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Reactor analysis of a river system Wastewater treatment plant

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Abstract: Increasing the development of industrialisation and population growth have brought a considerably rise of hazardous residues to the forefront. The overall aim of this report is to study the BOD flowing into a river and lake system for two hours caused by a fault of an outfall from a wastewater treatment plant. This wastewater outfall has usually 20 mg/l of BOD At the final stage of the system in a city example of approximately 25,000 inhabitants (UK) is located. BOD levels of all points of the system have to be maintained below 6 mg/l according to EU Freshwater Fish Directive. The concept of environmental modelling has emerged as one of the main tools for environmental science, not only because of increasing concerns about climate change, but also because the constant grow of computer tools. A complex real process can be simplified with a numerical or analytical model that shows the chemicals transformations in a specific volume and the velocity of these ones. Reactor engineering is the core of essentially most of the environmental analysis and is based on chemical kinetics (to determine the rates of reaction) and the mass balance. In this context, chemical processes can be approximated by assuming a finite volume reactor tanks involving flow and mixing profiles. The mathematical model is generally selected depending on the flow regime of the river and the process In order to predict the behaviour of the leakage and how long it is necessary to reach the city, the current system is modelled by using two tank reactor models: CSTR (Continuous Stirred-Tank Reactor) and PFR (Plug Flow Reactor). Last option modelled was the combination of both suggestions: building an outfall pond and enlarging the flood storage. The favourable volumes were 5000 m^3 for the pond and 30000 m^3 for the extension of the flood storage.

Keywords: Environment, Wastewater treatment plant, outfall river system, reactor engineering, BOD levels, mathematical simulation models.

1. Introduction

Water is one of the main natural supplies. Along with air, soil and solar radiation, it is considered as a part of the basic resources supporting progress. However, the importance of water quality has undertaken a slow development since it was not until the 19^{th} century when it was recognised as the origin of many infectious diseases.

Nowadays, the significance of both the quality and the quantity of water is beyond belief. Water is one of the most abundant compounds in nature and it fills three fourths of the earth's surface. But contrary to what it might seems, diverse factors restrict the water availability for human use. More than 97% of the overall amount of planet's water is localized in oceans and other saline masses and it's not suitable for hardly any purpose. Out of the remaining 3%, more than 2% is virtually inaccessible [1]. Therefore, there is just barely 0.9% of water (located in lakes, rivers and ground waters) suitable for humans and their industrial activities. It is known that the amount of water available is certainly scarce, but its irregular distribution throughout the planet is even a bigger problem.

The use of natural resources alters the ecosystems where they are extracted from and those ones where they are used in. When it comes to water, we are facing one of the clearest examples: a higher water supply entails a greater waste waters load. Also, it is important to bear in mind that human being influences over the water cycle in two different ways: either directly through extraction and subsequent spill of polluted waters, or indirectly altering vegetation and the waters quality.

Sustainable development is understood as the balance between the use of natural resources and the ecosystems preservation. Our world has been neglected and mistreated by human beings for many years. Industrialization and modernism are among many factors contributing to our environment pollution.

1.1 Municipal wastewater. Sewage

The main forms of recent industrial wastes can be split into combustible wastes, solid wastes, wastewater and sludge and slurry wastes [2]. All of them are latent sources of pollution for atmosphere, land and water. However, in this assigment is just focused on wastewaters which may come from industries or domestic use and can harm a whole ecosystem.

Plants and animals who live in seas, rivers and cities obtain all food and air from the surrounded water. Microorganisms live here in equilibrium, but human beings weaken such equilibrium. All rubbish that cities generate is discharged in the water. The contaminants in aquatic environments can be in different states: suspended and dissolved, which means that they can be in form of particles or drops and consequently, travel long distances. This biological consideration is essential to recuperate contaminated places because flora and fauna in either water or soil modify the circulation and concentration of pollutants.

