International Journal of Social, Humanities and Life Sciences ISSN XXXX-XXXX
Vol. 1, No. 1, 2023, pp. 48-61

Mitigation of High BOD Levels in Sewage Treatment Plants Using Outfall Storage Solutions

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Abstract

This report deals with a situation when the control system at a sewage treatment plant results in plant to be partially bypassed. This results in sewage with high BOD level which varies with time. BOD levels are calculated at several stages throughout the flow system using Microsoft Excel. It is found out that BOD level is above the standard when the water flows into Worm Ville. Therefore, an outfall storage tank is added at the outflow of sewage outfall to control the BOD level at Worm Ville. After successful similar calculations, it was found out that adding a outfall storage was successful in reducing BOD levels and met the standards.

Keywords*: Sewage treatment plant, control system, BOD levels, time-varying BOD, Microsoft Excel calculations, outfall storage tank, wastewater management, environmental standards, Worm Ville.*

1. Introduction

Problem statement: EU Urban Waste Water Treatment Directive (91/271/EEC) has set a limit of BOD level 25 mg/l on sewage flowing out to the river. This limit is set keeping in mind the regulations set by The EU Freshwater Fish Directive (78/659/EEC) for BOD levels to be less than 6 mg/l throughout the system [1]. However, due to a fault in the control system at sewage treatment plant, BOD levels have exceeded the regulations. As a result, BOD concentration throughout the river system is greater than the standard set by The EU Freshwater Fish Directive [2].

Overview: Human activities has raised an issue of water pollution. It is therefore important to understand how chemicals and other waste behave in water and effect aquatic environment. Advection results in movement of pollutant molecules in rivers. However, dispersion together with mixing of river with tributaries and other discharges is also responsible for transportation of pollutants across river [3]. Some chemicals present in water are inert i.e. they don't react with chemicals in their surroundings. Their concentration changes only through dispersion, mixing and advection. While concentration of some chemicals or organic waste change after they undergo process like oxidation, photolysis, etc [4].

River models are particularly created to mathematically model the pattern of concentrations in space and time. Finite Difference Method is the mostly used for mathematical representation. FDM segments the movement of chemicals through a spatial grid in steps 2 dimensional grid in space and time [5]. Lower reaches of rivers are generally subject to tidal influence. Such reaches are hydraulically much more complex, and require more complex and specialized models [6].

2. Biological oxygen demand

Introduction to bod: Organic matter that is present in the water includes sewage, dead plants and their leaves, manure and food waste. Organic matter present in water thus becomes feed for microorganisms such as bacteria. When bacteria begins breaking down waste present in water, they require oxygen. These microorganism thus extract dissolved oxygen from water which affects other aquatic organisms because they need oxygen for their survival [7]. Biological Oxygen Demand (BOD) is the measure of the oxygen used by bacteria (microorganisms) to decompose organic waste in water. If water contains large amounts of waste, BOD level will be high because bacteria will require more oxygen to decompose organic waste present. When organic waste will start to reduce after bacteria has broken it down, BOD level will begin to go down. High BOD level is dangerous for fish and other aquatic organism since less oxygen is left in water for their survival [8].

Presence of Nitrates and Phosphates in water can also contribute to high level of BOD. Nitrates and Phosphates are plant nutrients and thus increase the growth rate of plants and algae. As plants and algae grow quickly, they die quickly as well. As a result, there is an increase in organic waste in water and thus an increase in microorganisms which result in an increase in BOD levels [9].

Test procedure: To measure BOD, two equal volumes of water is taken from the water to be tested. Each specimen is diluted with a known volume of distilled water. Distilled water should be thoroughly shaken to ensure oxygen saturation [10]. Oxygen meter is used to determine Dissolved Oxygen (DO) level. DO level is taken from the first sample immediately and recorded. Second water sample is placed in an incubator for 5 days in complete darkness at 20^{o}C. After 5 days, DO level is obtained from this sample. This reading is subtracted from the DO reading of the first sample which was taken immediately at the very beginning of the test. Final value calculated is the BOD level and is recorded in *ppm (parts per million)* [11].

ANALYSIS OF RESULTS: Different values of BOD suggest different amount of organic waste present in water .

BOD level of;

1) 1-2 suggest that water quality is very good,
2) 3-5 suggest that water is moderately clean,
3) 6-9 suggest that water is polluted to some extent,
4) 100 or greater values suggest that water is extremely polluted.

3. Types of reactors

Batch reactors: A batch reactor is a non-continuous and perfectly mixed closed container and has no flow in or out. In the unit time, the concentration will be able to change only in virtue of a chemical reaction. Mass balance given in equation 3.1 quantifies this change [12].

$$QC_{in} - QC_{out} + rdV = \frac{dm}{dt} \quad (3.11)$$

In – Out + Generation = Accumulation

For a first order reaction, $r = -kC$, is the rate of decay.

Because there is no flow in or out of the reactor, $Q = 0$ and reactor has a constant volume V.

$$\frac{dm}{dt} = \frac{d(CV)}{dt} = V\frac{dc}{dt} = Vr$$

$$\frac{dc}{dt} = r \quad (3.12)$$

Substituting $r = -kC$ in equation 3.2 yields [5],

$$\frac{dc}{dt} = -kC$$

Where $c = c(t)$ is the concentration at any time inside the reactor [5].

$$ln\frac{C}{C_o} = -kt$$

$$C = C_o e^{-kt} \quad (3.13)$$

Continuous flow reactors: In this type of reactor it is assumed that the fluid entering the reactor is fully mixed immediately upon its entry. Pollutant is instantaneously mixed when it enters the reactor therefore the concentration at the output of the fluid is the same as the concentration of the fluid in the reactor [13].

