

MODELING OF MUNICIPAL SECONDARY AND TERTIARY WASTEWATER TREATMENT PLANTS

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ABSTRACT

The analysis and design of wastewater treatment plants is important for civil and environmental engineers. In the US today nearly all wastewater treatment plants operate at the secondary or tertiary treatment level. The analysis of such plants is complex as numerous biological reactions must be considered as well as the recycling of flow from secondary clarifiers back into the aeration tanks. In this paper a numerical simulation software package is used to model a treatment plant. The software provides the students with an operating interface from which they have to supply all the relevant plant characteristics and reactions. In this manner the software is not a black box and acts only as a convenient tool, which is ideal for teaching. A worked case study is included.

INTRODUCTION

Wastewater treatment plants are used to treat domestic and industrial wastewater so that final effluent concentrations meet acceptable criteria. Treatment plants have been in use in the US since the 1850's. By the early 1900's approximately 60 cities in the US had some form of municipal treatment. Early treatment plants were designed to settle particulates and remove floatable material. This treatment process became known as primary treatment. By the 1950's and 60's the introduction of more advanced facilities began that built on primary treatment. These plants used biological, or secondary, treatment and by the 1970's were the norm (ASCE (1998)). The emphasis of secondary treatment plants was to reduce biochemical oxygen demand (BOD) by removing soluble or colloidal organic matter that would not settle out

during primary treatment. Secondary treatment plants also removed ammonia and suspended solids. At the present time many treatment plants are at the level of advanced secondary treatment in which the emphasis is on nitrogen removal. Some plants also have post secondary treatment operations (eg to remove phosphorus or metals) and are known as tertiary treatment plants.

With the move from primary to secondary treatment the operation, understanding and design of wastewater treatment plants became an order of magnitude more complex. The understanding of the processes utilized in secondary treatment involves dealing with a series of biochemical reactions. A feature of secondary treatment is the recycling, or return, of some of the plant flow back to previous treatment units. This feedback system also adds to the difficulty of solving the design equations and makes it very tedious to try various design alternatives.

The obvious solution to this problem is to use a computer based approach. There are a few commercial packages that provide a framework to numerically model treatment plants (Biowin32 from Envirosim Inc., GPS-X from Hydromantis Inc.) and this paper describes the use of one such program called EnviroPro Designer (Intelligen, Inc (1998)).

OVERVIEW OF MODELING SOFTWARE

EnviroPro Designer is a modeling environment that can be used to simulate any type of process system. It is made with a wide scope in mind and is not particularly focused on being a municipal wastewater treatment plant model. It is this fact that in many ways makes it

an excellent teaching tool as it requires the user to define his/her problem in an appropriate way. This means that the student is responsible for defining the variables to be modeled as well as the important reactions and processes that take place. What the software provides is a fairly user friendly environment to operate in, as well as a mathematical solver to handle the numerics of the simulation.

The interface to EnviroPro is via a graphical flowsheet. The main interface is shown in Figure 1. The graphics that can be placed into the work area, which is initially blank, basically fall into 3 categories and are summarized below:

1. Unit Operations – a total of 12 main operations that cover just about every physical and chemical process available. Figure 2 shows the drop down menu for the unit operations. For modeling wastewater treatment plants all of the process steps can be specified – clarifiers, anoxic tanks, aeration tanks, sludge digesters, sludge dewatering, chlorine contactors and so on. There is also the ability for some operations to be modeled either as well mixed systems or plug flow systems. In all there are some 61 different options available for specifying unit processes.
2. Connecting Streams – flow is moved from one unit to another via these connecting streams. Flow one stream can be split into two or more streams using a splitter unit from the unit operations menu. Similarly multiple flows can be combined using a mixing unit. For treatment plant modeling this capacity is a necessity given the flow recycling that is done from one process to another.
3. Aesthetics – provision is made to place other text and graphics that are not associated with the process calculation on the worksheet for purely aesthetic purposes. There is a standard pallet of drawing and text options similar to what can be found in Microsoft Word or Excel.

