

**Estimation Of Costs Of Phosphorus Removal In Wastewater
Treatment Facilities:
Construction *De Novo***

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Estimation Of Costs Of Phosphorus Removal In Wastewater Treatment Facilities: Construction *De Novo*

Abstract

With the increase in interest on the part of the U.S. EPA in the use of market mechanisms (such as “offset banking”) as a cost-efficient means by which water pollution might be managed, there has been a growing realization that there is a considerable gap in the state of the art of our understanding of costs associated with one of the major beneficiaries from such programs: waste treatment plants. To our knowledge, there exists no comprehensive study of costs incurred by such plants for meeting alternative pollution standards, and this is particularly the case with phosphorus. It is these costs, of course, that are basic to any considerations related to possible gains that might obtain from phosphorus reductions at other sites that might serve as a “bank” from which the treatment plant acquires credits for increases in the concentration of phosphorus in discharges to water courses.

This study sets out eight designs of wastewater treatment facilities covering a wide range of phosphorus removal. Generally, there are two approaches to the problem of estimating the costs of phosphorus removal: through entirely new facilities, constructed *de novo*, essentially on “Greenfield sites,” and through the adaptation of existing facilities. The present study focuses on the former method. The second method will be the topic of a later study.

Capital, operation/maintenance, and total costs for the construction and operation of plants removing between 20% and 99.3% of phosphorus with capacities ranging between 1 and 100 million gallons per day are developed. Results are subject to some site-specific variability, since land prices are obviously site specific. However, where there may be significant disagreement about the estimates of costs and the feasibility of suggested process designs, the view taken here is that such uncertainty will simply have to be taken into account in any future studies based on the tentative results reported herein.

ESTIMATION OF COSTS OF PHOSPHORUS REMOVAL IN WASTEWATER TREATMENT FACILITIES: CONSTRUCTION *DE NOVO*

1. INTRODUCTION

The discharge of phosphorus to surface waters causes accelerated eutrophication of lakes, reservoirs, and ponds. That discharged in municipal and industrial wastewater has been identified as one of the principal sources of phosphorus readily available for uptake by aquatic micro-organisms (algae). Since the 1970s phosphorus has been identified as the most important rate-limiting factor for algal growth in freshwater systems, and its removal from these wastewaters has therefore become increasingly important. It is apparent that greater attention will be focused on the control of phosphorus in rivers, lakes and impoundments in the near future. It is just as apparent that the Environmental Protection Agency (EPA) has a keen interest in exploring whether such “control” can be implemented by market mechanisms. The present study is motivated, therefore, by the prospect of lowering the discharge of nutrients – from both point and nonpoint sources – using an offset banking scheme for pollutant trading between, in particular, the two kinds of sources (Cummings *et al*, 2003). However, in order to explore such a trading mechanism it is necessary to have appropriately developed cost relationships, in this instance, specifically for the costs of building and operating point-source wastewater treatment facilities for removing phosphorus at various levels (indeed, ideally along the continuum from 0% through 100% removal). Estimating these cost relationships is the focus of the present report.

Several unit processes have been developed for elimination of phosphorus. These include biological nutrient removal (BNR) (Lee *et al*, 1997), enhanced biological phosphorus removal (EBPR) (Smolders *et al*, 1996; Wild *et al*, 1996), the modified Renphosystem (Rensink *et al*, 1997), crystallization (Van Dijk *et al*, 1984; Battistoni *et al*, 1997; Joko, 1984; Momberg *et al*, 1992; Munch *et al*, 2001), and activated aluminum adsorption (Donnert *et al*, 1999; Brattebø *et al*, 1986; Hano *et al*, 1997). Section 2 sets out eight designs of wastewater treatment facilities covering the required range of rates of phosphorus removal. We treat these eight configurations as our reference designs for this study. Generally there are two approaches to the problem of estimating the cost of phosphorus removal: (i) through entirely new facilities, constructed *de*

novo, essentially on “greenfield sites”; and (ii) through the adaptation of existing facilities, i.e., through modifications intended to provide a higher level of treatment for phosphorus removal. The former is the focus of this report whereas the latter, which may be the more relevant in most situations, will be the subject of a subsequent report.