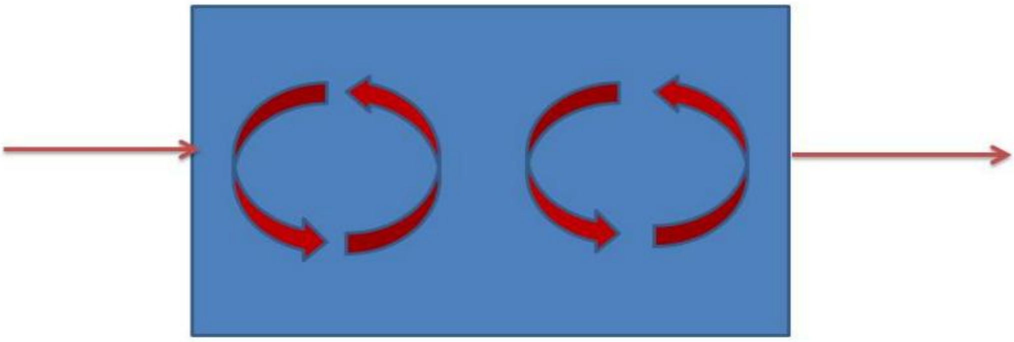

Figure 1: Continuous Flow Stirred Reactor

Mass balance equation of CFSTR is;

$$QC_i - QC = V\frac{dC}{dt} \quad (3.21)$$

Mass inflow – mass outflow = Accumulation

Solving the equation further gives [3];

$$C = C_o \exp\left(-\frac{t}{\emptyset}\right) + C_i\left[1 - \exp\left(-\frac{t}{\emptyset}\right)\right] \quad (3.22)$$

For any time increment we have for the substance entering and leaving the tank

Mass inflow – Mass outflow = Accumulation

A Finite Difference solution for a substance undergoing first order decay can be derived by following way

$$\frac{(Q_{in1}C_{in1} + Q_{in2}C_{in2})}{2}\Delta t - \frac{(Q_{out1}C_{out1} + Q_{out2}C_{out2})}{2}\Delta t - kV\Delta t\left(\frac{C_{out1} + C_{out2}}{2}\right) = C_{out2}V - C_{out1}V \quad (3.33)$$

Where k is the first order reaction decay constant. Rearranging equation 3.33 gives;

$$\frac{(Q_{in1}C_{in1} + Q_{in2}C_{in2})}{2}\Delta t + C_{out1}\left[V\left\{1 - \frac{k\Delta t}{2}\right\} - \frac{Q_{out1}}{2}\Delta t\right] = C_{out2}\left[V\left\{1 + \frac{k\Delta t}{2}\right\} + \frac{Q_{out2}}{2\Delta t}\right] \quad (3.34)$$

Solving gives [3];

$$\frac{(C_{in1} + C_{in2)}}{2}\Delta t + C_{out1}\left[\emptyset - (1 + k\emptyset)\frac{\Delta t}{2}\right] = C_{out2}\left[\emptyset + (1 + k\emptyset)\frac{\Delta t}{2}\right] \quad (3.35)$$

Plug flow reactors: In plug flow reactor a longitudinal concentration gradient is assumed with complete lateral mixing. It can be thought of as a long straight pipe as shown in figure xxx.

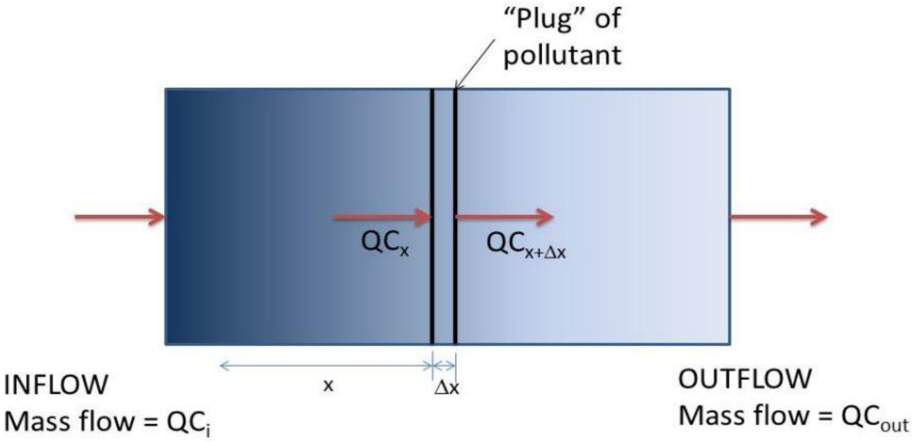

Figure 2: Plug Flow Reactor

For mass balance in plug element

$$QC_x - Q\left[C_x + \frac{\partial C}{\partial x}\Delta x\right] + r\Delta V = \frac{\partial C}{\partial t}\Delta V \quad (3.31)$$