The actual process simulation is based on mass balances. The mass of all constituents of interest (including water) is followed through each of the processes. The properties of each constituent are specified by the user. Common compounds like water, ammonia and oxygen are already specified in the database of substances that comes with the software.

Other features that EnviroPro includes are schedule reporting and cost analysis. For a treatment plant that operates in a continuous mode the scheduling options are not relevant. For batch operations these options are vitally important and the software also allows the users to make Gantt charts to visualize the information. The cost analysis options allow fairly detailed economics to be performed and are a good way to introduce students to the subject in an applied manner. Finally there are extensive reporting provisions that allow the user to generate up to 6 reports – stream information, economic evaluation, itemized costs, throughput analysis, environmental impact assessment and input data reports.

One of the useful features of EnviroPro is the ability to import the worksheets into just about any other program like Word, Excel or AutoCAD by selecting the format that the worksheet should be exported as. The worksheet can either be linked and embedded so that it will run in another program or simply inserted as a graphic.

CASE STUDY: MUNICIPAL WASTEWATER TREATMENT PLANT

A. Simulation Variables and Plant Data

The following case study was set up for a medium size municipal wastewater treatment plant that has an average flow of 8 million gallons per day (8 MGD). The plant has primary treatment from primary clarifiers and secondary treatment via aeration tanks and secondary clarifiers. There is a recycle of the activated sludge from the secondary clarifier back to the aeration tanks to maintain an acceptable

bacterial biomass in the aeration tanks. The plant is designed to achieve high levels of BOD and ammonia removal. The physical plant data are given in Table 1.

Table 1. Wastewater treatment plant design details.

Unit	Details
Primary Clarifiers	2 tanks @ 75ft diameter with mean depth of 10ft
Aeration Tanks	4 tanks Length = 150ft, Width = 75ft, Depth = 15ft
Secondary Clarifiers	2 tanks @ 105ft diameter with mean depth of 12ft
Chlorine Contactors	2 tanks Depth = 8ft, Width = 32ft, Length = 50ft

The EnviroPro flowsheet for the plant is shown in Figure 3. A total of 6 variables were used in the simulation – 5 day biochemical oxygen demand BOD₅, NH₃, NO₃, non-volatile suspended solids (SS), volatile suspended solids (VSS) and water. The raw influent concentrations are given in Table 2. The selection of which variables to model is the key to obtaining a successful simulation. The use of BOD as a variable is one that both seems obvious and not obvious depending on the point of view. The obvious reason to model BOD comes from the fact that BOD is always measured at treatment plants and is specified in the final effluent standards that the plant must meet. The reason not to directly include BOD comes from the fact that BOD is not actually a physical compound but rather a surrogate measure of organic matter. Therefore it could be argued that it makes more sense to model the actual physical substances rather than the surrogate. The problem that arises is that we end up modeling components that are not usually

measured (ie organic matter) and so there is little or no data with which to compare against. Hence BOD (modeled as BOD₅) is included directly.

Table 2. Plant influent concentrations.

Variable	Concentration (mg/L)
BOD ₅	200
NH ₃	33
NO ₃	0
NVSS	50
VSS	150

Secondary or biological treatment involves the growing and wasting of bacterial biomass. This biomass is in the form of solids and is modeled through the volatile suspended solids (VSS) variable. Solids which are not biological in nature (ie. inorganic) are modeled separately as non-volatile suspended solids (SS). Taken together these two groups represent the total suspended solids or TSS. TSS is routinely measured and is used in final effluent permit standards.

One further aspect to variable selection is to note that VSS can contribute to BOD. It is estimated that approximately 50% of the final effluent BOD comes from VSS in the effluent. The only place the BOD calculation is affected by this relationship is in the clarifiers where some BOD will be removed as VSS settles out. A value of 50% is used in the model, ie. if 100 mg/L of VSS settle out in a clarifier then 50 mg/L of BOD will be removed as well. This necessitates specifying BOD as a solid in EnviroPro, even though much of the BOD is actually soluble. In general terms BOD is always thought of as the substrate and VSS the end component.