The various estimated costs (capital, operating, total annual economic costs) of the system designs of Section 2 are presented in Section 3. These results are derived from procedures and data drawn from a combination of a 1980 EPA cost study (USEPA, 1980), various private sources, and other public reports (USEPA, 1971; USEPA, 1979; USEPA, 1987; USEPA, 1998). Details of the estimation procedures are provided in the Appendices to the present report. Our results will be subject to some site-specific variability, since land prices are obviously site specific. However, where there may be significant disagreement about the estimates of costs and the feasibility of suggested process designs, the view is taken that such uncertainty will simply have to be taken into account in any further studies based on the results of the present report. It would be naïve to suppose that there is no uncertainty in the estimates of costs and unnecessary, since we routinely deal with uncertainty in both the science base and aspirations of stakeholders in watershed management more generally (Beck *et al*, 2002; Osidele *et al*, 2003). Estimates for capital, O&M, and total costs are developed in section III. Concluding remarks are offered in section IV.

2. PROCESS DESCRIPTIONS

Phosphorus removal from wastewater effluents can be achieved in two fundamentally different ways: by physical-chemical precipitation and by enhanced biological removal (although both, in essence, entail the creation of particulate matter that can be separated from the water). The former utilizes the solubility of phosphorus-metallic compounds to precipitate the phosphorus down to levels approaching the solubility product of the compounds, and then employs a physical separation process to remove the precipitate from the wastewater. The latter takes advantage of the “luxury uptake” of phosphorus by poly-phosphate accumulating organisms (PAOs). Depending upon the level of phosphorus removal to be achieved, one can use physical-chemical processes, the biological process, or a blend of the two. Several researchers have shown that the biological process has a lower overall operating cost, when compared with

chemical precipitation (Levlin *et al*, 2003; Gullet *et al*, 2003). However, the biological process may not be as reliable, and cannot achieve the same high levels of phosphorus removal as a well-run physical-chemical process. Since phosphorus is an essential nutrient for the growth of organisms it is reasonable to use the biological uptake as the main removal process, while employing a chemical process as a complementary and supplementary method.

Many countries set 1 mg/L and 2 mg/L as the limit for total phosphorus concentrations in discharges of wastewater treatment plants. One of the reasons for this low limit is that P concentrations below 0.5 mg/L have been shown to be the limiting value for algal growth (Dryden and Stern, 1968), i.e., at P concentrations below 0.5 mg/L algal growth in a natural, freshwater environment is essentially inhibited or blocked. This notwithstanding, requirements for wastewater treatment plants are being made ever more stringent, such that herein we consider a range of plant designs that would meet limits of between 0.05 and 2.00 mg/L of total phosphorus in their effluents.

Sections 2.1 through 2.8 will discuss the various types of phosphorus removal systems, the mechanisms for that removal, and the approximate levels of phosphorus discharged by the given system.

2.1 One-stage Activated Sludge Process (AS)

This is the conventional activated sludge process (Figure 1). The phosphorus is incorporated into the bacteria as cell-building material. The heterotrophic biomass responsible for organic matter degradation has a relatively limited metabolic phosphorus requirement and, in most cases, the biologically available phosphorus present in the wastewater exceeds the basic requirements of the heterotrophic biomass (Roques, 1995), which can be derived from the stoichiometry of the biomass, i.e., $C_{118}H_{170}O_{51}N_{17}P$. The approximate C/P ratio is about 100/1. That is, only one unit of phosphorus is incorporated when 100 units of BOD are removed. Consequently, it turns out that only some 10-25% of the phosphorus in the wastewater will be removed through this normal growth of cell material (Metcalf and Eddy Inc., 1991). For example, a typical crude sewage entering a wastewater treatment plant has about 250 mg/L of BOD in it, while its phosphorus concentration can be anywhere from 5 to 20 mg/L (US Department of the Army, 1978). Given a customary efficiency of no more than 90% BOD removal in a treatment plant, this would indicate the removal of about

