High-level Phosphorus Removal in a Small Municipal Wastewater Treatment Plant (WWTP)

By

Yukiyasu Sumi

Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING
IN CIVIL AND ENVIRONMENTAL ENGINEERING

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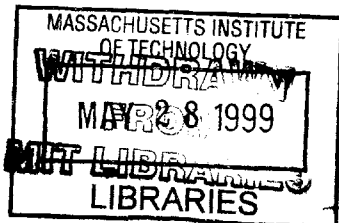MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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ABSTRACT

The objectives of the project are to investigate the feasibility of high-efficiency phosphorus removal wastewater treatment in the Town of Acton, Massachusetts and to figure out the appropriate configurations for the proposed wastewater treatment facilities.

The five wastewater treatment facilities on the Assabet River upstream of the proposed Acton wastewater treatment plant have caused eutrophication of the river. Accelerated eutrophication in the river is due to excess nutrients, phosphorus in particular, being discharged from these point sources. Because of the current situation of water quality in the river, the EPA and the Town of Acton are concerned about additional wastewater effluent discharges to the river. The EPA has proposed that an effluent total phosphorus concentration of 0.1 mg/L should be a criterion in order for a new permit application to be considered for the Acton plant. This work concludes that high-level phosphorus removal (less than or equal to 0.1 mg TP/L) is possible, and that there are two cases to be recommended for high-level phosphorus removal in small municipalities: (i) the combination of chemical enhanced primary treatment (CEPT), sequencing batch reactor (SBR) and physical effluent-polishing (EP) process (solids contact clarifier and filtration), and (ii) the combination of SBR with coagulants added and physical EP process.

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Table of Contents:

List of Tables:

List of figures:

1 Introduction and objectives

This thesis is based on the Master of Engineering project undertaken in 1998 and 1999 by the author and fellow students.

The five wastewater treatment facilities on the Assabet River upstream of the proposed Acton wastewater treatment plant have caused eutrophication of the river. Accelerated eutrophication in the river is due to excess nutrients, phosphorus in particular, being discharged from these point sources. Phosphorus and its effects on the environment are detailed in Section 2.

Because of the current situation of water quality in the river, the EPA and the Town of Acton are concerned about additional wastewater effluent discharges to the river. The EPA has proposed that an effluent total phosphorus concentration of 0.1 mg/L should be a criterion in order for a new permit application to be considered for the Acton plant.

The objectives of the project are:

- To investigate the feasibility of high-efficiency phosphorus removal wastewater treatment in the Town of Acton, Massachusetts.
- To figure out the appropriate configurations for the proposed wastewater treatment facilities.

The following table shows the design assumptions taken in the project. Although the effluent requirements for TSS are not obvious, the author considers 3 mg/L crucial to the achievement of the EPA target level (0.1 mg P/L) (explained in Section 4). The maximum flow rate is estimated by multiplying the average flow rate by 2.5 (safety factor).

Table 1. Design Assumptions and Effluent Requirements

Parameters	Influent design assumptions	Effluent requirements
Average flow rate (Q)	2,233 m^3/d	2,233 m^3/d
Maximum flow rate (Q)	5,583 m^3/d	5,583 m^3/d
Biological oxygen demand (BOD)	200 mg/L	Less than 10 mg/L
Total suspended solids (TSS)	200 mg/L	Less than 3 mg/L*
Ammonia-nitrogen (NH$_4$-N)	30 mg/L	2 mg/L @ 15 °C 4 mg/L @ 10 °C
Total phosphorus (TP)	8 mg/L	0.1 mg/L
* This is not the requirement, but 3 mg/L crucial to the achievement of the EPA target level (0.1 mg P/L).		

By taking other environmental impacts such as sludge production into consideration, the best solution to eutrophication is proposed.

Phosphorus (P) is typically removed from wastewater by chemical precipitation, biological treatment, and/or physical separation. The principles of each treatment process are described in Sections 3, 4 and 5. Chemical precipitates are formed by adding chemicals to produce insoluble salts when combined with soluble phosphate. Phosphorus is also removed in biological treatment by utilizing an anaerobic[1] zone before aerobic[2] or anoxic[3] zones. The phosphorus removed is dependent on the solids produced and removed from the wastewater treatment system and on their phosphorus content. Filtration is utilized in effluent-polishing processes to remove phosphorus-containing suspended solids.

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[1] *Anaerobic* zone refers to a zone without aeration, devoid of DO, nitrite, or nitrate.

[2] *Aerobic* zone refers to a zone with the liquid rich in DO. Nitrification only occurs under aerobic conditions.

[3] *Anoxic* zone refers to a zone where DO is absent but nitrate is present. Anoxic zones are used for denitrification.

2   *Chemistry of Phosphorus*

2.1   Why control phosphorus?

To address eutrophication in rivers and lakes, point sources, which are immobile sources of nutrients such as municipal and industrial wastewater treatment plants (WWTPs), are targeted by EPA to control nutrients.

Although phosphorus content in algae is almost negligible, ranging from 0.5 to 1.0% in the biomass, the growth of algae is considered to be controlled by the small amount of phosphorus. The concentrations of phosphorus in wastewater can be easily removed to about 1.0 mg P/L by precipitation with the use of alum, ferric salts, or lime. Phosphorus can also be removed by enhanced biological phosphorus removal (EBPR) processes as described in Section 3 (Water Environment Federation, 1998).

Typically, nutrient control strategies take advantage of a microorganism's necessity for nitrogen and phosphorus. In this project, phosphorus removal is mainly targeted due to its stronger role in terms of eutrophication in the Assabet River.

2.2   Eutrophication

The major adverse effect of phosphorus is termed eutrophication. This typically causes an increase in plant and animal biomass, shortage of oxygen or presence of anoxic condition in water, and a decrease in biodiversity in water. The causes of eutrophication are as follows:

1. Fertilizers,
2. Sewage overflows which causes an increase in the amount of nutrients,
3. Domestic wastewater, and
4. Animal waste.

The removal of nutrients in effluent from sewage plants should be achieved in this project to address eutrophication in the Assabet River and its neighboring lakes.

Eutrophic means waters with a high degree of biological productivity. Several parameters represent how waters are eutrophic: standing crop of phytoplankton, level of chlorophyll, volume of algae, level of oxygen production, level of oxygen depletion, Secchi disk readings, or a combination of all these parameters. If dissolved oxygen becomes depleted and the waters become anoxic or anaerobic in the bottom layer of a lake during summer, the waters are considered eutrophic. The degree of eutrophy is estimated by the time it takes for anoxic or anaerobic conditions to develop after the onset of stratification (Water Environment Federation, 1998).

2.3   Chemical forms and sources of phosphorus

The typical form of phosphorus in aquatic environments is the +5 valence state, as salts and esters of phosphoric acid due to this chemical form of phosphorus. Inorganic phosphates such as orthophosphates[4], which are essential for biological metabolism, can be produced from phosphoric acid. Bacteria and many microorganisms utilize orthophosphates to create organic phosphates to build their solid-phase structures. For example, calcium phosphate is the basic component of bone. Energy production and reproduction of microorganisms depend on organic phosphates found in nucleic acids, phospholipids, adenosine triphosphate (ATP), hormones, and many other compounds (Water Environment Federation, 1998).

Wastewater containing human excrement, food wastes, synthetic laundry detergents, household cleaners, and industrial and commercial discharges causes an increase in the amount of nutrients in the receiving waters. Various kinds of synthetic laundry detergents from domestic wastewater are the major sources of phosphorus. Though phosphate detergents for industrial use have been banned, the effect of the ban has been limited because household cleaners and commercial

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[4] Orthophosphates typically take the form of soluble phosphorus.

detergents are typically excluded from the ban. Generally speaking, industries such as fertilizer manufacturers, feed lots, and meat, milk, and food processors have contributed to high concentrations of phosphorus in the environment (Water Environment Federation, 1998).

As there seem to be few industries that might significantly affect the Assabet River in Acton, it seems reasonable to assume that a wastewater treatment plant would mainly collect domestic wastewater.

2.4   Typical phosphorus concentrations in influent municipal wastewater

In general, phosphorus contributions from human excrement, food waste, household cleaners, and commercial detergents are relatively consistent throughout the U.S. Therefore, the concentrations of detergents in wastewater flowing into municipal wastewater treatment plants determine the wastewater phosphorus concentration. The average total phosphorus concentration was measured 8 mg/L before the phosphate ban, which went into effect on December 1, 1988, in Virginia, and 5.4 mg/L after the ban. The average orthophosphate concentration was 6 mg/L before and 3.7 mg/L after the phosphate ban (Water Environment Federation, 1998).

As conducted in Section 11, the calculations of phosphorus concentrations conducted are based on the information above. The total phosphorus and soluble concentrations in influent municipal wastewater are conservatively assumed to be 8 mg/L and 5 mg/L, respectively.

9

3   Overview of phosphorus removal processes

Phosphorus removal must rely on the process in which phosphorus is converted to particulate (solids) form and is removed as a particulate. Table 2 summarizes the various options for removing soluble phosphorus species (Water Environment Federation, 1998).

Table 2. Phosphorus Species and Reactions (Water Environment Federation, 1998).

Species	Comments
Organic-P	Organic phosphorus can be converted to orthophosphate and polyphosphate
Orthophosphate	Most abundant phosphorus species Reactive species in chemical reactions and consumed in biological growth
Polyphosphates	Condensed orthophosphates Possibly reacts with metal salts Can be used for biological growth
Chemical phosphorus	Precipitated phosphates formed by reacting orthophosphate with metal salts, or precipitates as phosphate hydroxides
Biological phosphorus	Phosphorus incorporated into the biomass for growth Excess phosphorus may accumulate under certain conditions

Phosphorus removal is typically achieved by three types of processes described below (Water Environment Federation, 1998).

- Conversion of soluble phosphorus to chemical compounds by adding metal salts or lime. The efficiency of phosphorus removal is dependent on two factors: the chemical equilibrium between the phosphorus liquid and solid phases, and the efficiency of the solids removal process. Typically, removal of suspended solids controls removal efficiency.

- Incorporation of phosphorus into biomass. Typically, the phosphorus content in biomass is

10

1.5 to 2.5% (w/w) phosphorus per volatile solids. As described later in this section, under enhanced biological phosphorus removal (EBPR) processes, this option utilizes the function of biomass that can accumulate phosphorus far in excess of the nutritional requirements to 4 - 12% phosphorus. The phosphorus removal efficiency of this system is dependent on the phosphorus content of the sludge removed and the efficiency of the solids separation process. This implies that both an EBPR system and the system that can effectively remove suspended solids, such as filtration after the EBPR process, are necessary in this project.

- Reverse osmosis, or nanofilters, can be used to remove phosphorus. Though membrane treatment is expensive and not practically used for mainstream phosphorus removal, membranes can be used for the removal of the suspended solids that escape from primary and secondary treatment or dissolved solids removal.

Typically, phosphorus removal processes can be grouped into three: chemical processes, biological processes and physical processes. The following subsections describe each typical phosphorus removal process. The selection of a specific process must be based on a case-by-case evaluation of the system costs and its effectiveness.

3.1 Chemical phosphorus removal

One of the principles of chemical phosphorus removal is precipitation by chemical addition to wastewater. Calcium [Ca^{+2}], aluminum [Al^{+3}], and iron [Fe^{+3}] or [Fe^{+2}] are most commonly used for precipitation in wastewater treatment plants. The chemistry of phosphate precipitation with aluminum [Al^{+3}] and ferric iron [Fe^{+3}] is almost the same. Their reactions are presented in Section 4.

Although chemical phosphorus removal is simple and easy to implement, one has to consider increased sludge production and additional operation and maintenance (O&M) costs as a result of chemical sludge produced by chemical addition. Usually, chemicals are added to wastewater in primary settling tanks or in activated sludge systems to enhance precipitation. In advanced treatment systems, filtration with chemical addition, in which chemical precipitates are filtered,

is utilized for phosphorus and suspended solids removal. The Water Environmental Federation (1998) reported that phosphorus levels less than 0.1 mg P/L can consistently be achieved with chemical addition and well-designed filtration facilities.