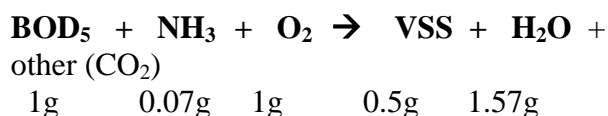
Once the components to be modeled have been chosen the properties of each one must be specified. As wastewater treatment plants operate at ambient temperatures and pressures many of component properties have no effect (heat capacity, vapor pressure, Henry's constant,

etc). Some of the properties that are relevant include density, whether the component is biomass, whether the component is a solid, and the boiling point. The default boiling points used in EnviroPro tend to be very low and below the ambient temperatures that a plant would operate at. If these temperatures are not reset to higher values this causes major problems in the analysis.

B. Reaction Set

Once the variables to be modeled have been decided the relevant reactions must be specified. In this case all the reactions take place in the aeration tanks. The reactions are written on a mass basis and are given as follows (Qasim (1999), ASCE (1998), Horan (1991), Randall et al (1992), Rozich and Gaudy (1992)):

BOD UPTAKE



This reaction describes the uptake of organic matter (as BOD₅) and conversion to bacterial biomass (VSS). The ratio between VSS/BOD₅ is the yield coefficient and a value of 0.5 mg VSS/mg BOD₅ is common. Because CO₂ is not a modeled component any mass attributable to untracked components is put into water where it will have no effect on the calculation but allow mass requirements to be satisfied. The reaction rate is specified below. All constants are given in Table 3.

$$\text{Rate} = k_{\text{BOD}} * \frac{\text{BOD}_5}{K_{\text{S-BOD}} + \text{BOD}_5} * \text{VSS}$$

NITRIFICATION



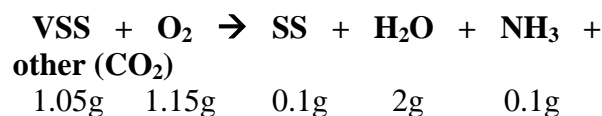
This reaction describes the process by which ammonia is oxidized via a bacterially mediated reaction and is converted to nitrate and bacterial biomass (VSS). This process is called

nitrification. Note that the bacteria produced in this reaction (nitrifiers) are different from those in the previous reaction but are classified as VSS. Again components not tracked (CO₂) are omitted from the calculation and adjustments are made to water to account for this. The reaction rate is specified below.

$$\text{Rate} = k_{\text{NIT}} * \frac{\text{NH}_3}{K_{\text{S-NH}_3} + \text{NH}_3} * \text{VSS}$$

Usually the VSS used in the nitrification reaction would only include nitrifying bacteria. As this is not explicitly tracked the first order constant k_{NIT} is reduced by the fraction of nitrifiers in the VSS, which is usually about 2%.

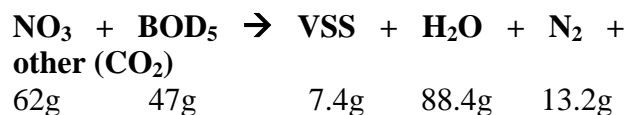
VSS DECAY



This reaction allows for the fact the bacteria die off as well as grow. The reaction is:

$$\text{Rate} = k_d * \text{VSS}$$

DENITRIFICATION



Although this case study does not show the use of anoxic tanks the denitrification reaction is included for completeness. The reaction rate is:

$$\text{Rate} = k_{\text{DN}} * \frac{\text{NO}_3}{K_{\text{S-NO}_3} + \text{NO}_3} * \text{VSS}$$

C. Simulation Results

The results of the simulation are given in Table 4. The results are all within expected ranges for a municipal wastewater treatment plant operated with a conventional secondary treatment stage (Qasim (1999), WPCF (1988)).