Inflow – outflow + production = Accumulation

Volume of the reactor $\Delta V = A\Delta x$ is substituted in equation 3.31.

$$-Q\frac{\partial C}{\partial x}\Delta x + rA\Delta x = \frac{\partial C}{\partial t}A\Delta x$$

It can also be written as

$$\frac{\partial C}{\partial t} + \frac{Q}{A}\frac{\partial C}{\partial x} = r \quad (3.32)$$

For first order decay, equation 3.22 becomes

$$\frac{\partial C}{\partial t} + \frac{Q}{A}\frac{\partial C}{\partial x} = -kC \quad (3.33)$$

For a concentration wave moving along with velocity$\frac{Q}{A}$, equation 3.23 can be written as [3];

$$\frac{dC}{dt} = -kC$$

$$\frac{dC}{C} = -kdt \quad (3.34)$$

Integrating gives

$$lnC = -kt + X \quad (3.35)$$

Initial conditions assumed are; At $t = 0, x = 0$ and $C = C_i$.

Therefore;

$$C = C_i \exp(-kt) \quad (3.36)$$

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Since the wave is moving along with velocity $\frac{Q}{A}$, equation 3.26, for any distance x, can be written as

$$t = \frac{A}{Q}x \quad (3.37)$$

Substituting equation 3.27 into equation 3.26 gives [3];

$$C = C_i \exp\left(-k\frac{Ax}{Q}\right) \quad (3.38)$$

At the tank outlet $x = L$, equation 3.38 becomes

$$C_{out} = C_i \exp(-k\emptyset) \quad (3.39)$$

4. Reactor modelling

Reaches, sewage outfall and tributary are modelled as Continuous Flow Stirred Reactor. It is assumed for this part that perfect mixing takes place along the river, sewage outfall and tributary. This assumption is valid because rivers or reaches are long enough for perfect mixing to occur throughout and output concentration to be equal to the concentration of pollutant throughout the river [14]. Lake is modelled as a Plug Flow Reactor. This is because lake has small length and pollutants do not mix properly and concentration gradient exists [15].

There are two methods used to calculate pollutant levels in water. These are;

1) Step Response Method
2) Finite Difference Method

Step Response Method works by setting the initial time to zero and by setting initial output concentration to the final output concentration of previous step and by using the new input value for the concentration [16].

Finite Difference Method is used in this report to analyze BOD levels across the network.

$\emptyset = \frac{V}{Q}$ is called the detention time. It is the average time that the substance remains in the tank.

Decay constant k is given by $\frac{0.15}{24\times3600} = 1.734 \times 10^{-6}$.

CASE 1: In the first case, the outfall from a sewage treatment plant feeds into a river which then flows into a lake. The river flows out of the lake to pass through the town of Wormville. A tributary flows into the river between the lake and Wormville [17].

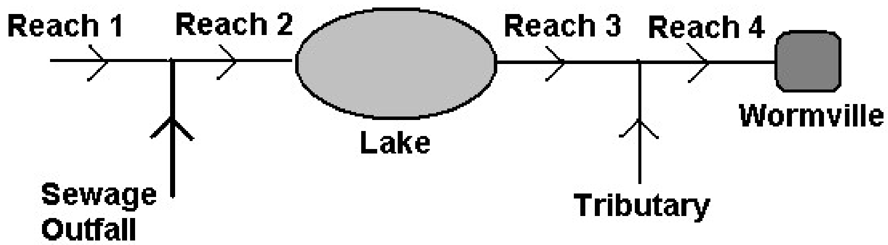

Figure 3: Case 1

The sewage flowing into the river normally has a biochemical oxygen demand (BOD) 25mg/l. This is designed to maintain river BOD levels at less than 6mg/l throughout the system as recommended in the EU Freshwater Fish Directive (78/659/EEC) for coarse fish Rivers [18]. However due to a fault in the control system at the sewage treatment plant causes the plant to be partially by-passed. This results in sewage with high BOD entering the river over a two hour period [19]. The variation in this BOD level

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with time is shown in Figure 4. The leakage began on Friday 13th December at 9.00am, which is shown as time zero on Figure 2. The geographical and flow data for this problem are given in data schedules A and B respectively in Appendix.

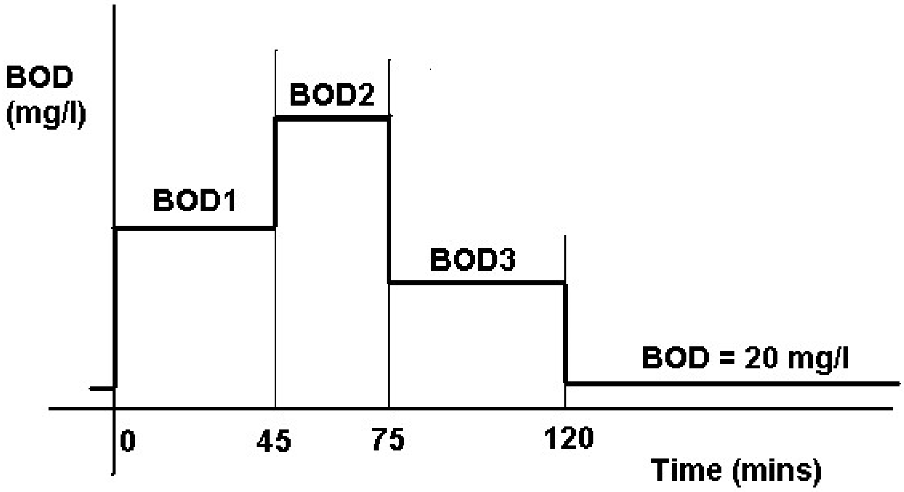


Figure 4: BOD variation chart

As stated above, concentration formula for Pug Flow Reactors is used throughout except for lake. Reach 2 has an inflow of sewage outfall plus reach 1. This flow rate remains constant throughout in lake and reach 3. Reach 4 has an inflow of reach 3 and tributary added together. Flow data is taken from Data Schedule B in Appendix.