3.2 Biological phosphorus removal

Energy production and reproduction of microorganisms depend on organic phosphates found in microorganisms, and phosphorus is required in intracellular energy transfer. Phosphorus content of microbial solids in conventional activated sludge systems is 1.5 to 2.5% on a dry weight basis. A sequential system of anaerobic and aerobic zones results in the selection of organisms (so-called phosphorus-removing bacteria) capable of taking up phosphorus at rates beyond the typical requirements for microbial growth. With an anaerobic condition followed by an aerobic step, the biomass can accumulate phosphorus up to 4 to 12% of the microbial solids. Phosphorus can be more effectively reduced in the combination of anaerobic and aerobic conditions than in conventional activated sludge systems. The organism associated with this biological phosphorus removal process is called *Acinetobacter* (Water Environment Federation, 1992).

The mechanism in which excessive phosphorus removal can be achieved is called enhanced biological phosphorus removal (EBPR). The mechanism currently accepted is shown in Figure 1. Acetate and other short-chain fatty acids produced by fermentation reactions, which occur in the conditions as in the anaerobic zone, are taken up in phosphorus- removing bacteria. These substrates are most commonly stored as poly-hydroxy-butyrate (PHB). Microorganisms must consume some energy in the uptake of soluble organic acids to store PHB. In the anaerobic zone, phosphorus-removing bacteria can obtain this energy by splitting high-energy phosphate bonds in stored long-chain inorganic polyphosphate. As a result of the split of polyphosphate, orthophosphate is produced in solution under anaerobic conditions (Water Environment Federation, 1992). Only phosphorus-removing bacteria (i.e. *Acinetobacter*), which can survive under anaerobic conditions, accumulate.

Soluble orthophosphate is re-synthesized into polyphosphates in the aerobic zone, while PHB

stored in cells of phosphorus-removing bacteria is oxidized to CO_2, H_2O, and new cells. Residual soluble BOD is also metabolized under aerobic conditions. Typical profiles of phosphorus concentrations indicate a rapid increase in soluble phosphorus in anaerobic zones and a rapid decrease in phosphorus in aerobic zones due to the selective accumulation of phosphorus-removing bacteria. The kinetics of phosphorus release and uptake is not yet fully understood. Thus, design engineers must rely on empirical observations and pilot-plant experiments to obtain information for process design and modifications (Water Environment Federation, 1992).
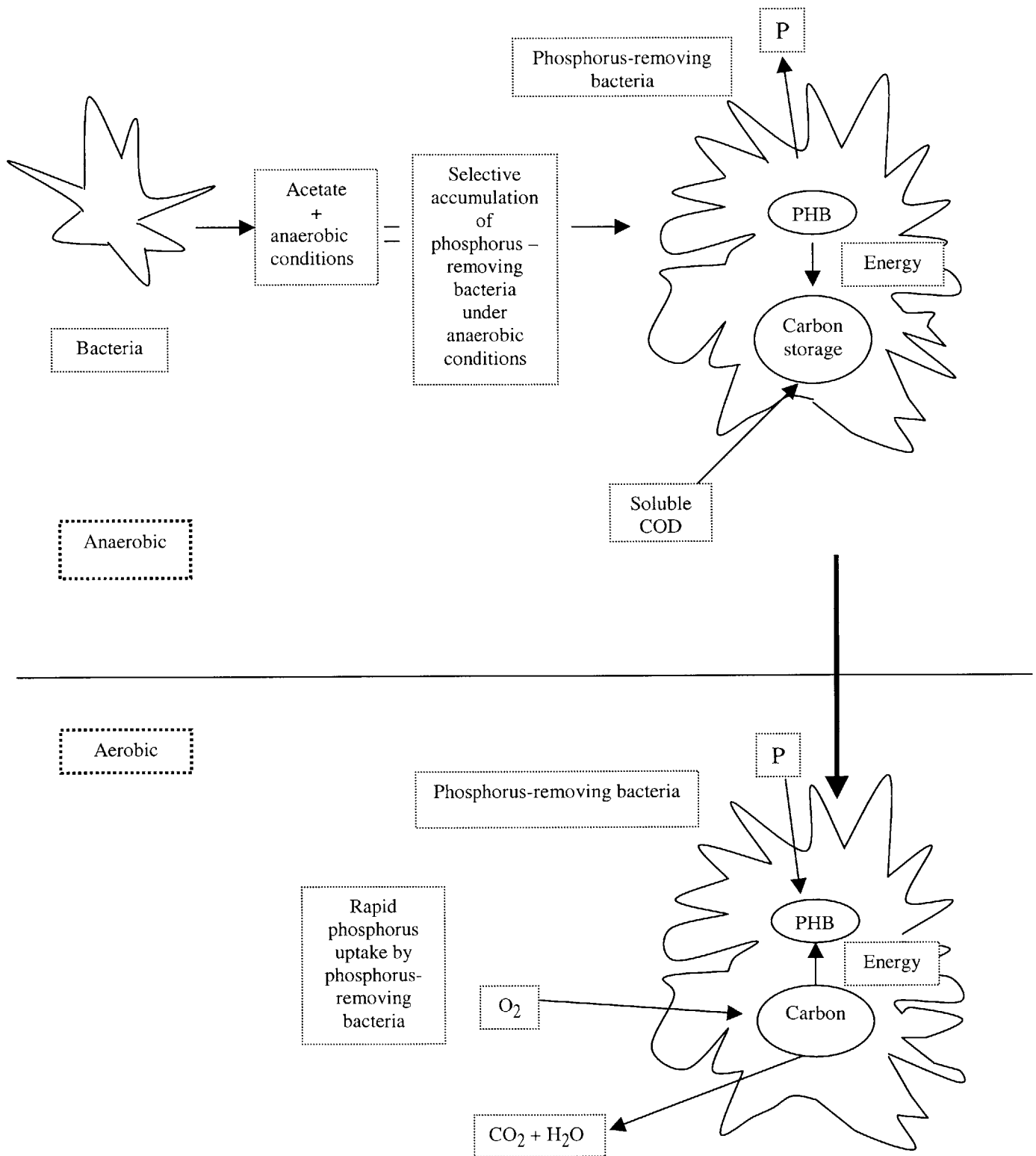
Figure 1. Mechanism of Enhanced Biological Phosphorus Removal (PHB = poly-β-hydroxybutyrate). (created by the author based on Water Environment Federation, 1992)

14

3.3 Physical phosphorus removal

Desire to control eutrophication leads to stringent effluent requirements for phosphorus. Although attention has been mainly focused on the integrated removal processes of phosphorus and nitrogen, it is doubtful whether the resulting effluent quality will be sufficient to meet the stringent requirements. The effluent-polishing (EP) process should be introduced to WWTPs that seek to meet the stringent requirements. In this process, phosphorus, heavy metals, organic micro-pollutants, microorganisms and suspended solids have to be removed. Filtration seems to be the most appropriate for this effluent-polishing step.

4   Principles of chemical phosphorus removal

Precipitation is the basic principle of chemical phosphorus (P) removal, in which soluble phosphorus is transformed to insoluble particulate, and then removed by sedimentation. Removal during primary settling depends on the efficiency of the primary clarifiers. Chemically enhanced primary treatment (CEPT) can be used to transform soluble P to insoluble particulate and to enhance the sedimentation in primary settling tanks. In biological treatment processes, chemicals can be added to precipitate excessive phosphorus (Water Environment Federation, 1998).

Effluent total phosphorus (TP) concentrations can be estimated as

$$TP = SP + m \cdot (SS) \quad \cdots\cdots (1)$$

Where

   SP = soluble phosphorus (mainly soluble orthophosphate), mg/L;

   SS = effluent suspended solids concentration, mg/L; and

   m = phosphorus content in SS dry mass, mg P/mg SS.

For conventional activated sludge, m is 15 to 25 mg P/g volatile suspended solids (VSS) (1.5 to 2.5%). For chemical phosphorus removal, m varies between 40 to 100 mg P/g suspended solids

15

(4 to 10%). The equation above emphasizes that phosphorus removal is proportional to solids removal (Water Environment Federation, 1998). For example, if effluent suspended solids concentration is 4 mg/L with a phosphorus content of 2.5% (25 mg P/g SS), a total phosphorus concentration below 0.1 mg TP/L cannot be achieved. Therefore, the author proposes that the effluent TSS be less than 3 mg/L.

In the three next subsections, an overview of each chemical utilized in wastewater treatment is presented.

4.1   Ferrous iron

Ferrous iron [Fe^{+2}] is a convenient and economical precipitating agent. However, it is reported that the precipitate formed by oxidized Fe^{+2} in clean water is inferior to that from Fe^{+3} (Water Environment Federation, 1998). From various sources, the author found that effluent TP concentrations from secondary treatments plants using ferrous iron as a precipitating agent could not achieve high-level phosphorus removal (less than 1.0 mg TP/L). Therefore, ferrous iron is not considered to be a candidate for a chemical in this project.

4.2   Ferric iron and aluminum

As chemical precipitation using aluminum or ferric iron coagulants is proved to be effective in phosphate removal, these two chemicals are considered as chemical alternatives. The primary reactions of coagulation combine orthophosphate with metal cations such as aluminum and ferric iron. Polyphosphates and organic phosphorus compounds are probably removed by being entrapped in, or adsorbed on, the floc particles. Aluminum and ferric salts combine with phosphate ions as follows (Hammer et $al.$, 1996).

$$Al^{3+} + H_2PO_4^- \rightarrow AlPO_4(s) + 2H^+ \quad \cdots\cdots (2)$$

$$Fe^{3+} + H_2PO_4^- \rightarrow FePO_4(s) + 2H^+ \quad \cdots\cdots (3)$$
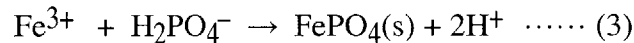
The excess metal cations also react with hydroxide ions. The reactions are shown below:

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3(s) + 3H^+ \quad \cdots\cdots (4)$$

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+ \quad \cdots\cdots (5)$$
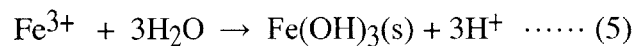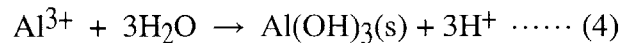
The formation of metal hydroxides makes it difficult to predict actual chemical reactions and the amount of the sludge produced with chemical addition. Calculations of chemical sludge produced are based on the following steps:

1. Al or Fe dose is determined based on the empirical data presented in Water Environment Federation, 1998, which gives us metal salt to phosphorus ratios. For example, if the soluble P level of 0.1 mg/L is required, the metal salt to phosphorus ratio should be Al/P=3 or Fe/P=5.

2. Instead of Equations (2) and (3), the following equation is proposed as the actual chemical reaction occurring in chemical processes of wastewater treatment (Water Environment Federation, 1998):

$$r \, Me^{3+} + H_2PO_4^- + (3r-1) \, OH^- \rightarrow Me_r(H_2PO_4)(OH)_{3r-1}(s) \quad \cdots\cdots (6)$$
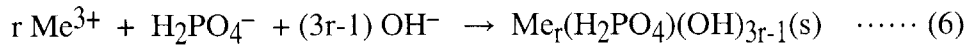
$$r = 0.8 \text{ for Al(III)}, \ 1.6 \text{ for Fe(III)}$$

3. The formation of metal hydroxide is calculated based on the amount of metal salts added in wastewater minus the amount of metal salts used to remove phosphate.

The reactions produce a significant amount of sludge (2.9 mg solids/mg Al for alum and 1.9 mg solids/mg Fe for ferric chloride) that must be processed through dewatering and disposal and thus increases operation and maintenance (O&M) costs (Water Environment Federation, 1998).

4.3   Calcium

Calcium salt is conventionally added as lime. Though phosphate precipitation with lime was the earliest method of phosphorus removal, calcium is not considered for an alternative for chemical treatment because of two reasons stated below:

- The formation of insoluble compounds of lime and phosphate depend on pH and wastewater alkalinity and significant phosphate removal can only be achieved at higher pH values. For example, removal of phosphate values below 1 mg/L requires values of pH of 10.5 to 11. (Water Environment Federation, 1998). The wastewater in the Town of Acton is assumed to be the typical municipal wastewater, in which pH is around 7.2, and a high pH could cause biological treatment processes to break down (Water Environment Federation, 1998).