Table 3. Reaction rate parameters

Reaction	Constant	Value
BOD uptake	k_{BOD}	4 d^{-1}
	K_{S-BOD}	80 mg/L
Nitrification	k_{NIT}	0.12 d^{-1}
	K_{S-NH3}	1.4 mg/L
VSS decay	k_d	0.05 d^{-1}
Denitrification	k_{DN}	0.144 d^{-1}
	K_{S-NO3}	0.44 mg/L

OTHER ANALYSIS OPTIONS

The case study presented above really represents the simplest analysis that can be made of a secondary treatment plant operation. Other extensions that can be built from this framework include the modeling of phosphorus removal processes, and the removal of nitrogen via denitrification using anoxic zones in the aeration tanks. Four commonly used process methods of nitrogen removal are Wurhmann (1954) (Figure 4), Ludzack- Ettinger (1962) (Figure 5), Modified Ludzack-Ettinger (Barnard (1973a)) (Figure 6) and the Bardenpho (1973b)

process (Figure 7). All of these more complex simulations are readily built upon the basic case study shown above and utilize the same reaction set outlined in this paper.

CONCLUSIONS

The analysis of secondary wastewater treatment plants is complex and difficult to do effectively by hand. The use of a modeling tool like EnviroPro greatly expands the teaching options by placing computational power behind the calculations. The student is still required to know and implement the underlying principles otherwise the simulation will fail. The software allows the student to explore different design options for a plant and also to examine the effect that changes have on the results. This interactive approach is difficult to achieve using hand calculations given the iterative procedure needed to solve the mass balances. From a teaching viewpoint the software is ideal as it is not a “black box” and acts merely as a tool that opens the possibilities for the analysis.

Table 4. Results of case study simulation.

Process Step	BOD ₅ (mg/L)	NH ₃ (mgN/L)	NO ₃ (mgN/L)	SS (mg/L)	VSS (mg/L)	Flow (m ³ /hr)
Influent	150	33	0	50	150	1515
Primary Clarifier Effluent	107	33	0	20	61	1491
Primary Clarifier Sludge	5455	33	0	1818	5455	24
Aeration Tank Effluent	697	2	24	312	1381	1771
Mixed Liquor	92	28	4	311	1350	1771
Return Activated Sludge	4088	2	24	1840	8143	295
Wasted Sludge	4086	2	24	1840	8140	15
Final Effluent	3	2	24	4	17	1476

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BIOGRAPHICAL INFORMATION

Scott Lowe is an Associate Professor in the Civil and Environmental Engineering Department at Manhattan College, New York, and a Senior Project Manager for Lawler, Matucky and Skelly Engineers in Pearl River, New York. He specializes in numerical modeling of environmental systems.

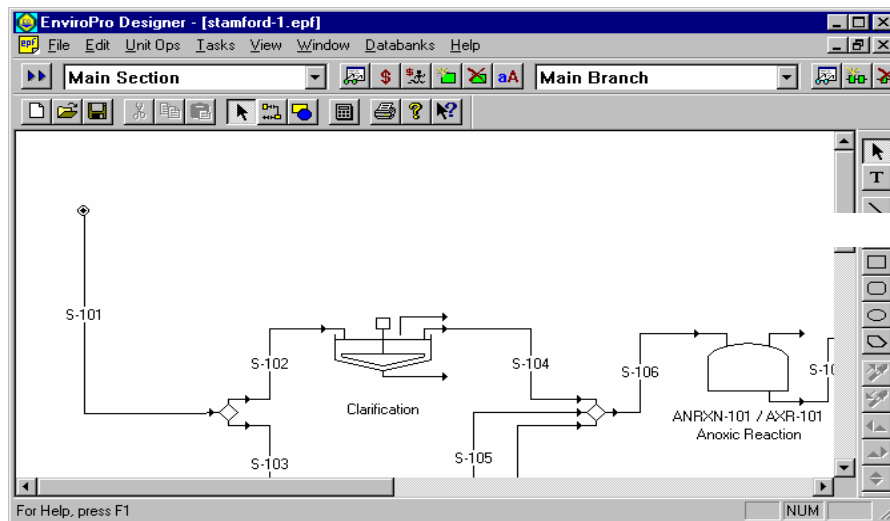


Figure 1. Main EnviroPro Designer interface.

