kWh/d.
d → electricity price, USD/kWh.

$$C_2 = Q.\ a.\ b \tag{16}$$

Here, Q → treatment capacity, ton/d;
a → medical consumption, mg/L;
b → medical price, USD/ton.

$$C_3 = \text{Labor salary} \times \text{number of labors} \tag{17}$$

$$C_4 = \text{original value of fixed assets} \times \text{depreciation rate} \tag{18}$$

$$C_5 = \text{original value of fixed assets} \times \text{heavy repair rate} \tag{19}$$

$$C_6 = \text{original value of fixed assets} \times \text{maintenance rate} \tag{20}$$

$$C_7 = (C_1 + C_2 + C_3 + C_4 + C_5 + C_6) \times 15\% \tag{21}$$

$$C_8 = \text{total debt} \times \text{annual interest rate} \tag{22}$$

$$\text{Total cost, TC} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 \tag{23}$$

$$\text{cUnit treatment cost, UC} = \frac{TC}{\sum Q} \quad (24)$$

In which, $\sum Q$ is the total amount of treated wastewater. The depreciation rate is 5% (equipment 5.33%, sewage pipeline 3.2%, automatic control equipment 9.6%, main structure 3.2%), heavy repair rate is 2%, and maintenance rate 1% [42–52]. Each financial channel has its potential role and possible problems when used in DWWT. Therefore, a multiple financial structure is recommended so that various financial channels could be complementary to each other. The suggestions in previous sections provide basic principles on choice of financial structure with regard to local economic conditions. However, further research based on detailed information of each area is required. In the short term, local residents in rural areas will not be able to pay for the full operation cost of wastewater treatment. Subsidy from local government is strongly required to maintain satisfied operation of the DWWT facilities.

7. Design advantages and limitations

The new wastewater treatment plant is discussed and designed in this paper which is very much cost effective. The plant is easy to make and it treats the water by removing waste from it especially BOD, Nitrogen, and phosphorus. It can be implemented in not only rural areas but also in semi-urban areas. It does not need any modern machinery rather it can be build using very low initial investment comparing to other centralized and de-centralized methods. Any big family or small two to four families can easily use one plant for water treatment. In the above design, some assumptions have been done for various parameters for calculation. In some cases, assumptions may not be similar to reality. Also, the temperature has been considered as 28 °C, which may be a bit lower than the real situation. This is considered to make the calculation simple. Chosen area is considered as a typical village, but there are areas with different topography than the designed one. So, this design may not be appropriate for hilly or coastal regions in the southern and southwest part of Bangladesh. Nitrogen and phosphorus removal for the designed system has been calculated with a rough estimation. The efficiency could be different in the practical case. This design is an example and a model of the recommended solution. When implementing this solution, in reality, some changes according to necessity could be done. Such as for places with a high groundwater table, depth of anaerobic pond or septic tank could be adjusted. In addition, some specific value of the area of this village has not been found. Therefore, an estimation and assumption have been done. pH of the total system was assumed to be in between 6.5–7, which in real case may differ a little. TDS and arsenic were not considered here to be much severe because the area of design has a very few rates of arsenic and TDS in the ground level. So, those were assumed as constants. If necessary funds can be generated then this project can be investigated further in a big scale.

8. Conclusion

Nowadays, clean drinking water is one of the crying needs of the general wellbeing of Bangladesh. Every now and then the drinking water quality is greatly hampered due to natural disasters or different man-made deeds. In this paper, a new type of decentralized low-cost water treatment plant is designed considering all the important parameters for implementing in rural regions of Bangladesh. The plant is very much cost effective and the running and operating costs are comparatively low. The plant is well suited for 3 or 4 small families in the village area. Finally, it is interesting to mention some future recommendations related to this research work:

(1) In this paper, the plant is designed for Bangladesh taking Khulna as a standard district. The climatic conditions for different places are different. So, in case of designing the plant for other districts the climatic conditions must be taken into account.

(2) In this design, no special treatment for pathogens are considered, though septic tank and secondary facilities are capable of removing 70% of pathogens. In future research, treatment of pathogens must be considered.

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Conflict of interest

The authors declare no conflict of interest.

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Appendixes

Appendix	Parameter	Unit	Equation	Result
1. Water flow and BOD	Q	m^3/person/d	N/A	0.083
	Q_D	m^3/person/d	% of wastewater flow.Q	87.17
	B	g/capita	N/A	40
	C_0	g/m^3	B/Q_D	565.8
2. Anaerobic Pond	λ_v	g/m^3/day	N/A	350
	V_A	m^3	C_0Q_D/λ_v	141
	t_{AN}	day	V_A/Q_D	1.6
3. Facultative Pond (30% BOD removal)	λ_s(T = 28 ^{0}C)	kg/ha.day	20T-120	440
	A_F	m^2	$10C_0Q_D/\lambda_v$	784.926
	D	m	N/A	1.5
	Q_E	m^3/day	Q_I—$0.001A_F$.e [As, $Q_D = Q_I$]	84
	Q_M	m^3/day	$(Q_I + Q_E)/2$	86
	T_F	day	A_FD/Q_M	14
4. Wetland	θ	constant	N/A	1.1
	K_{20}	m/day	N/A	0.5
	K_T [T = 28 ^{0}C]	m/day	$K_{20}.\theta^{(T-20)}$	1.08
	C_0	constant	N/A	396.2
	C_T	constant	N/A	10
	A_W	m^2	$KQ_D (\ln C_0 - \ln C_T)$	345.386
5. Sand Filter	Load Rating	L/day/m^2	N/A	163
	A_S	m^2	Q_D/Loading Rate	534.785