- Usually, the use of calcium causes high sludge production, and then results in high capital and O&M costs for the facilities related to sludge processing.

18

5   *Principles of biological phosphorus removal*

5.1   Enhanced biological phosphorus removal (EBPR)

The following operating characteristics emerged with respect to EBPR systems (Water Environment Federation, 1998):

- As microorganisms in an anaerobic zone require enough substrates to nurture them, the return sludge and the mixed liquor should be introduced at the inlet end of the anaerobic zone.

- Aeration should provide a high dissolved oxygen (DO) content at the outlet of the basin to prevent anaerobic conditions from developing in secondary clarifiers.

- As oxidation occurs in the presence of nitrification, the degree of nitrification in an anaerobic zone should be kept to a minimum.

- Solids should be rapidly removed from the secondary clarifiers and returned to the anaerobic zone. If the wastewater is allowed to become anaerobic in the secondary clarifiers, phosphorus release will result in an increase in effluent phosphorus concentrations.

The importance of an anaerobic zone in activated-sludge systems to remove phosphorus is clearly established as described in this report. However, the mechanism (microbiology and biochemistry) is still in dispute and the design of systems remains largely empirical.

5.2   Microbiology

Though the microbiology of the activated sludge system is complex, kinetic data on the growth of phosphorus-removing bacteria such as *Acinetobacter* can be obtained from various sources (Water Environment Federation, 1998). The typical growth kinetic coefficients useful in this project are shown below:

- dry cell yields (Y) = 0.3 to 0.4 to g VSS/g COD or 0.7 to 1.0 g VSS/g BOD
- endogenous decay rates (k_d) = 0.03 to 0.04/day
- phosphorus content in sludge = 4 to 12%

As the data on maximum growth rates (μ_{max}) for phosphorus-removing bacteria vary from source to source, the typical μ_{max} for the activated-sludge system is used in this report. The calculation method of μ_{max} for nitrification is established by EPA and the author relies on this method to calculate the amount of sludge produced.

5.3   Temperature and pH

Although the EBPR processes are relatively insensitive to temperature changes (Water Environment Federation, 1998), nitrification and denitrification are affected by temperature. In this report, the calculation of mean-cell residence time (MCRT), which is an essential component in designing activated sludge systems, is based on the established calculation method for nitrification. Considering the climate in Massachusetts, the design water temperature is set at 10 °C in winter.

The phosphorus uptake rate is reported to be optimum between pH 6.6 and 7.4 , but to decrease rapidly as the pH drops below 6.2 (Water Environment Federation, 1998). In this project, the pH is assumed to be that of the typical municipal wastewater, around pH 7.2. If pH is below 7.2, soda ash can be added, as many wastewater treatment plants.

6   *Screening methods*

The strategy described below for selecting a phosphorus removal system is invented, based on the screening process proposed by EPA (1987). The five steps of the selective screening process adapted here are described below and illustrated in Figure 2.

Step 1:   Determine whether the effluent nutrient discharge limitations are for phosphorus only. In this case, phosphorus is the limiting nutrient. This does not mean nitrogen removal is ignored in this project.

Step 2:   Propose alternatives to be considered and classify them as associated with three basic processes (chemical, biological and physical processes).

Step 3:   Determine which P-removal processes can meet phosphorus limitations (0.1 mg/l in this project).

Step 4:   Estimate the capital, operation and maintenance, and total present-worth costs for applicable alternatives. This comprehensive cost-effectiveness analysis will result in the selection of a system that meets project objectives at the lowest present-worth cost.

Step 5:   Consider non-monetary factors including:

- Non-water-quality environmental impacts such as sludge production or waste disposal, and
- Operator skill levels required for successful operation.

Figure 2. Screening Process Flow-sheet

| Step | Phosphorus removal or simultaneous phosphorus/nitrogen removal? |

Mainly phosphorus removal

| Step 2 | What are chemical, biological and physical alternatives that seem to be appropriate? |

Chemical treatments

Biological treatments

Physical treatments

| Step 3 | Which alternatives can meet the EPA target P level (0.1 mg/L) by the combination of three technologies and are in practical use? |

| Step 4 | What are the cheapest alternatives? |

Cost-effective analysis

| Step 5 | Are the selected alternatives environmentally friendly and easy to operate? |

Process selection

7   *Second step of screening (alternatives)*

The following table shows various applicable technologies for phosphorus removal. These technologies are collected through literature review or the information collected from the technical advisors.

Table 3. Alternatives		
Technologies	Feasible effluent concentrations	Descriptions
Chemical treatments		
GCR20 (liquid aluminum chloride-ferric chloride)	0.18 mg/L (tertiary clarifier effluent) 0.06 mg/L (filtered final effluent)	• Used as cheaper chemical additions (about half the cost of ferric chloride) than ferric chloride or aluminum chloride, being the byproduct of a process used primarily for cleaning computer chips and circuits (Gupta *et al.*). This technology is not in practical use yet.
Ferric chloride	Less than 0.1 mg/L when combined with other treatment processes	• Used in some wastewater treatment plants for high-level phosphorus removal (XCG Consultants Limited, 1996).
Alum	Less than 0.1 mg/L when combined with other treatment processes	• More expensive than ferric chloride (XCG Consultants Limited, 1996).

Phormidium laminosum	0.05 mg/L (effluent after residence time of 12 hour)	• Using the thermophilic cyanobacterium immobilized on cellulose hollow fibres in the tubular photobioreactor at 43 °C (Sawayama,1998). This technology is technically feasible but not in practical use yet.
Biological teatments		
Activated sludge treatment (SBR)	0.5 to 1.0 mg/L (secondary effluent) less than 0.1 mg/L with other chemical and physical treatment processes (Shin *et al.*, 1992; Rim *et al.*, 1997; Hamamoto *et al.*, 1997)	• Sequencing batch reactor (SBR) system is appropriate for small-sized plants like this project. • SBR can be removed both phosphorus and nitrogen.
Physical treatments		
Contact clarifier and microfiltration	60-90 µg/L (without ferric dosing) 30-50 µg/L (with ferric dosing)	• Three microfiltration systems with a pore size of 0.2 µm have been tested in small-scale pilot plants (Dittrich *et al*, 1996). This technology is technically feasible, yet seems expensive.
Contact clarifier and ultrafiltration	<0.1 mg/L	• This technology is being piloted in Hopewell, Virginia and has been installed in full-scale wastewater treatment plants in Canada and Europe.

Contact clarifier and filtration	0.05-0.1 mg/L	• Secondary effluent containing dissolved oxygen is dosed with ferric chloride or alum solution and then contacted with filter media (XCG Consultants Limited, 1996).

7.1   Chemical treatment methods

As mentioned in Section 4, chemical treatment methods include ferrous iron, ferric iron and aluminum, and calcium. Ferric iron and aluminum are practically used for high-rate phosphorus removal in the U.S. Calcium is not frequently used in practice because calcium causes high sludge production. The author considers the effectiveness of ferrous iron speculative for high-rate phosphorus removal. Therefore, ferrous chloride and calcium should not be considered as the alternative chemical treatments. Ferric iron and aluminum are included as the alternative chemical treatments here.

Effluent from the Durham Wastewater Treatment Facility, Oregon must meet extremely stringent effluent limits in order to protect the water quality of the Tualatin River. The plant uses alum to attain an effluent phosphorus concentration of 0.08 mg/L. The plant has secondary treatment processes to provide biological nutrient removal, chemical clarifiers, and mixed-media effluent filters (Unified Sewerage Agency of Washington County, Oregon, 1998).

One of the operators of the plant suggested that they added 30 mg/L alum in both primary and tertiary clarifiers. With biological phosphorus removal instituted for part of the plant, they were able to cut the total dose to 20 mg/L in the tertiary clarifiers since, at times, secondary effluent soluble phosphorus was lower than 0.1 mg/L.

7.2   Biological treatment methods

The Table 4 shows the matrix for the biological process selection. Though, in this project, only phosphorus removal is targeted to address eutrophication, nitrification would likely also be required. The matrix here explains which biological treatment technologies are appropriate for specific target levels of nitrogen and phosphorus.

Treatment in a sequencing batch reactor (SBR) is recommended because SBRs are less expensive, efficient, and controllable, particularly for small-flow systems like this project. In conventional activated-sludge treatment systems, the processes are carried out simultaneously in separate tanks, whereas in SBR operation the processes are carried out sequentially in the same tank (see Figure 3).
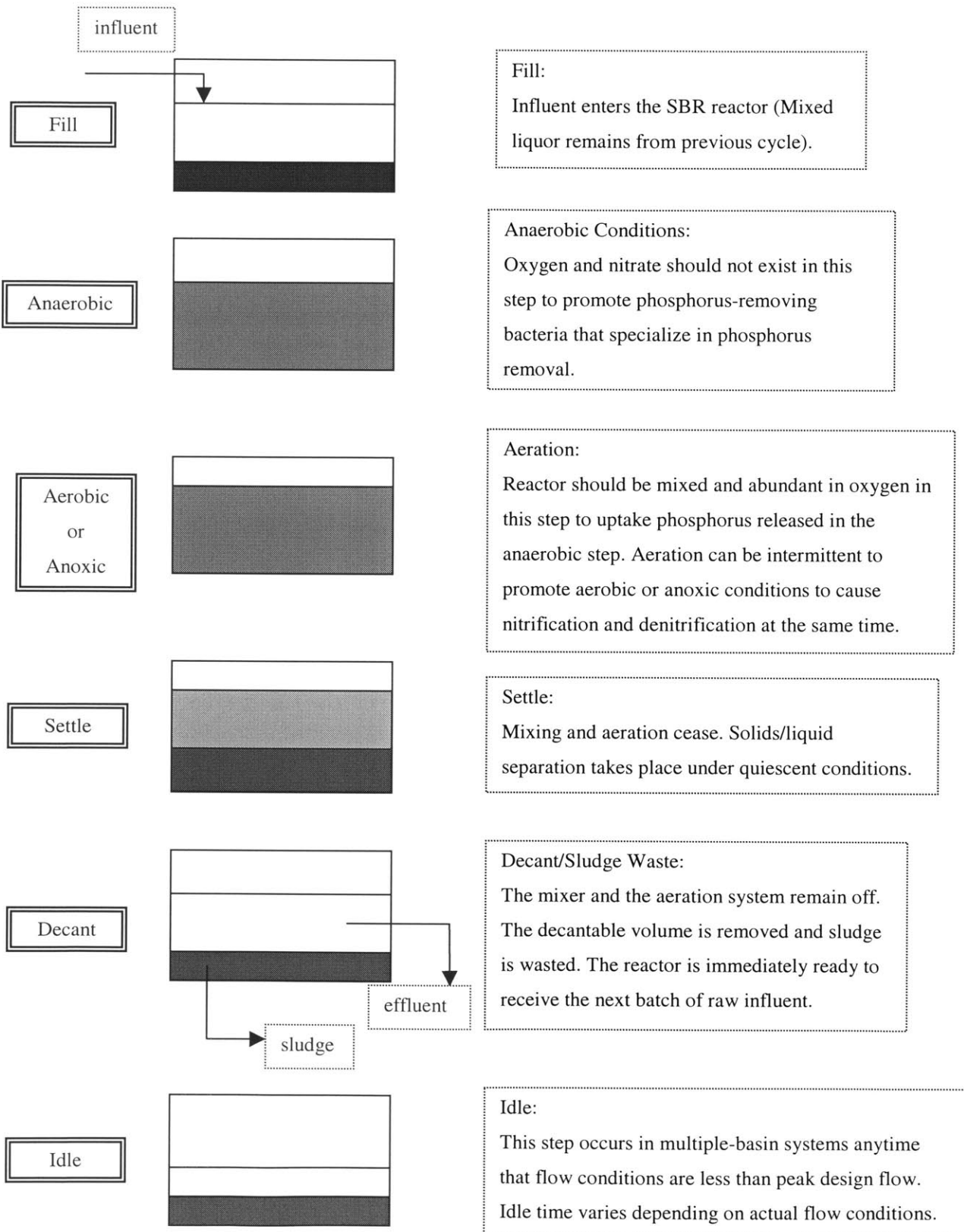
Shin et al. (1992) reported in their research that phosphorus removal efficiencies were about 60% to 95%. Rim et al. (1997) found in their experiments that the average BOD, SS, total nitrogen and phosphorus removal rates were observed to be 95%, 89%, 70% and 77%, respectively. Hamamoto et al. (1997) also reported in their pilot-plant experiments the average nitrogen and phosphorus removal rates of 86% and 82%, respectively.