Construction, agriculture, industry or household activities are the major sources of surface water pollution. Wastewaters pollutants can be categorised in [3]:

- **Chemical pollutants**. i) *Organic* pollutants (proteins, carbohydrats and oils)are the most common in municipal and agroalimentarie industry. For example: feaces, waste food and toilet paper. Their fundamental effect is the reduction of Dissolved Oxygen (DO) in water as a result of their breaking down. ii) *Inorganic* pollutants are diverse in nature and include surface sediments, metals and soil. Although they can be in any wastewater, they abound in indusrtrial wastes. The most important consequence of inorganic pollutants is their possible toxic effect.
- **Physical contaminants**. ii) *Thermal changes* such as sewage coming from heat exchangers affect strongly reaction chemical velocities. ii) *Water turbidity and colour* change and limit the radiation sunlight in water and reduce the Dissolved Oxygen (DO) in body waters [4]. Aquatic living beings require light absorption for phosynthesis.
- **Biological pollutants** (pathogens) iii). Theses include bacteria, viruses, protozoa and helmiths that can cuase infectious diseases [5]. Domestic wastes are the most way for bilogical pollutants to enter water .

Therefore, contaminated water can carry suspended solids, biodegradable dissolved organic compounds, nutrients, metals, inorganic compounds and pathogenic microorganisms [6]. The concentration of these products, in milligrams of contaminant per litre, is the key feature to retain a well-balanced water body. Any water body is considered to be contaminated when a discharge of wastes interferes with the ecological equilibrium. The most abundant pollutant is BOD and nutrients [2]. The table below outlines these principal pollutants and their environmental impact.

Table 1. Principal sewage pollutants and their impact

POLLUTANT	ENVIRONMENTAL IMPACT
Suspended solids	▪ Odorous *sludge* ▪ *Reduction of penetration light*. It complicates the gases and nutrient transmission to aquatic organism.
Biodegradable dissolved organic compounds (Carbohydrates and proteins)	▪ They demand the dissolved oxygen content in the water because of their biological decomposition. ▪ Lack of Oxygen means anaerobic decomposition releases *volatile gases with bad odours* and the *death* of most of the fish. ▪ Excess of oxygen consumption may cause a *massive of living creatures* of the deep sea.
Nutrients	▪ Phosphor and Nitrogen are essential nutrients for aquatic life ▪ Excess of nutrients may entail an overgrowth of algae. Thus, oxygen concentration is reduced. *Eutrophication*. ▪ Large amounts of algae can produce distasteful water and odours.
Pathogens	Waterborne disease, serious infections that suppose a public health concern
Toxic and hazardous substances (Pesticides, detergents, phenols or heavy metals)	▪ Some are resistant to conventional treatment ▪ Harmful for all living organisms, humans included

Taking into account all mentioned previously, one can say that there are three main objectives of biological treatment:

i) Reduction of organic matter in water
ii) Reduction of nutrients
iii) Removing pathogens and parasites.

In order to preserve public health and to limit environmental impacts, new regulations are established to meet "water quality" standards. The implementation of European Water Framework Directive has improved the rivers water condition over the last two decades [7]. As can be seen on both figures below, the quantity of nutrients have fallen considerably as well as the biological and chemical qualities have increased dramatically. A high concentration of nutrients can cause overgrowth of plants and algae and as result, a shortage of Oxygen for the ecosystem.

1.2 Quantification of Surface Water Pollution. BOD

Wastewater or sewage management is strongly important to assess the impact and risk that any substance may cause to the environment or to people, but how we can quantify the organic pollution in water bodies caused by the discharge of sewage?

As it was mentioned previously in section 1.1, the excess of organic matter may bring a deficiency of OD. Oxygen enters water owing to photosynthesis of plants and algae. Then, this Oxygen is consumed by living creatures´ breathing and degradation of organic matter. This decay results in adding nutrients that can create an excessive of biological growth with its corresponding rise of Oxygen consumption. In other words, the stream system requires and releases Oxygen. The expression below illustrates these processes.

$$O_2 + Organic\ Matter \xrightarrow{Microorganisms} CO_2 + Biological\ growth$$

The amount of O_2 used by these microorganisms in decomposing the waste is called BOD. The BOD is proportional to the organic matter discomposed by the microorganisms. So, if BOD is high, DO concentration falls. Although there are many relevant parameters for evaluating the water condition, it is widely spread that the organic matter is the most important factor and it is evaluated as either Biological Oxygen Demand (BOD) or the Chemical Oxygen Demand (COD). The first one is the most widely manner of measuring the biological degradable organic matter in water [8].