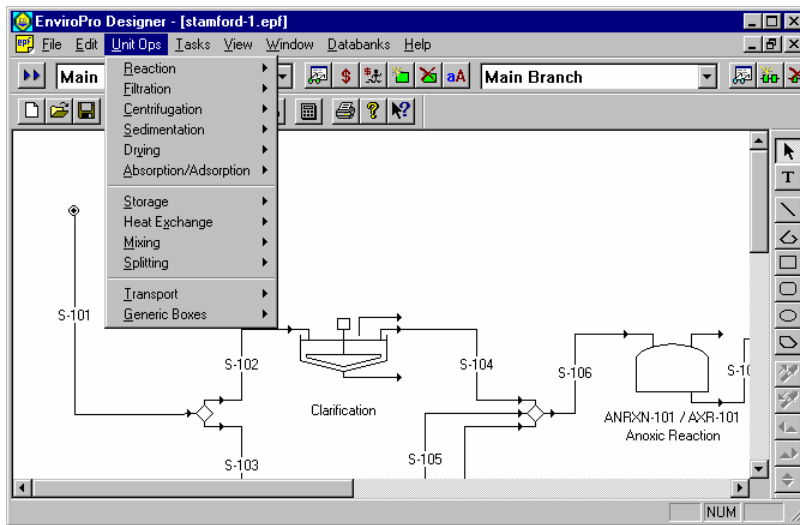


Figure 2. EnviroPro unit operations menu.

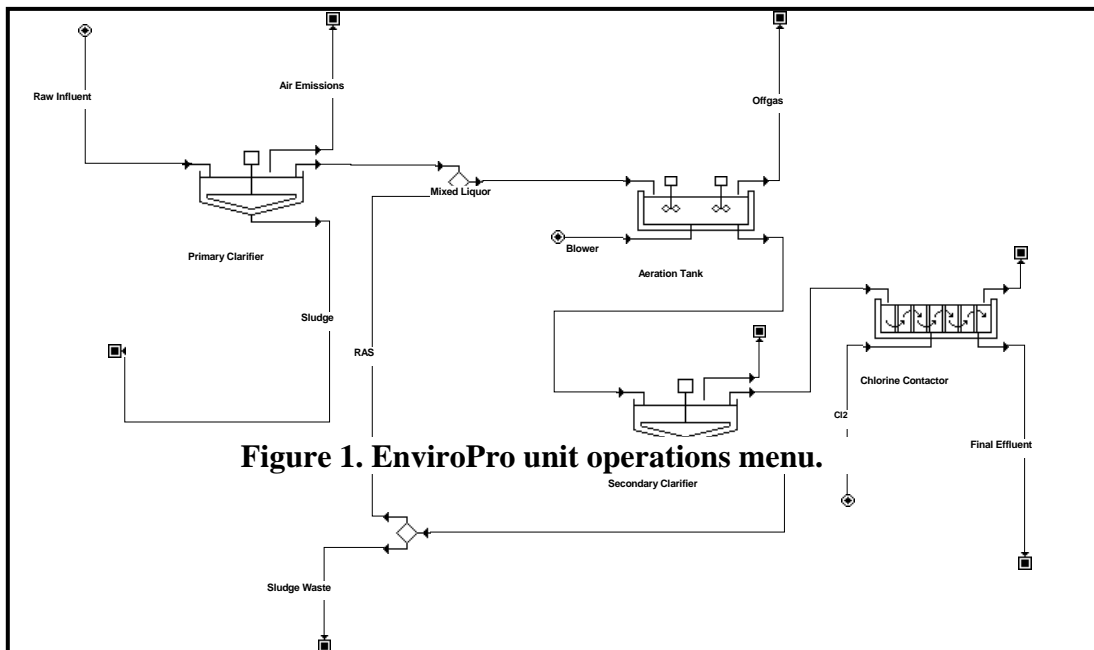


Figure 1. EnviroPro unit operations menu.