The calculations of secondary effluent BOD, TP, or sludge production from SBR undertaken in Section 11 are based on the values of the efficiencies quoted above. Phosphorus removal efficiencies around 80% seem to be applicable to the calculations of the concentrations.

Table 4. Process Selection Matrix for Nutrient Removal (Water Environment Federation, 1992).					
Approximate percentage removal (typical concentration, mg/L)	Nitrogen 0% (40) 30%(28)	Nitrogen removal	Nitrogen and phosphorus removal	Phosphorus removal	Phosphorus 0% (10) 30%(7)
		Conventional activated sludge (10 to 30%)	Conventional activated sludge	Conventional activated sludge (10 to 15%)	
	80% (8)	- MLE - A^2/O^{TM} - PhoStrip II^{TM} - Oxidation-ditch - Biodenitro^{TM} - Simpre^{TM} - UCT and VIP -	- Modified Bardenpho^{TM} - A^2/O with denite filters - Biodenitpho^{TM} - PhoStrip^{TM} - Operationally modified activated sludge - UCT - SBR - PhoStrip II^{TM}	- A/O^{TM} - PhoStrip^{TM} - Sequencing batch reactor (SBR) - OWASA	80% (2)
	(filters suggested) 95% (2)	- 4-stage Bardenpho^{TM} - Modified Wuhrman - Dual sludge - Three sludge - Post-aeration anoxic tank with methanol - Denitrification filters - Fluidized bed reactors - Phase isolation ditches	- Dual sludge with chemicals - Modified Bardenpho^{TM} with chemicals - A^2/O with denite filters and chemicals - Three sludge with chemicals	- PhoStrip^{TM}	(filters suggested) 98% (0.20)

Figure 3. Mechanism of Sequencing Batch Reactor

Fill

influent

Fill:
Influent enters the SBR reactor (Mixed liquor remains from previous cycle).

Anaerobic

Anaerobic Conditions:
Oxygen and nitrate should not exist in this step to promote phosphorus-removing bacteria that specialize in phosphorus removal.

Aerobic or Anoxic

Aeration:
Reactor should be mixed and abundant in oxygen in this step to uptake phosphorus released in the anaerobic step. Aeration can be intermittent to promote aerobic or anoxic conditions to cause nitrification and denitrification at the same time.

Settle

Settle:
Mixing and aeration cease. Solids/liquid separation takes place under quiescent conditions.

Decant

effluent

sludge

Decant/Sludge Waste:
The mixer and the aeration system remain off. The decantable volume is removed and sludge is wasted. The reactor is immediately ready to receive the next batch of raw influent.

Idle

Idle:
This step occurs in multiple-basin systems anytime that flow conditions are less than peak design flow. Idle time varies depending on actual flow conditions.

7.3   Physical treatment methods

(a) Solids contact clarifier

Usually, solids contact clarifiers are used in advanced wastewater treatment to provide high-rate treatment of wastewater for SS removal. The low concentration effluent from the previous processes (typically secondary treatment) is mixed with the highly concentrated settled solids and precipitating chemicals in solids contact clarifiers and the mixture is dispersed into the reaction well, where the solids coagulate and settle (Water-Online, 1998).

The following three alternatives utilize the filtration process with solids contact clarifiers ahead of them to reduce remaining suspended solids that are the major contributor to the concentrations of effluent total phosphorus.

(b) Contact clarifier and ultrafiltration

Monat (1998) proposes the sizes of various types of filtration and their usage as shown in Figure 4. Ultrafiltration (UF) has finer pores (membrane pore sizes approximately between 0.01 to 1.0 μm) than microfiltration (MF) and UF is utilized to remove suspended solids, fine particulate, colloids, emulsified oils, bacteria, macromolecules and so forth. The separation is primarily based on the size of the species in the liquid relative to the size of the membrane pores.
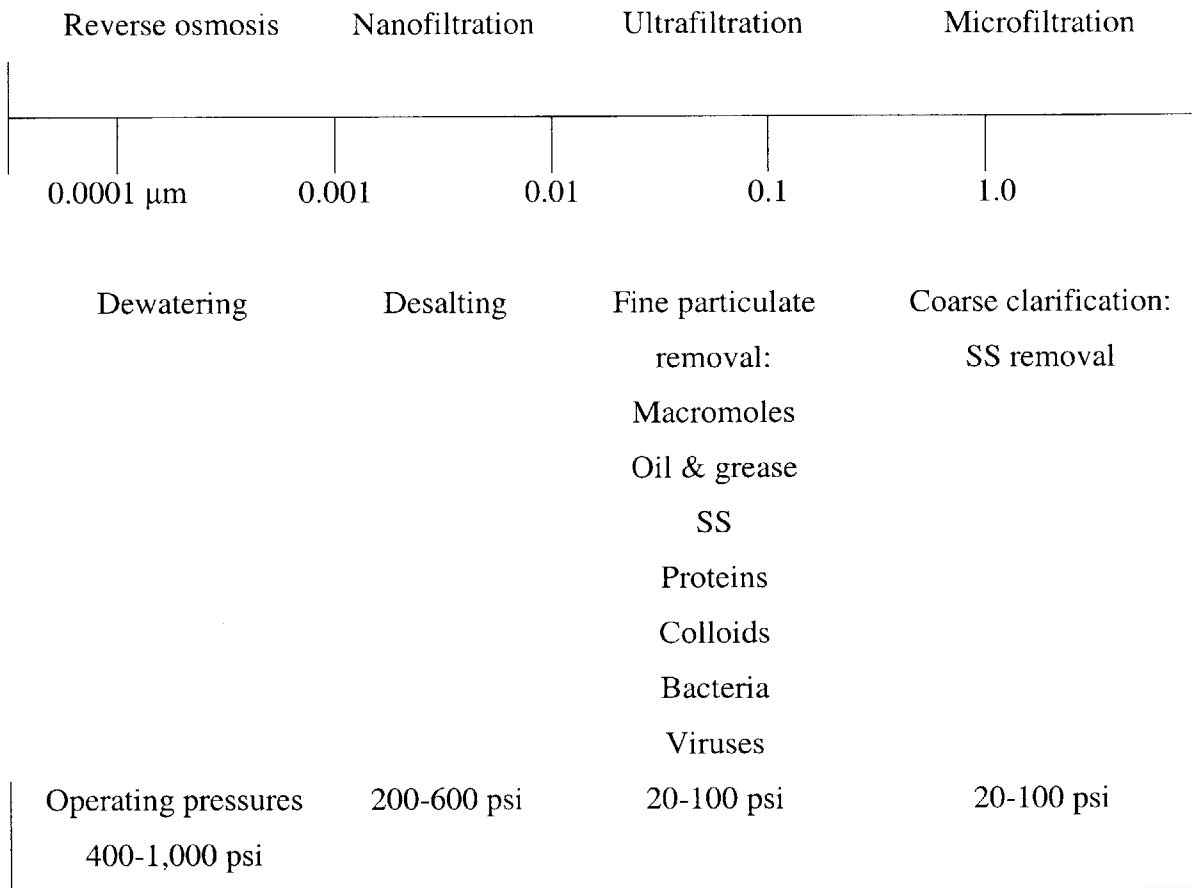
Reverse osmosis	Nanofiltration	Ultrafiltration	Microfiltration
0.0001 μm	0.001	0.01 0.1	1.0
Dewatering	Desalting	Fine particulate removal: Macromoles Oil & grease SS Proteins Colloids Bacteria Viruses	Coarse clarification: SS removal
Operating pressures 400-1,000 psi	200-600 psi	20-100 psi	20-100 psi

Figure 4. Filter Sizes and Usage (Monat, 1998)

(c) Contact clarifier and microfiltration

Dittrich *et al.* (1996) conducted an experiment to show whether microfiltration (MF) is a technically feasible and economically competitive process for disinfection and phosphorus removal of secondary effluent and reported that the average concentrations for total phosphorus (TP) in the effluent are 60 to 90 μg/L without the use of precipitants, and 30 to 50 μg/L with ferric chloride dosing. The following table shows the results of the experiment conducted by Dittrich *et al.*

30

Table 5. Average Phosphorus Concentrations in the Influent and Effluent of the MF Pilot Plants With and Without Chemical Dosing for three types of microfiltration (μg/L) (Dittrich et al., 1996).

		Influent	Effluent		
			DOW*	Starcosa*	Memcor*
Without Ferric dosing	TP	186	62	93	60
	Dissolved P	93	-	-	-
	PO_4-P	<30	<28	52	<26
With ferric dosing (0.77 mg Fe/L)	TP	120	49	43	35
	Dissolved P	70	30	33	27
	PO_4-P	33	10	11	7

*DOW, Starcosa and Memcor are the names of the products and commonly used microfiltration.

Oesterholt and Bult (1993) conducted a 3-month experiment to test microfiltration, and concluded that iron has to be added so that suspended solids and phosphorus can be removed in sufficient quantities. In that case, they reported 90% removal of total phosphorus with microfiltration. The following table shows the results of the experiment by Oesterholt and Bult.

Table 6. Average Effluent Concentrations after Microfiltration Combined with Iron Flocculation (Oesterholt and Bult, 1993).

	Influent	Effluent
SS (mg/L)	20	<1
COD (mg/L)	40	27
TKN (mg/L)	1.7	1.4
TP (mg/L)	2.5	0.09
Escherichia coli *	26,000	2

* number of micro-organisms per 100 mL.

Oesterholt and Bult (1993) commented that from a technical point of view, microfiltration is

preferred because of its high removal efficiency for all the components, but from a financial point of view, it is not feasible.

(d) Contact clarifier and traveling bridge filter

Ross *et al.* (1996) evaluated alternative treatment processes capable of achieving phosphorus concentrations of less than or equal to 0.10 mg/L. They reported that post-precipitation (i.e. chemical addition to secondary effluent before filtration), in a full-scale demonstration at two Ontario WWTPs with conventional tertiary filters, succeeded in achieving total phosphorus concentrations less than 0.10 mg/L. They found that phosphorus could be removed effectively with the metal salt addition of 3 to 5 mg/L in the post-precipitation mode. At these metal salt concentrations, soluble phosphorus was found to be removed to about 0.03 mg/L. Therefore, the aluminum and ferric iron concentrations of 3 to 5 mg/L in the effluent-polishing step are applied to the calculations of total phosphorus concentrations in this project.

For the wastewater used in their pilot studies, Ross *et al.* (1996) also found that to achieve the target TP of less than or equal to 0.10 mg/L, the maximum suspended solids level in tertiary effluent should be less than 5 mg/L, based on a phosphorus content of 1.5% in the solids. In Section 11, the required effluent total suspended solids is conservatively assumed to be 3 mg/L in this project to satisfy this assumption. The test results of the experiment conducted by Ross *et al.* are shown in Table 7 on the next page.

Table 7. Full-scale Post-precipitation Demonstration Program Results (Ross *et al.*, 1996).