The BOD test consists of measure the concentration of DO over a period of time in a water sample at a specific temperature. There are two stages in the test: a carbonaceous and nitrogenous stage. The first one depicts the change of organic carbon to carbon dioxide, while the second stage refers to the combination of carbon plus nitrogen demand which starts after around 6 days [9]. The figure below illustrates both stages.

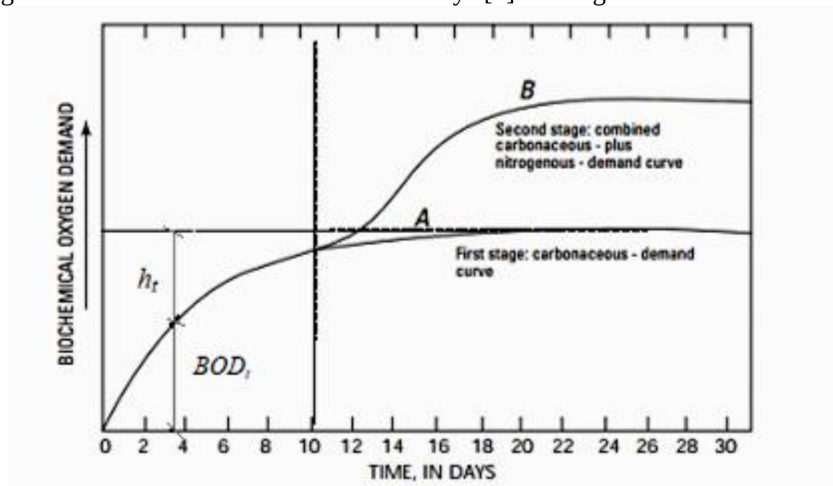

Figure 1. Biochemical Oxygen Demand curves. i) Carbonaceous demand curve and ii) Carbonaceous plus nitrogenous. Taken from US Geological Survey.

Although 20 days is considered to be a reasonable time to represent at least 95% of the total oxygen demand has been met [6]. The standard incubation period is 5 days at 20ºC (BOD5), period within the carbonaceous stage. The fundament of the measurement is to compare the initial concentration of DO with the concentration of DO after specific span. The difference between these values at each time period is plotted like in Figure 1. We can characterise the carbonaceous oxygen demand as first order decay process [10] as follows,

$$\left.\begin{array}{l} \dfrac{dht}{dt} = -K_d h_t \\ \text{As } h_t = h_0 \text{ at } t = 0 \rightarrow h_t = h_0 e^{-k_d t} \\ \text{and } h_0 = BOD_t + h_t \end{array}\right\} BOD_t = h_0 - h_t = ho(1 - \mathrm{e}^{-k_d t})$$

1.3 Environmental modelling

The concept of environmental modelling has emerged as one of the main tools for environmental science, not only because of increasing concerns about climate change, but also because the constant grow of computer tools.

In order to better understand natural systems and the way they react to different conditions a mathematical model must be established. Thus, a complex real process can be simplified with a numerical or analytical model that shows the chemicals transformations in a specific volume and the velocity of these ones.

Reactor engineering is the core of essentially most of the environmental analysis and is based on chemical kinetics (to determine the rates of reaction) and the mass balance [11]. In this context, chemical processes can be approximated by assuming a finite volume reactor tanks involving flow and mixing profiles. The mathematical model is generally selected depending on the flow regime of the river and the process [12]. There are three relevant types of models operating at steady state which can be generally divided into [13],

I. **The Continuous Stirred-Tank Reactor (CSTR)**: the concentration on the incoming flow (the pollutant) is equal to the concentration throughout the volume of the tank. It is considered that the mixing is fully rapid and the composition does not change with the position in the reaction. The reactants are entirely mixed.
It is important to point out that the reaction takes place within the tank, but it is that instantaneous that one can neglect it. It is a steady-state situation where there are no variable modifications.