Figure 3. Flowsheet for wastewater treatment plant.

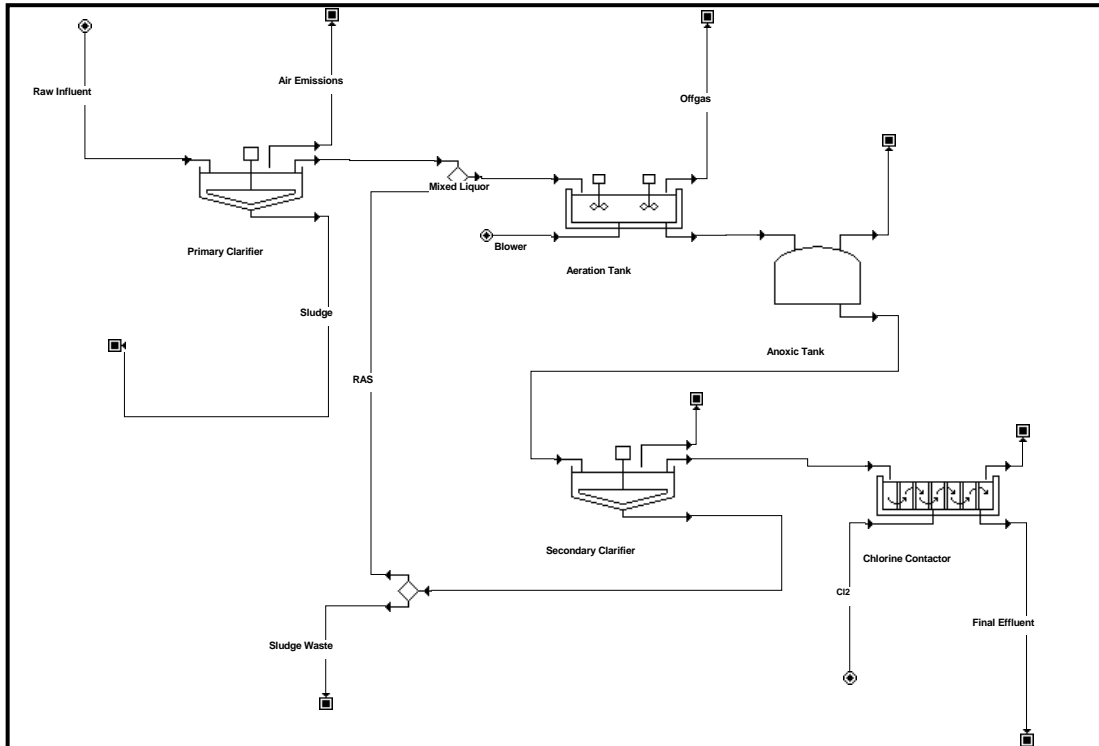


Figure 4. Wurhmann Process flowsheet