Parameter	Plant 1	Plant 2
Plant type	Conventional activated sludge	Conventional activated sludge
Plant capacity	13,000 m^3/d (3.4 mgd) average 32,300 m^3/d (8.5 mgd) peak	18,200 m^3/d (4.8 mgd) average 36,400 m^3/d (9.6 mgd) peak
Filter type	Gravity-type dual media	Gravity-type, travelling bridge, sand
Hydraulic loading during study	4 m/h at average flow 10 m/h at peak flow	4 m/h at peak flow

Baseline filter effluent:
  TSS
  TP
  Soluble P
	3 mg/L
	0.27 mg/L
	0.21 mg/L
		<3 mg/L
		0.36 mg/L
		0.29 mg/L

Post-precipitation filter effluent:
  TSS
  TP
  Soluble P
	<3 mg/L
	0.09 mg/L
	0.06 mg/L
		<3 mg/L
		0.07 mg/L
		0.03 mg/L

Precipitant dosage:
  Baseline metal dosage
 	
  Post-precip. metal dosage
	6.2 mg Al/L (simultaneous)
	
	7.5 mg Al/L (6.5 simult., 1.3 post)
		12.3 mg Fe/L (pre)
		
		15.2 mg Fe/ L (12.3 simult., 3.2 post)

Notes: Average of fifteen 24-hour composite samples collected over an hour to six week period.		

Ross *et al.* (1996) commented that by adding precipitants in the post-precipitation mode (chemical addition after secondary treatment), the desired soluble phosphorus removal efficiency was achieved at lower dosages than by single point pre- or simultaneous precipitant addition (chemical addition to primary or secondary clarifier influent). That is, high pre- or simultaneous chemical dosage leads to higher chemical costs, increased sludge production and generation of a lighter, fluffier sludge with more potential for pin-floc development.

8 Third step of screening (technical feasibility)

The following table shows which alternatives are technically screened out or retained for further consideration. Technologies that cannot meet the target level of total phosphorus (0.1 mg/L) by the combination of chemical, biological and physical processes or that are not in practical use are canceled out and are no longer candidates for further consideration. Technologies that are technically feasible enough to meet the EPA target level are held to analyze their cost effectiveness in the next step.

Table 8. Alternatives Screened or Canceled.	
Technologies	Reasons for cancellation or selection.
	Alternatives retained
	Alternatives canceled out
Chemical treatments	
GCR20 (liquid aluminum chloride-ferric chloride)	Very attractive but not in practical use. Furthermore, the information is limited.
Ferric chloride	Used in actual cases.
Alum	Used in actual cases.
Biophysical treatment	
Phormidium laminosum	Not in practical use yet and seems too expensive.
Biological treatments	
SBR	Utilized in many cases and much information available. Cost-effective and appropriate for smaller municipalities.
Physical treatments	
Contact clarifier and microfiltration	Technically feasible. Need further analyses in terms of economy.
Contact clarifier and ultrafiltration	Technically feasible. Need further analyses in terms of economy.
Contact clarifier and filtration	Not only technically feasible, but economically sounds reasonable.

9 Fourth step of screening (cost-effectiveness)

Table 9 shows the typical sizes and the budget costs for each alternative technology retained in the previous section. Because SBR is the only biological treatment technology, it does not need cost-effectiveness analysis to select out. For typical wastewater treatment plants, more than two units of filtration systems or contact clarifiers should be prepared. The cost data are obtained from the companies that are producing each technology.

Table 9. Size and Costs of Alternatives.				
Alternative	# of units	Size (LxWxH) etc.	Contents	Costs
Micro-filtration (Memcor)	4	• Size: 6.3m x 2.3m x 2.8m [21'x7.5' x 9.2'] • Max flow: 390-450 USGPM	0.1<pore sizes<10.0 microns. Requires the following ancillary equipment to be connected to the units: feed, filtrate, waste and cleaning system manifolds, clean-in-place (CIP) chemical storage and recirculation components, compressed air supply system, and pneumatic and electrical controls (USFilter/Memcor, 1999). To avoid clogging, 4 units are recommended.	$1,815,000/system (including air supply system, CIP system, master PLC for full automation capability and SCADA software.) (U.S.Filter/ Memcor, 1999)
Ultra-filtration	4		0.01<pore sizes<1.0 micron. For about 500 gpm.	$650,000/unit (including building costs) $104,000/unit (annual operating costs) (Monat, 1998)
Travelling bridge filter	4	• 9' x 28'	For about 500 gpm.	$145,000/unit $85,000/unit (concrete units)
Ferric chloride		• 30-20 mg/L		$876/ton as Fe (dry weight) (XCG Consultants Limited, 1996)

Alum		• 30-20 mg/L		$2044/ton as Al (dry weight) (XCG Consultants Limited, 1996)

9.1 Cost comparison of the physical treatments

For the selection of the physical treatments, the cost of travelling bridge filters is compared with those of UF and MF. Though the contents of the cost estimation for each technology are a little different, the author assumes that the prices described in the above table basically have the same meaning because it generally seems that the technology of travelling bridge filters is relatively cheap, compared to the other two technologies. With limited information on the prices of these technologies, the comparison between the two technologies, UF and MF, is assumed to be less important than the comparison between UF/MF and travelling bridge filters.

I assume that each technology needs four units for the average flow rate of 2,233 m^3/d. (Because of the increased solids loading from a secondary sewage source or the contact clarifiers that are possibly flocculated, four units are recommended by the producers of these technologies.) The calculation is the following:

Camp Dresser & McKee (1998) estimated the total capital and the annual O&M costs for a 10 million gallon per day (mgd) microfiltration treatment process facility. The total capital cost for the MF plant is $36 million and the annual O&M cost is $2 million. CDM also estimated the total capital and the annual O&M costs for the full-scale advanced wastewater treatment (AWT) plant using a solids contact clarifier and filtration. The total capital cost for the AWT plant is $14 million and the annual O&M cost is $1.5 million. Therefore, the annual O&M costs for microfiltration and traveling bridge filters are assumed to be about 10% of the total capital costs. Obviously, microfiltration and ultrafiltration are much more expensive than traveling bridge filters.

9.2 Cost comparison of the chemical treatments

For the selection of the chemical treatments, the comparison between ferric chloride and aluminum chloride is conducted. XCG Consultants Limited (1996) reported that a alum dosage of 16 mg/L or a ferric chloride dosage of 22 mg/L is needed for high-rate phosphorus removal (less than 0.1 mg/L in effluent). Assuming that this estimation is correct, I calculated the costs for the chemicals as follows:

The average flow rate is 2,233 m^3/d. The annual cost for alum addition is:

$$\$2,050/t \times (16 \text{ g Al}/ m^3 \times 2,233 \text{ m}^3/d \times 365 \text{ days} \times 10^{-6} \text{ t/g}) = \$26,700/\text{year}.$$

The annual cost for ferric chloride addition is:

$$\$880/t \times (22g \text{ Fe}/ m^3 \times 2,233 \text{ m}^3/d \times 365 \text{ days} \times 10^{-6} \text{ t/g}) = \$15,800/\text{year}.$$

Although ferric chloride is cheaper than alum, we have to consider the use of two chemicals with regards to sludge production, as it is well known to wastewater treatment engineers that ferric chloride produces more sludge than alum. The calculation of sludge production is undertaken in Section 12.

10 Process diagram

As the result of the previous section, the process diagram is proposed in the next page (Figure 5). The process diagram shows the combination of three types of technologies (chemical, biological and physical technologies) screened out in the previous section. Two cases are proposed for further considerations.

In Case 1, wastewater first goes into the grit chamber to remove grit, and then goes through the primary clarifiers. Primary clarifiers are used before the biological treatment process and their function is to reduce the loads on the biological treatment units. After primary sedimentation, wastewater goes into the SBR, a form biological treatment, which can be operated to achieve carbon oxidation, nitrogen reduction, and phosphorus removal.

The next step is effluent-polishing (EP) where the secondary effluent passes through solids contact clarifiers and then filters. Phosphorus concentrations after filtration should be less than 0.1 mg/L. The effluent from the tertiary treatment process finally passes through the disinfection process in which chlorine is used to disinfect the effluent before discharge.

As primary clarifiers are optional in small wastewater plants like this project, in Case 2, wastewater enters the SBR after passing through the grit chamber. Some chemicals (alum + polymer or ferric chloride + polymer) can be added to the SBR process. After this process, wastewater is treated as in Case 1.

Process diagram

Influent
Q=1,024 gpm
BOD=200 mg/L
BOD=1117 kg/d
TSS=200 mg/L
TSS=1117 kg/d
TN=30 mg/L
TP=8 mg/L

Chemical dosage (Case 2 only)

Case 1 only

Chemical dosage

Effluent
Q=1,024 gpm
BOD=<10 mg/L
BOD=<55.8 kg/d
TSS=5mg/L
TSS=27.9 kg/d
TP=0.1 mg/L

Chemical dosage

Inflow

| Grit chamber | Primary Clarifier | SBR | Equalization | Contact Clarifier | Filtration | Disinfection |

outflow

Effluent-Polishing Step

Thickener

Haul

Figure 5. Proposed Process Diagram

40

11   BOD, TSS, TP, and sludge calculation

The concentrations of BOD, TSS and TP and the amount of sludge produced are calculated in the two cases. In Case 1, primary clarifiers are used before SBR and chemical dosing before primary clarification is applied, whereas, in Case 2, primary clarifiers are not used and SBR with chemical treatment is applied.

11.1   Case 1

<u>Primary effluent and primary sludge calculation</u>

By applying chemically enhanced primary treatment (CEPT), the removal rates for BOD and TSS can be improved from 35% to 50% and from 50% to 75%, respectively. Therefore, using the peak flow rate = 5,583 m^3/d and influent TSS of 200 mg/L, the primary sludge production by TSS removal is calculated as follows:

Primary sludge produced by TSS removal in dry basis

$$= 200 \text{ g/m}^3 \text{ x } 5{,}583 \text{ m}^3\text{/d x } 0.75 \text{ x } 10^{-3} \text{ kg/g} = 838 \text{ kg/d} \quad \cdots\cdots (7)$$

Primary effluent concentrations of BOD and TSS are:

Primary effluent BOD = 200 mg/L x (1-0.50) = 100 mg/L, and

Primary effluent TSS = 200 mg/L x (1-0.75) = 50 mg/L.

Because the soluble orthophosphate form is removed by chemical precipitation, the dose of aluminum required to remove orthophsphate (5 mg/L of soluble phosphorus in 8 mg/L of total phosphorus) in primary treatment is as follows:

Al dosage = (Al/P)·(soluble phosphorus in primary influent − soluble phosphorus in primary effluent)

For the soluble phosphorus concentration of 0.1 mg/L in the primary effluent, the Al/P (w/w) ratio = 3 is required (Water Environment Federation, 1998). Therefore,

Al dosage = 3 (5 − 0.1) = 14.7 mg/L

41

Primary effluent TP = soluble P + insoluble P

$$= 0.1 + 3.0 = 3.1 \text{ mg/L}$$

Using Al dosage = 15 mg/L = 15/27 = 0.555 mmole Al/L and P removed = 4.9 mg/L = 4.9/39 = 0.158 mmole P/L, Al required is calculated from Equation (6):

Stoichiometric Al required = 0.8 mole Al/mole P removed x 0.158 mmole/L = 0.126 mmole/L

Using excess Al added = 0.555 – 0.126 = 0.428 mmole/L, $Al_{0.8}(H_2PO_4)(OH)_{1.4}$ = 142.4 g/ mole, and $Al(OH)_3$ = 78 g/mole, the chemical sludge accrued from alum addition is calculated from Equations (2) and (4):

$$Al_{0.8}(H_2PO_4)(OH)_{1.4} \text{ sludge} = 0.158 \text{ mmole/L x } 142.4 \text{ g/mole} = 22.5 \text{ mg/L},$$

$$Al(OH)_3 \text{ sludge} = 0.428 \text{ mmole/L x } 78 \text{ g/mole} = 33.4 \text{ mg/L},$$

Total chemical sludge produced = 22.5 + 33.4 = 55.9 mg/L.

$$\text{Mass of chemical sludge} = 55.9 \text{ g/m}^3 \text{ x } 5{,}583 \text{ m}^3\text{/d x } 10^{-3} \text{ kg/g}$$

$$= 312 \text{ kg/d} \quad \cdots\cdots \text{ (8)}$$

From Equations (7) and (8), the total primary sludge is:

$$312 + 838 = 1{,}150 \text{ kg/d} \quad \cdots\cdots \text{ (9)}$$

Being calculated the same way as Al, the sludge produced by ferric chloride addition is as follows (primary effluent soluble P = 0.2 mg/L, Fe/P ratio = 5, $Fe_{1.6}(H_2PO_4)(OH)_{3.8}$= 251 g/mole and $Fe(OH)_3$ = 106.8 g/mole) (Water Environment Federation, 1998):

$$\text{Chemical sludge produced} = (38.9 + 19.4) \text{ g/m}^3 \text{ x } 5{,}583 \text{ m}^3\text{/d x } 10^{-3} \text{ kg/g}$$

$$= 325 \text{ kg/d} \quad \cdots\cdots \text{ (10)}$$

$$\text{Total primary sludge} = (7) + (10) = 325 + 838$$

$$= 1{,}163 \text{ kg/d} \quad \cdots\cdots \text{ (11)}$$

Consequently, ferric chloride produces a little more primary sludge than alum does. The primary effluent concentrations of TP are 3.1 mg/L by adding alum and 3.2 mg/L by adding ferric chloride.