Concentration calculated at the outflow of reach 1 is given by;

$$\frac{QC_{in1} + QC_{in2}}{Q_{out}}$$

Where; $Q = Q_{out}$=Flow rate in m^3/s, C_{in1} = Background BOD concentration and C_{in2}=Sewage outfall concentration.

All other reaches employ same procedure for concentration calculation at outflow.

Outfall concentration of lake is calculated using the equation 3.35;

$$\frac{(C_{in1} + C_{in2)}}{2}\Delta t + C_{out1}\left[\emptyset - (1 + k\emptyset)\frac{\Delta t}{2}\right] = C_{out2}\left[\emptyset + (1 + k\emptyset)\frac{\Delta t}{2}\right]$$

CASE 2: It is proposed to install an outfall storage pond in the outfall from the sewage works, as shown in figure xxx, in order to prevent the maximum allowable BOD being exceeded at Wormville in a leakage incident similar to that which occurred.

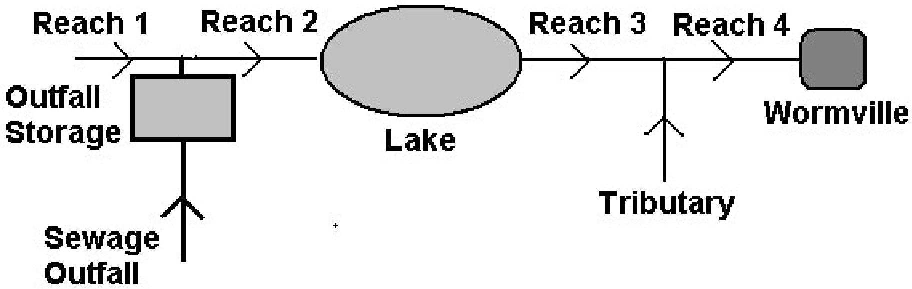


Figure 5: Case 2

Spreadsheet case 2 in Appendix shows outflow concentration each step. However, the most important point to note is that BOD concentration is below 6 mg/l and meets the criteria. In order to restrict BOD concentration less than 6 mg/l, an outfall storage tank of volume 7500m^3 is required [20].

Outfall storage is assumed to work as a Continuous Flow Stirred Reactor. Its volume has been worked out using trial and error. Flow rate in the storage is same as sewage outfall i.e. 0.5 m^3/s. Concentration of the outflow of BOD from outfall storage is calculated using the formula;

$$\frac{0.5t(C_{o1} + C_{o2}) + C_{o1}\alpha}{\beta}$$

Where; $\alpha = \emptyset + (1 + k\emptyset)$ and $\beta = \emptyset - (1 + k\emptyset)$

Rest of the calculations are done in the same manner as in case 1. Volume of the tank in spreadsheet is modified until desired concentration of BOD is achieved in river 4.

5. Results

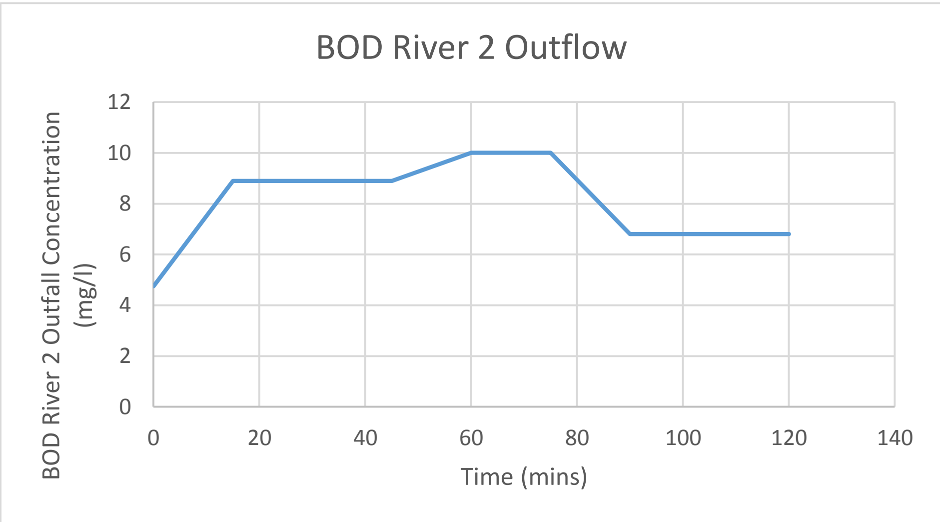
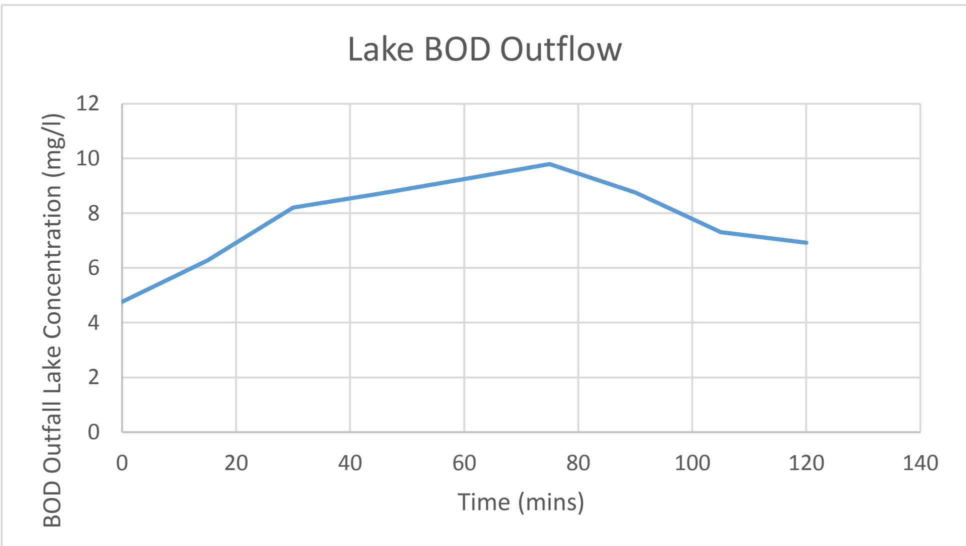