II. **The Plug Flow Reactor (PFR):** this model is used to predict the behaviour of chemical components by considering short reactors in pipes and tubes. Unlike the CSTR the concentration of the chemical reactors for PFR are perfectly mixed longitudinally, but not in radial direction of the tank. Other assumption is the plug flow.

III. **Packed bed reactor (PBR)**: the main different of this kind of reactor is that the reaction rate depends on solid catalyst instead of the reactor volume due to the fluid-solid heterogeneous process. Likewise PFR, it is considered not radial mixing.

The three idealized before mentioned kinds of reactor are mainly based on input-output data and the some parameters as tank material or the temperature are neglected leading to some uncertainties. More complex models are carried these days to asses precisely the organic matter in surface water. For example, **the mechanistic, compartmental model**. This model deals with interlinked submodels involving nitrogen and carbon cycles; the growth, decay and metabolism of bacteria and water and oxygen balances [14]**.** Air temperature, day lenght, precipitation, flow rate and concentration of BOD and Nitrogenous concentrations. The complexity of the model lies in the ordinary equations containing 42 parameters related to physical biological processes.

2. Objectives

The overall aim of this report is to study the BOD flowing into a river and lake system for two hours caused by a fault of an outfall from a wastewater treatment plant. This wastewater outfall has usually 20 mg/l of BOD At the final stage of the system the city example is located. BOD levels of all points of the system have to be maintained below 6 mg/l according to EU Freshwater Fish Directive [15].

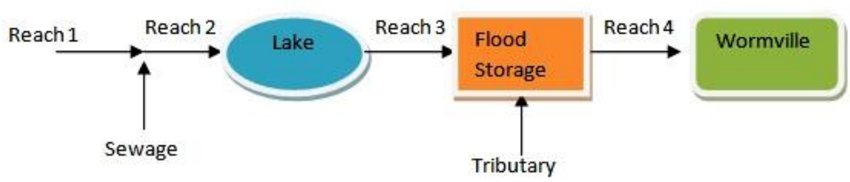

Figure 2. Diagram of the river and lake system

In order to predict the behaviour of the leakage and how long it is necessary to reach the city, the current system is modelled by using two tank reactor models: CSTR and PFR. The report consists of two parts aiming the following:

I. **Reactor modelling of the system**. Implementation of a mathematical model in an Excel spreadsheet to evaluate the flow of the sewage.
- Indentifying the time and the extent of the peak BOD levels at every point of the system.
- Identifying the time required to achieve safe conditions the city.
- Comparisons and sensitivity analysis between two models: by using Pulse Response and Finite Difference Method.

II. **BOD levels reduction**. Implementation of new schemes to impede the maximum allowable BOD.
- Building a storage pond in the outfall.
- Extending the Flood Storage next to the city.
- Finding out the optimum solution by considering the economy viability and soil conditions.

3. Methodology

In order to find out how long the sewage takes to reach the city as well as the BOD levels at every single component of the system, two mathematical models were used. To evaluate the rates of the reactions, the time increment used was 15 minutes. Particularly, the results of the BOD levels in The city were emphasised.

3.1 Step Response Method

The Step Response Method consists mainly of modifying the input concentration of every component of the system at series of time steps. In this case study every 15 minutes for above two hours.

Firstly, the components of the system were categorised as two different types of reactors. Rivers were considered Plug Flow Reactor or PFR, and lakes as well as storage were considered as Continuous Flow Stirred Reactor or CFSR with a first order decay.