Secondary effluent and activated sludge calculation

For effective operation of phosphorus removal (less than 1.0 mg TP/L), the COD:P ratio and the BOD:P ratio should be more than 40 and 20, respectively (Water Environment Federation, 1998). With the primary effluent BOD of 100 mg/L, COD of 250 mg/L and TP of 3.1 or 3.2 mg/L, the enhanced biological phosphorus removal (EBPR) treatment can be applied to the treatment of this wastewater.

As the State of Massachusetts requires nitrogen removal, the designing of the SBR is based on nitrification kinetics because the kinetics of phosphorus removal is neither well understood nor established enough to be applied to the calculations here.

The assumptions for the SBR design in Case 1 are as follows (the values of Y_S and k_d are from Water Environment Federation, 1998, the values of μ_{max}, Y_N and K_s are from Metcalf & Eddy, Inc., 1991):

MLVSS = 4,500 mg/L

P concentration in waste activated sludge = 5.0%

μ_{max} for aeration = maximum specific growth rate = 3/day

Y_S = 0.7 g MLVSS/g BOD removed

Y_N = 0.15 g MLVSS/g NH$_4$-N oxidized

k_d for NH$_4$-N = 0.04/day

k_d for aeration = 0.06/day

VSS/SS = 0.8

K_s = 60 mg BOD/L

peak flow rate (Q) = 5583 m^3/d

secondary effluent TSS = 10 mg/L

effluent requirements for NH$_4$-N = 2 mg/L @ 15 °C

$$= 4 \text{ mg/L @ } 10 \text{ °C}$$

1. It appears that a safety factor of 2 should be adequate from an engineering point of view.

2. Determine the maximum growth rate for the nitrifying organisms under the stated operating conditions. In general, the winter requirement for NH$_4$-N (the worse case) is to be the design variable and the following expression can be used here:

$$\mu_{max} = 0.47 \, e^{\, 0.098(T-15)} \times DO/(K_{O2}+DO) \times [1-0.833(7.2-pH)]$$

Temperature correction factor	Dissolved oxygen correction factor	pH correction factor
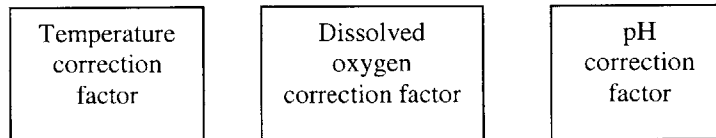
Where:

μ_{max} = growth rate under the stated conditions of temperature, dissolved oxygen, and pH

T   = temperature = 10 °C

DO = dissolved oxygen = 2.0 mg/L

K_{O2} = dissolved oxygen half velocity constant = 0.5 mg/L

pH = 7.2

k_d = 0.04/day

μ_{max} = (0.47/d) $e^{\, 0.098(10-15)} \times 2.0/(0.5+2.0) \times [1-0.833(7.2-7.2)]$

$$= 0.23/d$$

3. Determine μ:

$$\mu = \mu_{max} \times N/(K_N + N)$$

$$= 0.23/d \times 4/(0.22 + 4)$$

$$= 0.22/d$$

where:

N = effluent concentration of NH$_4$-N

K_N = half velocity constant = $10^{\, 0.051T-1.158}$ = 0.22 mg/L (at 10 °C)

4. Determine the minimum design mean cell-residence time.

(a) minimum $\theta_c{}^M$

$$1/\;\theta_c{}^M \approx \mu - k_d$$

$$1/\;\theta_c{}^M = 0.22/d - 0.04/d$$

$$= 0.18/d$$

$$\theta_c{}^M \quad = 1/(0.18/d) = 5.56\;d$$

(b) design θ_c

$$\theta_c = SF\;(\theta_c{}^M) = 2(5.56\;d) = 11.1\;days$$

It should be noted that the volume of the SBR has to recognize that the tank is not aerated all the time.

5. Assuming biodegradable portion of effluent suspended solids is 0.7, effluent soluble (S), insoluble and total BODs are:

$$S = Ks(1+ k_d\;\theta_c)/[\;\theta_c\;(\mu_{max} - k_d) -1]$$

$$= 60\;mg/L\;(1+ 0.06/d \cdot 11.1d)/\;[11.1d\;(3/d - 0.06/d) - 1]$$

$$= 3.2\;mg/L$$

$$\text{Insoluble BOD} = 0.7 \cdot 10\;mg/L$$

$$= 7.0\;mg/L$$

$$\text{Total BOD} = 3.2 + 7.0 = 10.2\;mg/L$$

6. Sludge production (P_X) is:

$$P_X = Q[Y_S(Si-S) + Y_N(Ni-N)]/\;(1 + k_d\;\theta_c)$$

$$= 5,583\;m^3/d[0.7\;gVSS/g\;BOD(100-3.2)+0.15\;gVSS/g\;NH_4-N(30-2)]g/m^3/(1+0.04/d \cdot 11.1\;d)$$

$$= 278kg\;VSS/d \;\cdots\cdots (12)$$

7. The total mass of SS is:

$$SS = VSS/0.8$$

$$= 278\;kg\;VSS/d\;/(0.8\;kg\;VSS/kg\;SS)$$

$$= 348 \text{ kg SS/d}$$

8. The sludge to be wasted is:

$$= 348 \text{ kg/d} - 15 \text{ g/m}^3 \times 5{,}583 \text{ m}^3/\text{d} \times 10^{-3} \text{ kg/g}$$

$$= 264 \text{ kg/d} \quad \cdots\cdots (13)$$

9. Assuming the phosphorus content = 5% in the activated sludge, the total, insoluble and soluble phosphorus concentrations in the secondary effluent are:

$$P \text{ removed in WAS} = 264 \text{ kg/d} \times 0.05$$

$$= 13.2 \text{ kg/d}$$

$$\text{TP in secondary effluent} = (17.3 - 13.2) \text{ kg/d} / 5{,}583 \text{ m}^3/\text{d} \times 10^3 \text{ g/kg}$$

$$= 0.73 \text{ mg/L}$$

$$\text{Insoluble P} = 0.05 \times 10 \text{ mg/L}$$

$$= 0.50 \text{ mg/L}$$

$$SP = 0.73 - 0.50 = 0.23 \text{ mg/L} \quad \cdots\cdots (14)$$

10. The P removal rate is:

$$= (3.1 - 0.73) \text{ mg/L} / 3.1 \text{ mg/L}$$

$$= 76\%$$

Tertiary effluent and sludge calculation

Assuming that alum required for tertiary treatment is 3 mg Al/L (polymer is also added to make precipitation more effective) and final effluent TSS is 3 mg/L which contains 2.5% phosphorus (phosphorus content in suspended solids is reduced from 5% to 2.5% because suspended solids in secondary effluent includes aluminum added) and (Ross *et al.*, 1996),

(a) Final effluent insoluble P is:

$$\text{Insoluble P} = 0.025 \times 3 \text{ mg/L}$$

$$= 0.075 \text{ mg/L}$$

(b) Final effluent soluble P should be:

$$\text{Soluble P} = 0.1 - 0.075$$

$$= 0.025 \text{ mg/L}$$

(c) $Al_{0.8}(H_2PO_4)(OH)_{1.4}$ and $Al(OH)_3$ sludge:

$$Al\ dose = 3\ mg/L\ /27\ mg/mmole = 0.11\ mmole/L$$

$$Soluble\ P\ removed = 0.23 - 0.025 + (0.05 - 0.025)10 = 0.45mg/L$$

$$= 0.45mg/L\ /31\ mg/\ mmole$$

$$= 0.014\ mmole/L$$

$$Stoichiometric\ Al\ required = 0.8\ mole\ Al\ /mole\ P\ removed\ x\ 0.014\ mmole$$

$$= 0.012\ mmole/L$$

$$Excess\ Al\ added = 0.11 - 0.012 = 0.098\ mmole/L$$

$$Al_{0.8}(H_2PO_4)(OH)_{1.4}\ sludge = 0.014\ mmole/L\ x\ 142.4\ g/mole = 2.0\ mg/L$$

$$Al(OH)_3\ sludge = 0.098\ mmole/L\ x\ 78\ g/mole = 7.6\ mg/L,$$

(d) The chemical and total sludge produced in the tertiary treatment:

$$Chemical\ sludge = (2.0 + 7.6)\ g/m^3\ x\ 5,583\ m^3/d\ x\ 10^{-3}\ kg/g$$

$$= 54\ kg/d$$

$$TSS\ removed = 10-3 = 7\ mg/L$$

$$Sludge\ produced\ by\ TSS\ removal = 7\ g/m^3\ x\ 5,583\ m^3/d\ x\ 10^{-3}\ kg/g$$

$$= 39\ kg/d$$

$$Sludge\ produced\ in\ EP\ step = 54 + 39 = 93\ kg/d \quad \cdots\cdots (15)$$

Being calculated the same way as Al, the sludge produced in the EP step by ferric chloride is:

$$Chemical\ sludge\ produced = (3.5+3.4)\ g/m^3\ x\ 5,583\ m^3/d\ x\ 10^{-3}\ kg/g$$