Figure 6: BOD River 2 Outflow



International Journal of Social, Humanities and Life Sciences
Vol. 1, No. 1, 2023, pp. 48-61 ISSN XXXX-XXXX

Figure 7: Lake BOD Outflow

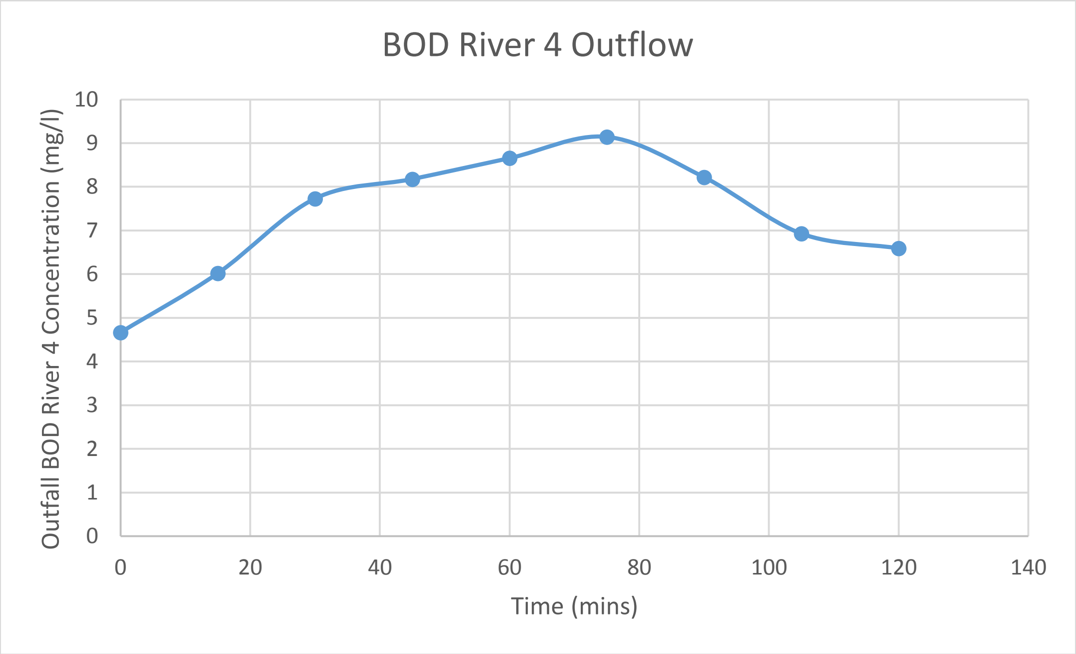


Figure 8: BOD River 4 Outflow

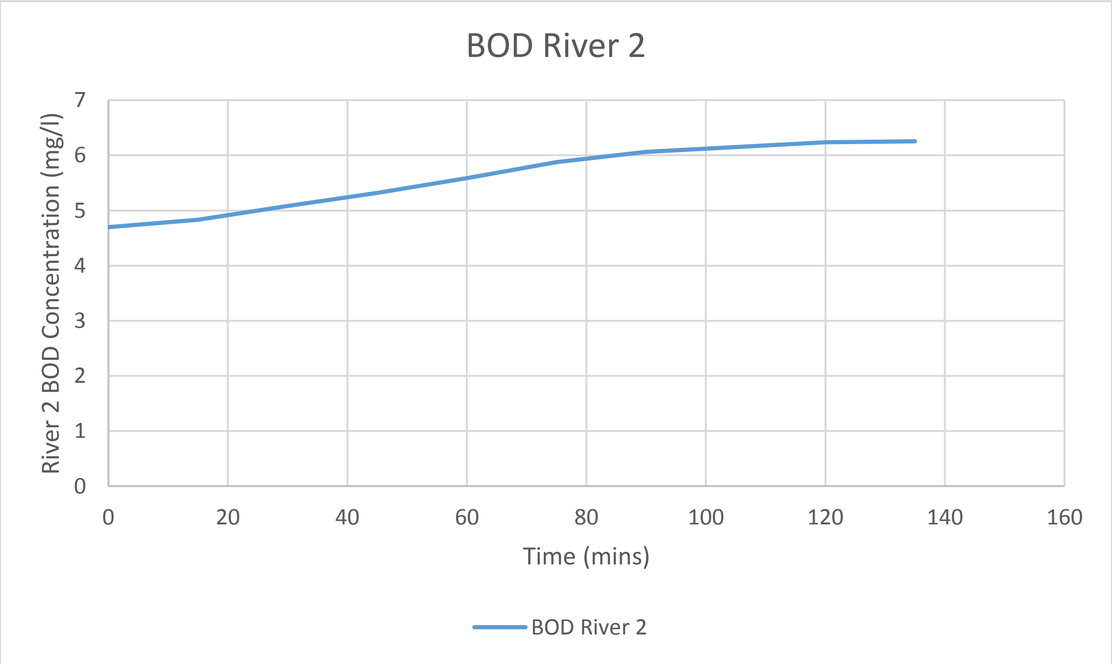


Figure 9: BOD River 2 Outflow

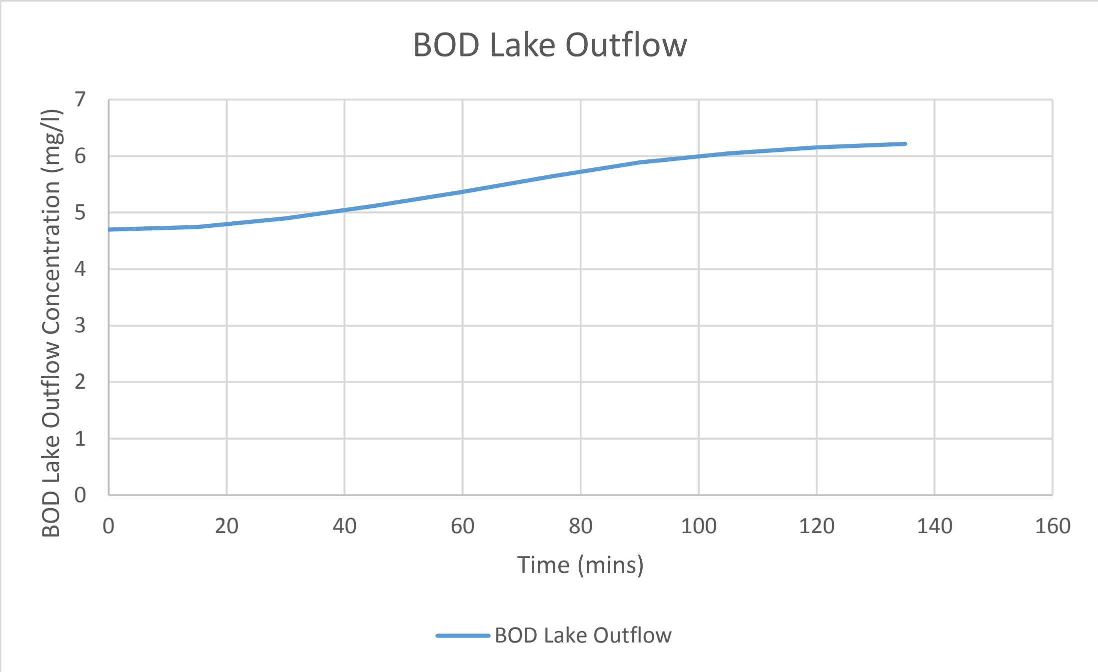


Figure 10: BOD Lake Outflow

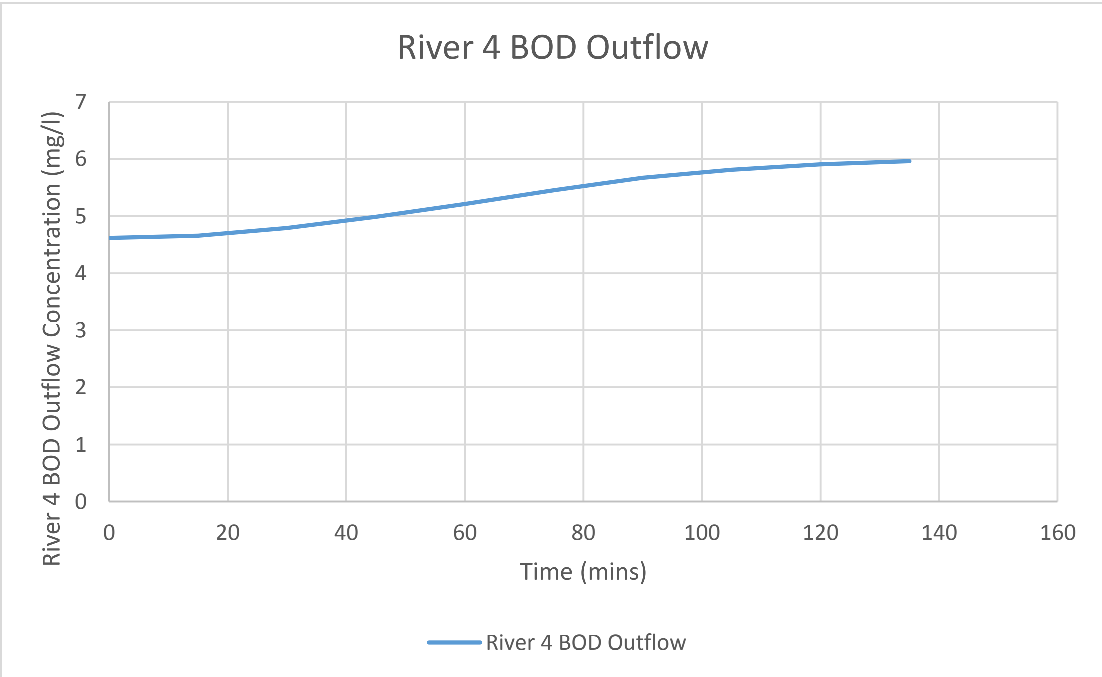


Figure 11: River 4 BOD Outflow

6. Discussion

Analysis of results: Figure 6, 7 and 8 shows variation of BOD in River 2, Lake and River 4 without storage outfall. It can be seen that a sharp increase in BOD results from an increase in BOD from sewage outfall. Sewage outfall strongly affects pollution in River 2. Concentration is peak from approximately 60 minutes to 75 minutes, reaching a maximum of 10mg/l. BOD concentration in lake also reaches nearly 10mg/l. However, it seen that river 4 outflow has maximum concentration of around 9mg/l [21]. This is because some of the pollutant has undergone decay. Moreover, as discussed in first chapter, concentration of pollutant also decreases with mixing in rivers and tributaries. By the time polluted water reaches worm Ville, it the water has undergone mixing with advection which has reduced BOD level slightly. Although, the concentration of BOD is much higher than standard and therefore an outfall storage is proposed to reduce BOD concentration to less than 6mg/l [22].