Following this approach, the next equations were introduced in the Excell spredsheet in order to model the BOD levels of every part of the system. The results are shown in *Appendix 1*.

$$\text{PFR} \quad C_{out} = C_i \exp\left(-k\frac{AL}{Q}\right) = C_i \exp\left(-k\frac{V}{Q}\right) = C_i \exp(-k\phi) \qquad 1)$$

$$\text{CFSR} \quad C_{out} = C_0 \exp\left(-\frac{(1+k\phi)}{\phi}t\right) + \frac{C_i}{(1+k\phi)}\left[1-\exp\left(-\frac{(1+k\phi)}{\phi}t\right)\right] \qquad 2)$$

Where,

C_{in} (mg/l) is the concentration of BOD flowing into the point in question. There are some points to study with more than one inflow with different volume flow, Q (m^3/s). Thus, the following formula with mass flow consideration was introduced,

$$C_i = \frac{(Q\cdot C)_{\text{element 1}} + (Q\cdot C)_{\text{element 2}}}{Q_{\text{element 1}} + Q_{\text{elemenet 2}}} \qquad 3)$$

C_0 (mg/l) in the equation 2, is the BOD concetration of the previous C_{out} (mg/l) of the same tank reactor. For the case of the first C_0 , it is the background BOD in river & lakes given by assigmnet, 4.5 mg/l.
K is the die-off rate constant that in this case is 0.15 min/day. A and L are the area and legth corresponding to the point to study. $\varnothing$ is called detention/retention time. It is the estimated time needed for our given volume flow of sewage to go from one side of every tank to another. It is described as the ratio of the volume (m^3) to the volume flow (m^3/s) as follows,

$$\phi = \frac{V}{Q} \qquad 4)$$

All geographical and flow features are given in the table below.

Table 2. Features of the lake-river system

BOD Outfall (mg/l)			River 1	River 2		River 3		River 4	
Period 1	Period 2	Period 3	Flow (m^3/s)	Area (m^2)	Length (m)	Area (m^2)	Length (m)	Area (m^2)	Length (m)
500	450	175	35	55	3500	55	4000	60	3000
Lake		Tributary		BOD decay constant		BOD background		Flood storage	

Volume (m^3)	Flow (m^3/s)	min/day	mg/l	Volume (m^3)
30000	5	0.15	4.5	10000

Following the diagram of Figure 2, the mass flow of reach 1 and the sewage outfall were introduced in equation 3) to obtain the output concentration of the reach 2 with equation 1), PFR method. It is relevant to mention that the mass flow of the river 1 is constant, but the BOD concentration of wastewater flow changes with the time according to

Table 2 and the figure below. Then, the concentration coming from reach 2 (C_{out} of reach 2) is the inflow of the lake. So, introducing the equation 2) for CFSR tank, the outflow concentration was obtained and so on and so forth until reach the city.

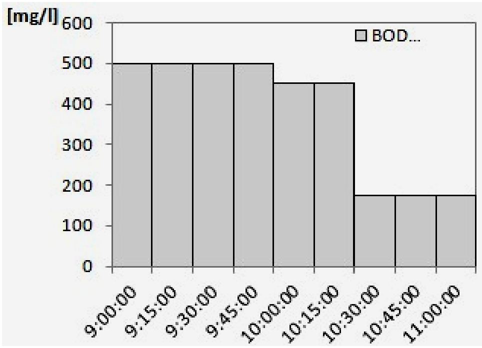

Figure 3. BOD outfall

3.2 Finite Difference Method

The Finite Difference Method was only applicable for the CFSR tank. The process was similar to the Step Response Method, but in this case the equation for the outflow concentration was as follows,

$$\frac{C_{in} + C_{in2}}{2}\Delta t + C_{out1}\underbrace{\left[\Phi - (1 + k\Phi)\frac{\Delta t}{2}\right]}_{\gamma} = C_{out2}\underbrace{\left[\Phi + (1 + k\Phi)\frac{\Delta t}{2}\right]}_{\gamma} \quad 5)$$

$$\rightarrow C_{out} = \frac{1}{\lambda}\left[\gamma_{Cout\ previous} + \frac{(C_{in\ previous} + C_{in\ present})t}{2}\right] \quad 6)$$

As one can see from the equations above, the mass inflow into the tank is the average of both. The reactors were modelled according to equations 1, 2, 5 and 6 which corresponds to first order decay.