$$= 39\ kg/d$$

$$Sludge\ produced\ in\ EP\ step = 39 + 39 = 78\ kg/d \quad \cdots\cdots (16)$$

The results are shown in Figures 6, 7 and 8.
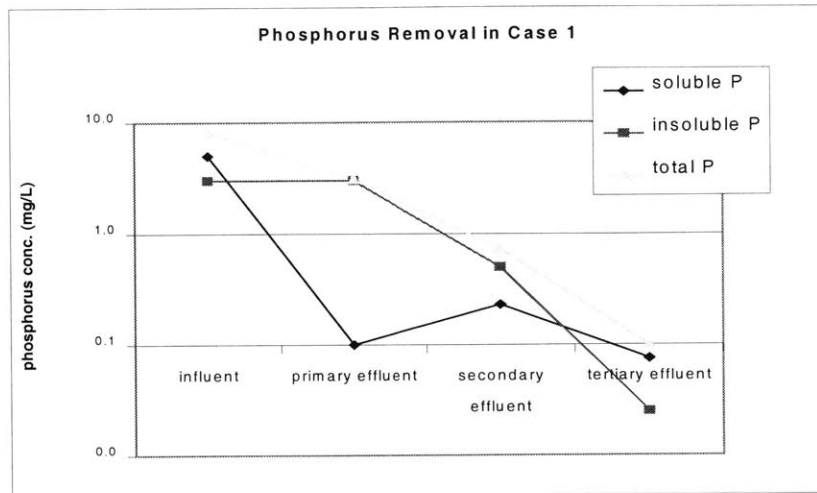
Figure 6. Phosphorus Removal in Case 1
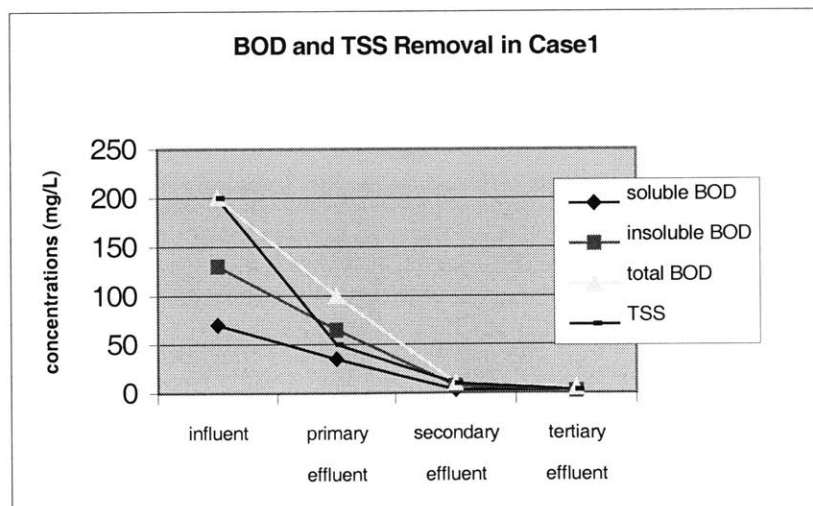
Figure 7. BOD and TSS Removal in Case 1
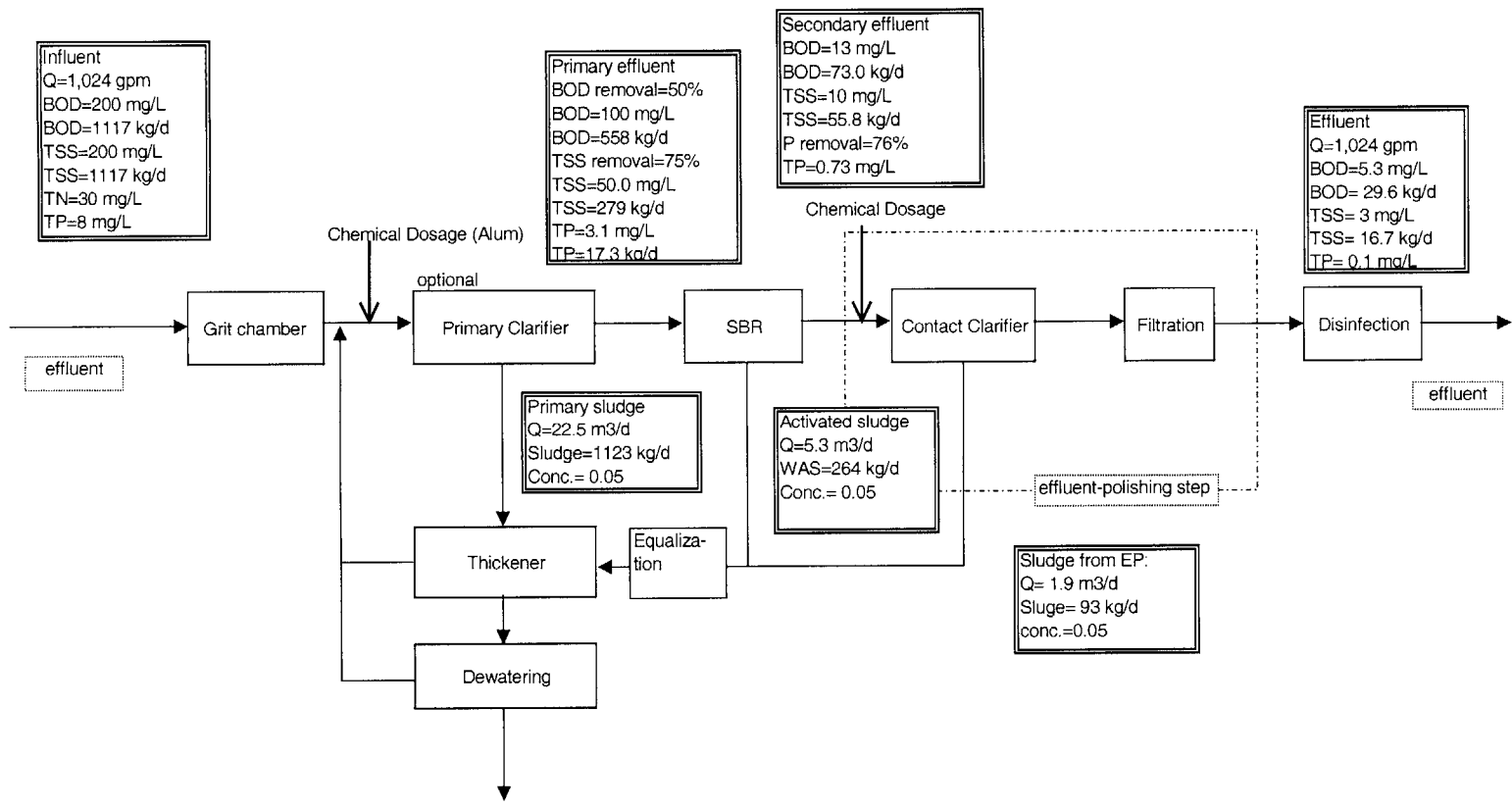
Figure 8. Process Diagram of Case 1

11.2 Case 2

Effluent after SBR and WAS calculation:

The assumptions for the SBR design in Case 2are as follows (the values of Y_S and k_d are from Water Environment Federation, 1998, the values of μ_{max}, Y_N and K_s are from Metcalf & Eddy, Inc., 1991):

MLVSS = 4,500 mg/L

P concentration in waste activated sludge = 4.0%

μ_{max} for aeration = maximum specific growth rate = 3/day

Y_S = 1.0 g MLVSS/g BOD removed

Y_N = 0.15 g MLVSS/g NH$_4$-N oxidized

k_d for NH$_4$-N = 0.04/day

k_d for aeration = 0.06/day

VSS/SS = 0.75

K_s = 60 mg BOD/L

peak flow rate (Q) = 5583 m^3/d

secondary effluent TSS = 15 mg/L

effluent requirements for NH$_4$-N = 2 mg/L @ 15 °C

$\qquad\qquad\qquad\qquad\qquad$ = 4 mg/L @ 10 °C

Four assumptions in Case 2 are different from those in Case 1. WAS contains 4% phosphorus due to greater amount of WAS in Case 2 than in Case 1. Y_S of 1.0 g MLVSS/g BOD removed in Case 2 is greater than that in Case 1, as Case 2 does not use primary clarifiers and SBRs in Case 2 are chemically enhanced. Effluent TSS of 15 mg/L in Case 2 is greater than that in Case 1 due to the lack of primary clarifiers in Case 2. The ratio of VSS to TSS is 0.75 in Case 2 due to chemicals added. From Equation (12), the sludge production is:

(a) Sludge produced in SBR (P_x):

$P_X = Q[Y_S(Si-S) + Y_N(Ni-N)]/ (1 + k_d \theta_c)$

$= 5,583 \text{ m}^3/\text{d}[1.0 \text{ gVSS/g BOD}(100-3.2)+0.15 \text{ gVSS/g NH}_4\text{-N}(30-2)]\text{g/m}^3$

$\div (1+0.04/\text{d}\cdot 11.1 \text{ d})$

$= 777 \text{ kg VSS/d}$

$SS = VSS/0.75$

$= 777 \text{ kg VSS/d} / (0.75 \text{ kg VSS/kg SS})$

$= 1,036 \text{ kg SS/d}$

(b) Sludge wasted:

$WAS = 1,036 \text{ kg/d} - 15 \text{ g/m}^3 \times 5,583 \text{ m}^3/\text{d} \times 10^{-3} \text{ kg/g}$

$= 952 \text{ kg/d} \quad \cdots\cdots (17)$

(c) The concentrations of TP, insoluble P and SP in effluent from SBR:

P removed in WAS $= 952 \text{ kg/d} \times 0.04$

$= 38.1 \text{ kg/d}$

$TP = (44.7 - 38.1) \text{ kg/d} /5,583 \text{ m}^3/\text{d} \times 10^3 \text{ g/kg}$

$= 1.19 \text{ mg/L}$

Insoluble $P = 0.04 \times 15 \text{ mg/L}$

$= 0.60 \text{ mg/L}$

$SP = 1.19 - 0.60 = 0.59 \text{ mg}$

(d) P removal rate:

P removal rate $= (8.0 - 1.19) \text{ mg/L} /8.0 \text{ mg/L}$

$= 85\%$

Effluent from the effluent-polishing step and sludge calculation:

Assuming that alum required for this step is 3 mg Al/L and final effluent TSS is 3 mg/L which contains 2% phosphorus,

(a) Final effluent insoluble P:

Insoluble P = 0.02 x 3 mg/L

= 0.06 mg/L

(b) Final effluent soluble P <u>should be</u>:

Soluble P = 0.1 − 0.06

= 0.04 mg/L

(d) $Al_{0.8}(H_2PO_4)(OH)_{1.4}$ and $Al(OH)_3$ sludge:

Al dose = 3 mg/L /27 mg/mmole = 0.11 mmole/L

P removed = 0.59 − 0.04 + (0.04-0.02)15 = 0.85mg/L

= 0.85 mg/L /31 mg/ mmole

= 0.027 mmole/L

Stoichiometric Al required = 0.8 mole Al /mole P removed x 0.027 mmole

= 0.022 mmole/L

Excess Al added = 0.11 − 0.022 = 0.088 mmole/L

$Al_{0.8}(H_2PO_4)(OH)_{1.4}$ sludge = 0.027 mmole/L x 142.4 g/mole = 3.8 mg/L

$Al(OH)_3$ sludge = 0.088 mmole/L x 78 g/mole = 6.9 mg/L,

(c) The sludge produced from the EP by alum:

Chemical sludge = (3.8 + 6.9) g/m^3 x 5,583 m^3/d x 10^{-3} kg/g = 60 kg/d

TSS removed = 15-3 = 12 mg/L

Sludge produced by TSS removed = 12 g/m^3 x 5,583 m^3/d x 10^{-3} kg/g = 67 kg/d

Sludge produced from the EP step = 60 + 67 = 127 kg/d $\cdots\cdots$ (18)

Being calculated the same way as Al, the sludge produced from the EP step by ferric chloride is (5 mg Fe/L and final effluent TSS = 3 mg/L):

Chemical sludge produced = (6.8+5.0) g/m^3 x 5,583 m^3/d x 10^{-3} kg/g

= 66 kg/d

Sludge produced from the EP step = 66 + 67 = 133 kg/d $\cdots\cdots$ (19)

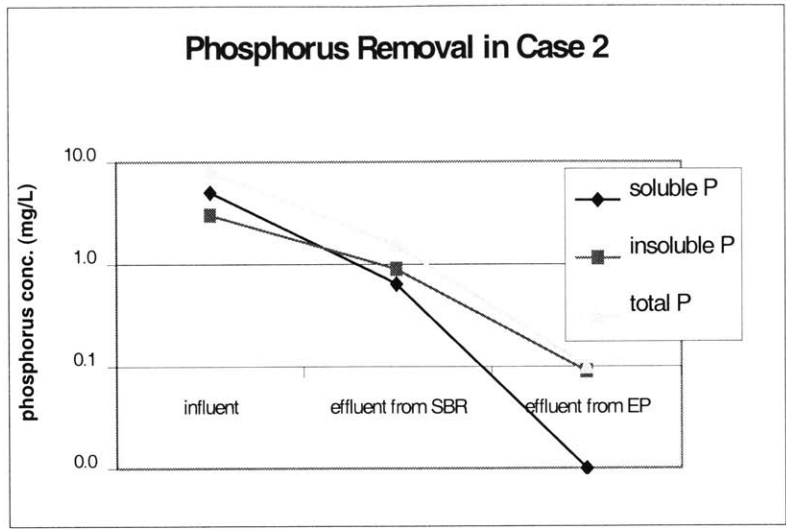The results are shown in Figures 9, 10 and 11 on the next pages.