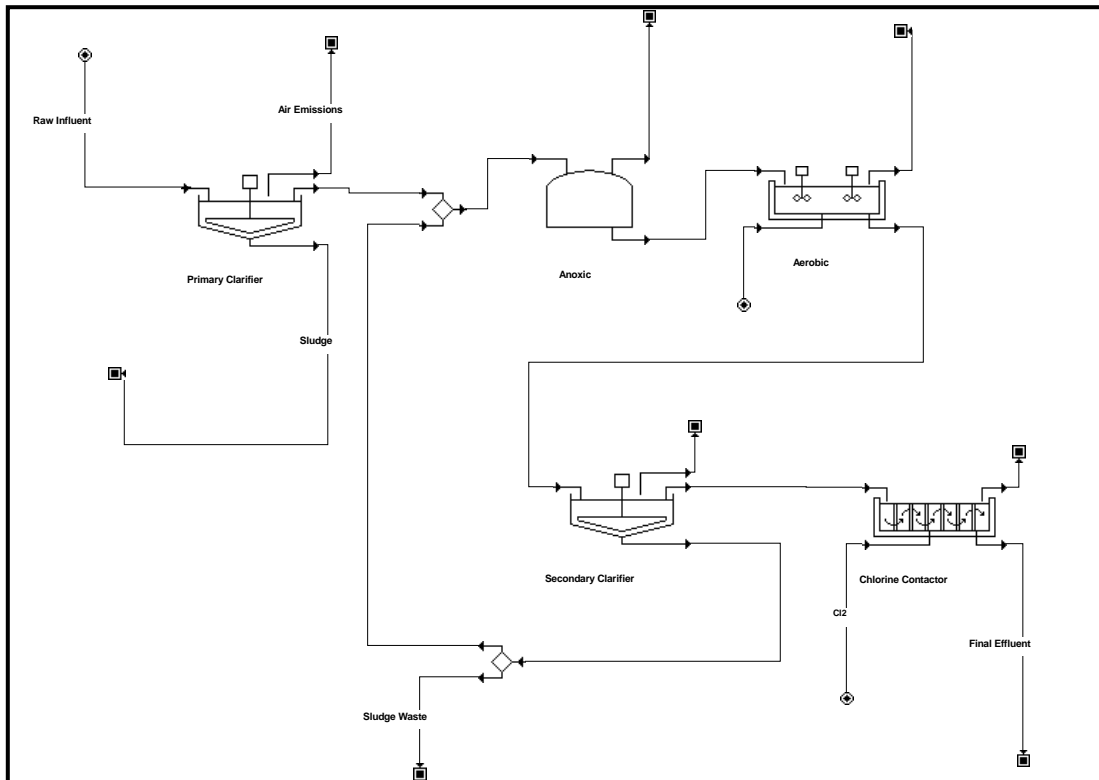


Figure 5. Ludzack-Ettinger Process flowsheet

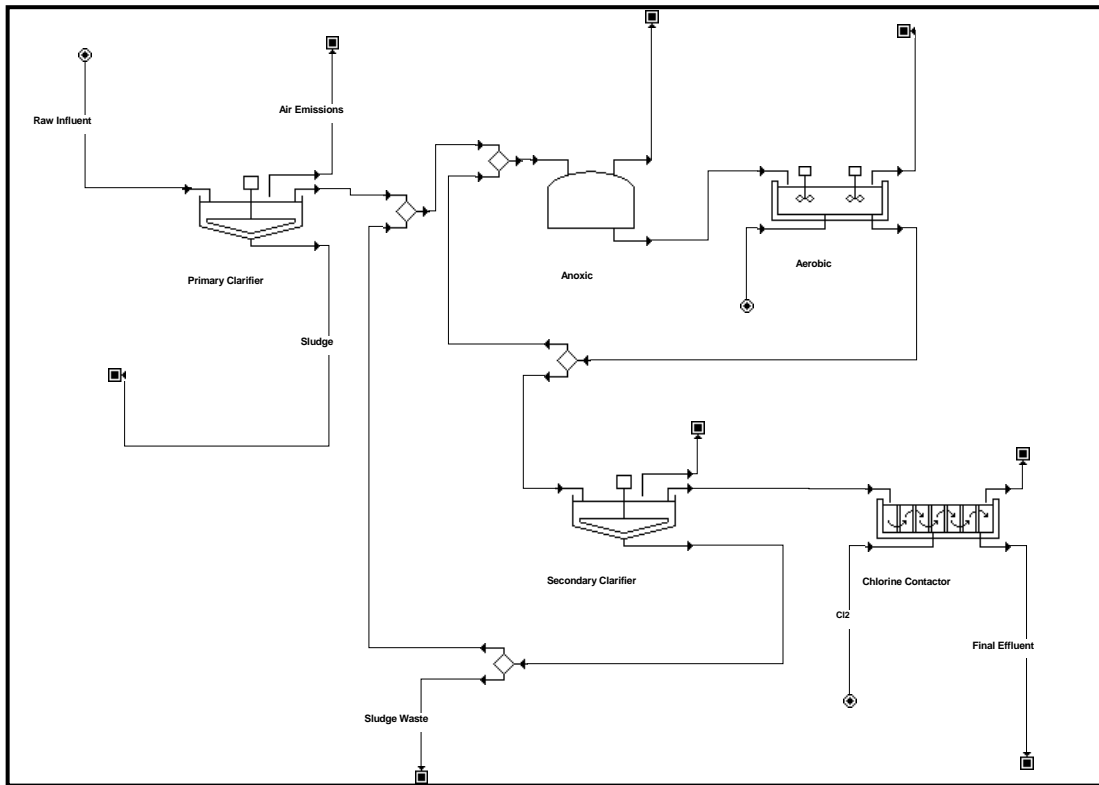