4. Results and discussion

4.1 Reactor modelling of the system

As a result of modelling our systems by using both models, it has been obtained the below graph showing the BOD levels coming from the sewage into the city over the time.

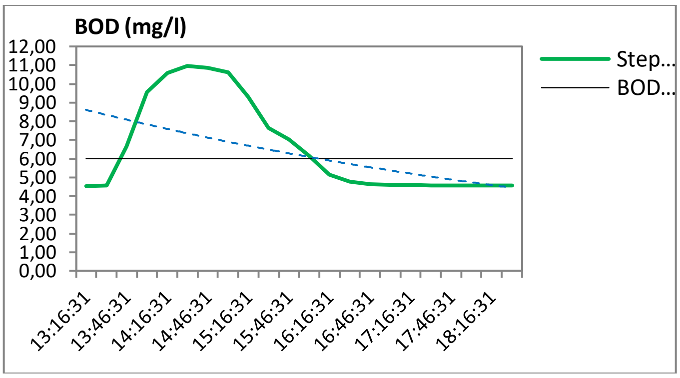

Figure 4. BOD levels in the city

The leakage starts at 9 am and it ends at 12 pm. At the beginning of that period the city has 4.52 mg/l of BOD, a smaller value than the permissible one, 6mg/l. Throughout Figure 4 one can see that the outfall reaches the town at 13.30 h and rises to its peak at 14.31/ h accounted by 10.95 mg/l of BOD. So, By considering the detention time of each component, the time taken for the outfall to reach the city is 4 hours and 46 minutes. It is important to point out that BOD levels are incremented by 140% in one hour in the city. Then, the concentration is recovered back to 4.55 mg/l after 2 hours and remains constant.

The graph also depicts the model of both methods used: the step response and the finite method. The striking feature of this graph is the small difference in the output of both methods. The relative error between them is **0.05** as average. However, this error rapidly increases at 10% just when the leakage starts because both models require time to respond to the new concentration levels, but then the error is reduced to remain almost constant. All calculations are shown in *Appendix 1*.

A *sensitivity analysis* is carried out for both methods to find out how the uncertainty in the output of the model affects the uncertainty in the output of the corresponding mathematical model. To assess the performance of a mathematical model, the uncertainty effect provides useful information. It is therefore two input parameters modified to show the accuracy of the methods:

- **Outfall mass flow**. The results display nearly 2.6% variation as average in the output for 10% change in the input for both methods. The calculations of this analysis are given in *Appendix 2* based on the below formula,

$$Sensitivity = \frac{C_{out}\ Original - C_{out}\ new C_{in}}{C_{out}\ Original} \cdot 100$$

- **Rivers length**. The lengths of the three rivers were incremented by 10%, but the change in the output concentration at the end of the system is 0.27% for both methods. So, this change does not affect.

4.2 BOD levels reduction.

In order to study how to reduce the BOD levels in the city, two schemes are implemented: the building of a storage pond in the outfall the extension of the Flood Storage before reach 4. These modifications are modelled only based on the Step Response method, since it has been shown that the relative error with the Finite Difference method is considerably low.

By allocating an outfall pond of 8500 m^3, the water conditions of the city are enhanced. It is achieved BOD levels below the maximum permissible at every time. Furthermore, as can be seen from Figure 5, the leakage reaches the town at 17:35 h, two hours later than before. The BOD concentration recovery occurs around after 2 hours.

The other suggested option to reduce the BOD levels in the city due to the outfall sewage is to enlarge the Flood Storage next to reach 4, Figure 2. This prevention is successful for a volume of 890000 m^3, Figure 5. The time required to recover the former milligrams per litre of BOD is substantially longer than for the previous scheme mentioned. From the economic point of view, increasing one unit volume the flood storage is twenty times cheaper than placing one unit volume a new outfall pond according to the assignment. However, it is needed such a large volume that is a great deal more expensive to enlarge the storage. This consideration is explained further in Table 3.