Figure 9, 10 and 11 shows BOD concentration in River 2, Lake and River 4 with an outfall storage. It is clearly observed that adding an outfall storage has significantly decreased BOD level. Sudden rise in BOD concentration has been avoided and more significantly, BOD is maintained at less than 6mg/l even during a fault in sewage treatment plant [23]. However, this demands an outfall storage volume of 7500$m^{3.}$ An increase in the reactor volume leads to a reduction in the effluent concentration and improved treatment because the waste remains in the reactor for a longer time. Hence the objective of maintaining BOD level at required standard has been achieved.

7. Conclusions

The dispose of contaminants and organic waste in the river water can cause the BOD level in water to rise. The level depends on the concentration of pollutants. Higher the BOD level in the water results in lesser Dissolved Oxygen, affecting the aquatic life which depends on oxygen. Several biological, chemical and physical processes can be used to control BOD level, depending on the type of pollutant. Model used in this case yields results that are satisfactory and confirms the fact that adding an additional reactor/tank significantly reduces BOD concentration. It also helps to control high BOD level reaching worm Ville in extenuating circumstances. It is also clear from the results that increasing the storage volume of the tank will delay the rise in pollutant concentration significantly.

Results obtained in previous chapter may have some inaccuracies. Background BOD level is taken constant however it may also wary with time depending on soil erosion and extra debris that water may carry with out in due course. Rain may also affect pollutant level. Rain may bring some pollutants from air and add inaccuracies to calculations, more specifically the size of outfall storage.

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APPENDIX

DATA SCHEDULE A

Flow (m3/s)	Design BOD Conc. (mg/l)	Length (m)	Area (m2)	Length (m)	Area (m2)	Length (m)	Flow (m3/s)	Decay constant k/day	Background BOD (mg/l)
0.5	25	3500	55	4000	60	3000	5	0.15	4.5

Outfall **River 2** **River 3** **River 4** **Tributary** **BOD**

DATA SCHEDULE B

River 1 Flow (m3/s)	River 2 X-Area (m2)	Lake Volume (m3)
45	45	35000

Period 1 BOD (mg/l)	Period 2 BOD (mg/l)	Period 3 BOD (mg/l)
400	500	210

SPREADSHEET CASE 1

	River 1				**Sewage Outfall**	
	Inflow		**Outflow**			
Time (mins)	**Flow (m3/s)**	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**
0	45	4.5	45	4.777777778	0.5	25
15	45	4.5	45	8.944444444	0.5	400
30	45	4.5	45	8.944444444	0.5	400
45	45	4.5	45	8.944444444	0.5	400
60	45	4.5	45	10.05555556	0.5	500
75	45	4.5	45	10.05555556	0.5	500
90	45	4.5	45	6.833333333	0.5	210
105	45	4.5	45	6.833333333	0.5	210
120	45	4.5	45	6.833333333	0.5	210
Volume (m3)	-					
Detention time (s)	-					
Decay constant, k	1.73611E-06					