Figure 6. Modified Ludzack-Ettinger Process flowsheet

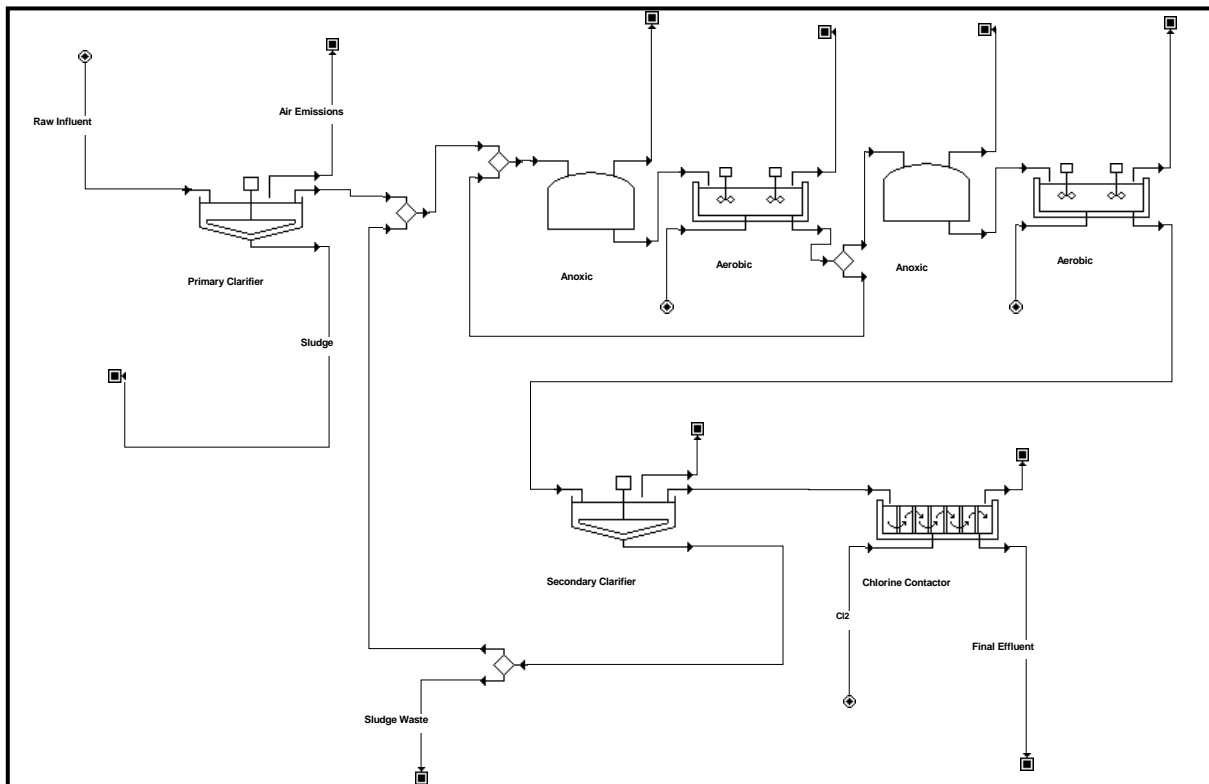


Figure 7. Bardenpho Process flowsheet