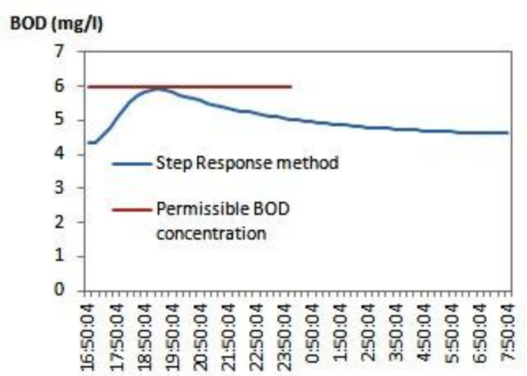

Figure 5. BOD levels in the city with an outfall pond

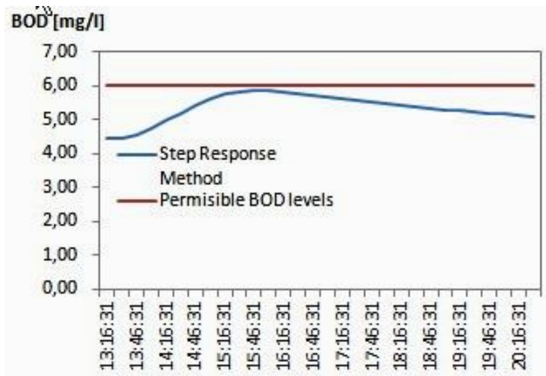

Figure 6. BOD levels in the city with an extension of the Flood Storage

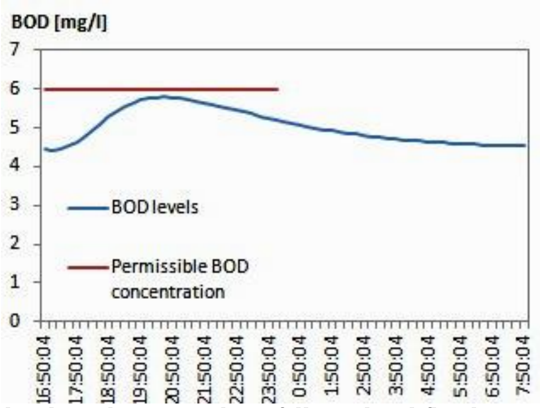

Figure 7. BOD levels in the city with outfall pond and flood storage enlargement

Last option modelled was the combination of both previous suggestions: building an outfall pond and enlarging the flood storage, Figure 7. The favourable volumes were 5000 m^3 for the pond and 30000 m^3 for the extension of the flood storage. The cost of this implementation is in between of only building the pond and only enlarging the storage.

Therefore, the optimum solution to control the water conditions and attenuate the BOD levels below 6 mg/l in the town is to place a pond in the sewage outfall. In terms of economy viability, it is far more cheaper. Furthermore soil conditions are more favourable and the time required recovering the former level of BOD before the leakage is smaller than for the other two suggested preventions.

Table 3. Reduction schemes

	Outfall Pond	Enlargement Flood Storage	Outfall Pond + Enlargement flood Storage
Volume (m^3)	8500	880000	5000+300000
Expenses (£)	**8500**	440000	19500
Time to reach (h)	17:35	13:46	19:20
Time peak BOD levels(h)	19:20	16:00	20:35
Time for recovery (h)	4:50	-	6:00

5. Conclusion

Water quality is a key issue of sustainable human development in recent years. According to the Water Framework Directive 2000/60/EC, water has to meet specific quality standards in terms of its chemical, physical and biological features depending on its final use.

This task is complex and mathematical methods and software are developed to simulate a real river system. Mathematicians, chemists and physics are needed to achieve this aim since it is required to evaluate accurately physico-chemical parameters.

This report deals with problem of a wastewater outfall in a river system. Two methods have been implemented in software to predict the behaviour of the BOD levels until they arrive to city axample. Some possibilities to reduce the concentration of BOD have been studied. It has been found that both Step Response and Finite Different Methods are helpful tools for the biological control in question.

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