River 2			**Lake**		
Inflow		**Outflow**	**Inflow**		**Outflow**
Flow (m3/s)	**Conc. (mg/l)**	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**	**Conc. (mg/l)**
45.5	4.777777778	4.752323508	45.5	4.752323508	4.752323508
45.5	8.944444444	8.896791683	45.5	8.896791683	6.276549108
45.5	8.944444444	8.896791683	45.5	8.896791683	8.203597183
45.5	8.944444444	8.896791683	45.5	8.896791683	8.706957558
45.5	10.05555556	10.0019832	45.5	10.0019832	9.246148156
45.5	10.05555556	10.0019832	45.5	10.0019832	9.794697896
45.5	6.833333333	6.796927808	45.5	6.796927808	8.755627838
45.5	6.833333333	6.796927808	45.5	6.796927808	7.301858786
45.5	6.833333333	6.796927808	45.5	6.796927808	6.922122679
157500			35000		
3461.538462			769.2307692		
1.74E-06			1.74E-06		

International Journal of Social, Humanities and Life Sciences ISSN XXXX-XXXX
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River 3			Tributory		River 4		
Inflow		Outflow			Inflow		Outflow
Flow (m3/s)	Conc. (mg/l)	Conc. (mg/l)	Flow (m3/s)	Conc. (mg/l)	Flow (m3/s)	Conc. (mg/l)	Conc. (mg/l)
45.5	4.752323508	4.712597653	5	4.5	50.5	4.69154838	4.662606163
45.5	6.276549108	6.224081872	5	4.5	50.5	6.053380696	6.016037319
45.5	8.203597183	8.135021272	5	4.5	50.5	7.775118176	7.72715338
45.5	8.706957558	8.634173933	5	4.5	50.5	8.224849781	8.174110585
45.5	9.246148156	9.168857302	5	4.5	50.5	8.706594203	8.65288312
45.5	9.794697896	9.712821578	5	4.5	50.5	9.196700629	9.139966074
45.5	8.755627838	8.682437365	5	4.5	50.5	8.268334655	8.217327201
45.5	7.301858786	7.240820731	5	4.5	50.5	6.969452342	6.926457708
45.5	6.922122679	6.864258932	5	4.5	50.5	6.630173889	6.589272268
220000					180000		
4835.164835					3564.356436		
1.73611E-06					1.73611E-06		

SPREADSHEET CASE 2

	Reach 1				Outfall	
	Inflow		Outflow		Inflow	
Time (mins)	**Flow (m3/s)**	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**
0	45	4.5	45	4.5	0.5	25
15	45	4.5	45	4.5	0.5	400
30	45	4.5	45	4.5	0.5	400
45	45	4.5	45	4.5	0.5	400
60	45	4.5	45	4.5	0.5	500
75	45	4.5	45	4.5	0.5	500
90	45	4.5	45	4.5	0.5	210
105	45	4.5	45	4.5	0.5	210
120	45	4.5	45	4.5	0.5	210
135	45	4.5	45	4.5	0.5	20

Storage	Column1	Reach 2		
		Inflow		Outflow
Flow (m3/s)	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**	**Conc. (mg/l)2**
0.5	25	45.5	4.725274725	4.700100173
0.5	36.94913896	45.5	4.856583945	4.830709824
0.5	59.76112582	45.5	5.107265119	5.08005546
0.5	81.85219982	45.5	5.350024174	5.321521182
0.5	106.2426019	45.5	5.618050571	5.588119632
0.5	132.8596679	45.5	5.910545801	5.879056554
0.5	149.9429421	45.5	6.098274089	6.065784693
0.5	157.793715	45.5	6.184546319	6.151597296

0.5	165.3963849	45.5	6.268092142	6.234698017
0.5	167.0636214	45.5	6.286413422	6.252921688

Lake			**Reach 3**		
Inflow		**Outflow**	**Inflow**		**Outflow**
Flow (m3/s)	**Conc. (mg/l)**	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**	**Conc. (mg/l)**
45.5	4.700100173	4.700100173	45.5	4.700100173	4.660810865
45.5	4.830709824	4.744869368	45.5	4.744869368	4.705205823
45.5	5.08005546	4.899294951	45.5	4.899294951	4.858340525
45.5	5.321521182	5.116911406	45.5	5.116911406	5.07413787
45.5	5.588119632	5.367218535	45.5	5.367218535	5.322352619
45.5	5.879056554	5.638783433	45.5	5.638783433	5.591647439
45.5	6.065784693	5.885356343	45.5	5.885356343	5.836159184
45.5	6.151597296	6.048360004	45.5	6.048360004	5.997800257
45.5	6.234698017	6.151865803	45.5	6.151865803	6.100440825
45.5	6.252921688	6.215349556	45.5	6.215349556	6.163393901

Tributary		**Reach 4**		
		Inflow		**Outflow**
Flow (m3/s)	**Conc. (mg/l)**	**Flow (m3/s)**	**Conc. (mg/l)**	**Conc. (mg/l)2**
5	4.5	50.5	4.644888997	4.616234622
5	4.5	50.5	4.684888415	4.655987283
5	4.5	50.5	4.822861265	4.793108977
5	4.5	50.5	5.017292536	4.986340799
5	4.5	50.5	5.240931568	5.208600199
5	4.5	50.5	5.483563534	5.449735365
5	4.5	50.5	5.703866195	5.668678977
5	4.5	50.5	5.849503202	5.813417548
5	4.5	50.5	5.941981337	5.905325184
5	4.5	50.5	5.998701436	5.961695376