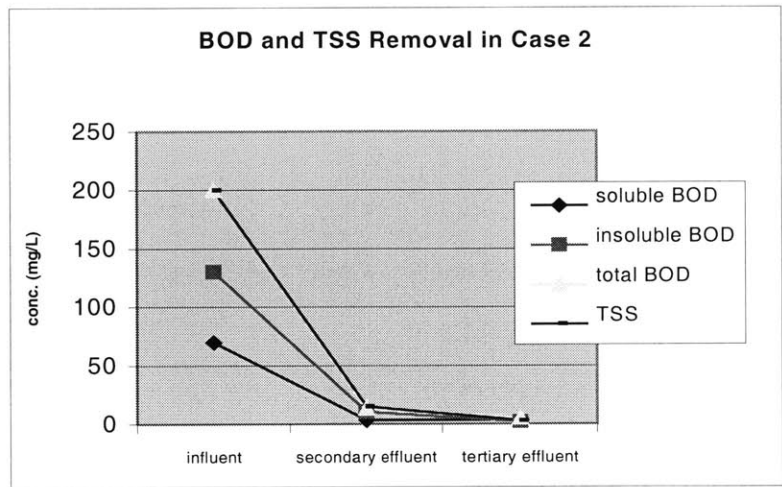Figure 9. Phosphorus Removal in Case 2
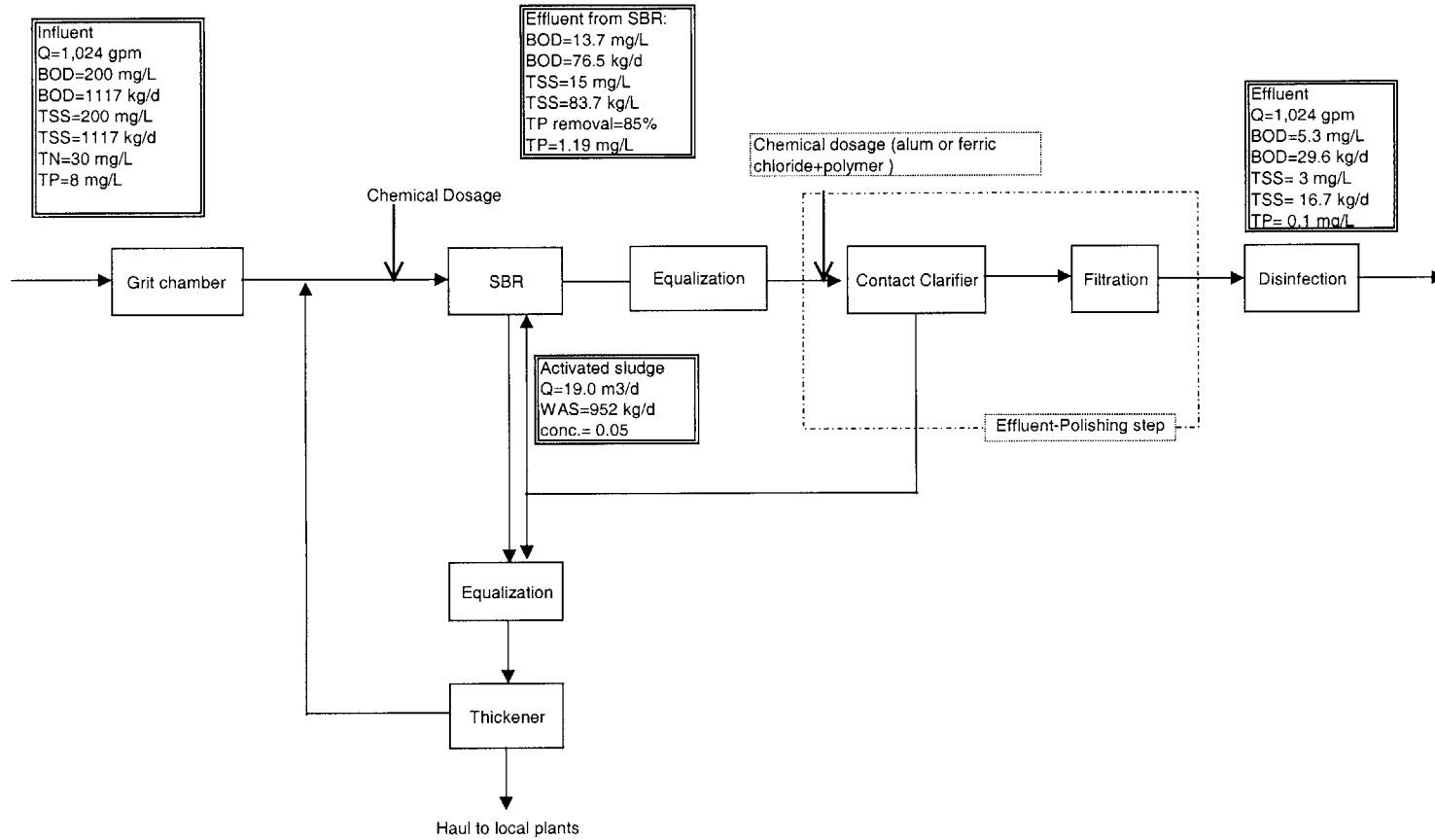

Figure 10. BOD and TSS Removal in Case 2

Figure 11. Process Diagram of Case 2

12 Fifth step of screening (sludge evaluation)

12.1 Case 1

The total sludge produced by alum addition is calculated from Equations (9), (13) and (15):

$$\text{Total sludge produced} = \text{primary sludge} + \text{sludge from SBR} + \text{sludge from ER}$$
$$= 1150 + 264 + 93$$
$$= 1507 \text{ kg/d}$$

The total sludge produced by ferric chloride addition is (from Equations (11), (13) and (16)):

$$\text{Total sludge produced} = \text{primary sludge} + \text{sludge from SBR} + \text{sludge from ER}$$
$$= 1163 + 264 + 78$$
$$= 1505 \text{ kg/d}$$

Alum produces about the same quantity of sludge as ferric chloride, as shown in Figure 12. However, alum is more expensive than ferric chloride, and ferric chloride is recommended in Case 1.

The amount of 264 kg waste activated sludge per day is produced in SBR (from Equation (13)). This calculation is based on the assumptions applied in the previous section. The mean-cell residence time (MCRT) of 11 days is typical in terms of activated sludge treatment, and we assume that the calculation methods for the general activated sludge treatment processes are applicable to that for SBR. With these assumptions, the amount of the activated sludge produced in SBR is 264 kg/d based on the 5% phosphorus content in sludge due to the anaerobic step before aeration.

12.2   Case 2

Assuming that waste activated sludge from SBR contains 4% (lower than in Case 1) due to greater amount of WAS produced in Case 2, the total sludge produced by alum addition is calculated from Equations (17) and (18):

$$\text{Total sludge produced} = \text{sludge from SBR} + \text{sludge from ER}$$
$$= 952 + 127$$
$$= 1{,}079 \text{ kg/d}$$

The total sludge produced by ferric chloride addition is (from Equations (17) and (19)):

$$\text{Total sludge produced} = \text{sludge from SBR} + \text{sludge from ER}$$
$$= 952 + 133$$
$$= 1{,}085 \text{ kg/d}$$

As ferric chloride produces about as much sludge as alum in both cases, ferric chloride has much advantage in terms of cost-effectiveness.

As shown in Figures 12 and 13, the sludge production without the CEPT process (Case 1) is smaller (less than half) than with the CEPT (Case 2). If Case 2 is possible in terms of the target phosphorus removal level (0.1 mg TP/L), we recommend that the clients use Case 2 without CEPT.
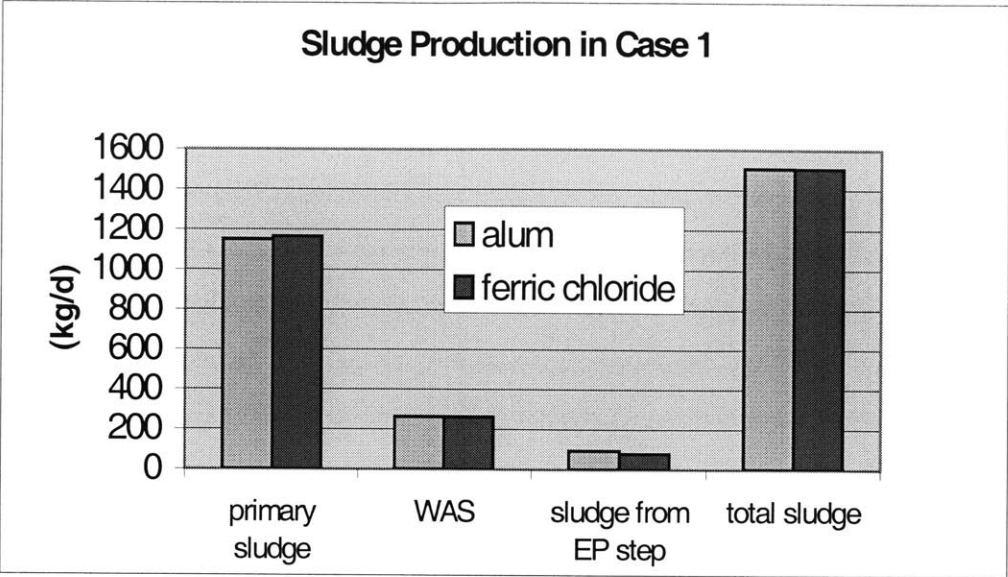
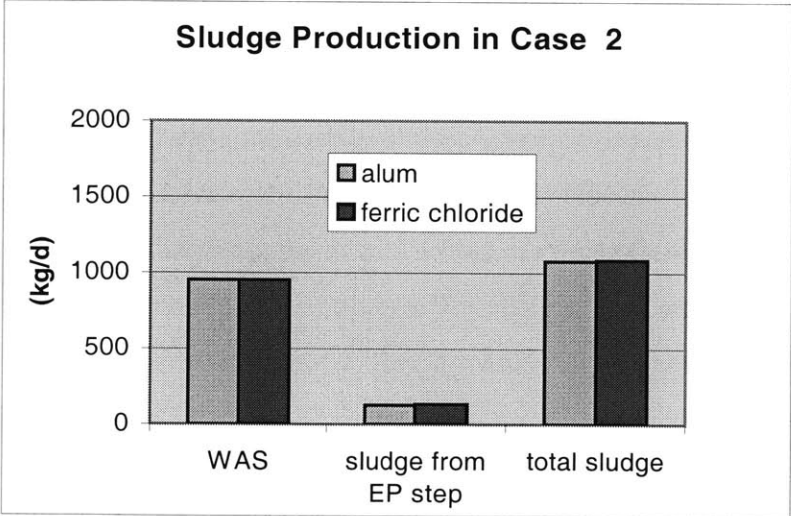Figure 12. Sludge Production in Case 1

Figure 13. Sludge Production in Case 2

13 Conclusions

The main points described in the previous sections are repeated as follows. There are seven main points to be borne in mind by the clients and engineers for the best approaches of the selection and to achieve the goals.

1. High-level phosphorus removal (less than or equal to 0.1 mg TP/L) is possible due to the advanced research and experiments cited in the reference list.

2. There are two cases to be recommended for high-level phosphorus removal in small municipalities: (i) the combination of chemical enhanced primary treatment (CEPT), sequencing batch reactor (SBR) and physical effluent-polishing (EP) process (solids contact clarifier and filtration), and (ii) the combination of SBR with coagulants added and physical EP process.

3. The primary sludge produced in Case 1 (CEPT+SBR+EP) is the main contributor to sludge production and primary clarifiers are optional for small-sized phosphorus removal facilities like the proposed facilities in the Town of Acton.

4. Ferric chloride is recommended in both cases. As ferric chloride produces as much sludge as alum in both cases and alum is about twice as expensive as ferric chloride, ferric chloride is recommended for chemical addition.

5. SBR is highly recommended in this project due to its applicability to small wastewater treatment facilities. SBR can be used for nutrient removal. In case the Town of Acton comes to need the nitrogen removal processes in the future, SBR can be easily modified to meet the demand.

6. As Case 1 produces about one and half times as much sludge as Case 2 does, Case 2 is highly recommended. However, SBR functions for phosphorus removal cannot be always relied upon. Therefore, the clients should take this into consideration in terms of their final decision-making.

7. Generally speaking, the costs for the construction of the wastewater treatment facilities to reduce total phosphorus to the level of 0.1 mg P/L is quite expensive for small municipalities like the Town of Acton. To achieve more effective and efficient

58

phosphorus reduction in the rivers and lakes in the Town of Acton, a regional wastewater treatment system is highly recommended, which enables not only the Town of Acton but also the neighboring towns and cities to strategically implement phosphorus removal alternatives.

Acknowledgements:

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