237 mg/L of BOD, which would correspond to the removal of some 2.37 mg/L of phosphorus, i.e., one-hundredth of the amount of BOD removed, based on the stoichiometric formula given above. Thus, technically, somewhere between 2.6 and 17.6 mg/L of total phosphorus would remain in the effluent stream, depending upon the concentration of total phosphorus in the influent crude sewage (of between 5 and 20 mg/L).¹

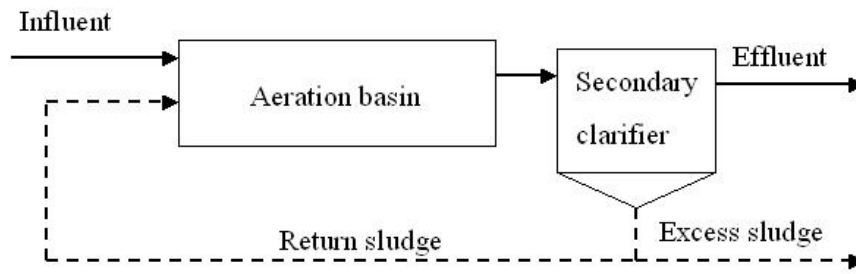


Figure 1. One-stage activated sludge process

2.2 Two-stage activated sludge process (AO)

The design shown in Figure 2 is a modification of the first design, in which an anoxic tank is added to the aeration tank. Nitrate-rich mixed liquor is recycled from the aeration tank to the anoxic tank, where the collection of organic materials in the influent can serve as hydrogen donors for the denitrification of the nitrates. As a result, part of the organic matter is consumed and nitrate is converted to nitrogen gas, with release to the atmosphere. The mixed liquor is then aerated in the aeration tank, so that the remaining organic matter and ammonia are oxidized. It was found, however, that good phosphorus removal can also be achieved in this process, although such performance is strongly affected by the nitrate concentration in the system, with higher values tending to inhibit phosphorus removal.

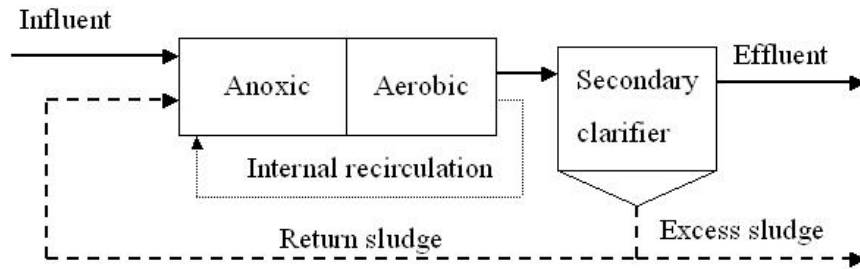


Figure 2. Two-stage activated sludge process

2.3 Three-stage Activated Sludge Process (AAO)

In this more advanced process design, the goal is to try and culture, preferentially, a form of bacteria known broadly as Phosphate Accumulating Organisms (PAOs), which have the capacity to incorporate more phosphorus into their cell material than the normal basic requirements discussed in the preceding section (Figure 3). For this reason, i.e., that the incorporation of so much phosphorus is not necessary for growth, the behavior of the PAO bacteria is termed “luxury uptake of phosphorus”. Figuratively, the phenomenon can be compared to the “starving man at the banquet”. In the AAO process design, the PAO organisms, having been starved of food in the clarifier (so to speak), are returned into the presence of a fresh supply of phosphorus at the head of the treatment works. The organisms take up more phosphorus than they normally require for their growth and store the excess phosphate until they require it, when exposed again to conditions of starvation. This crude explanation parallels the condition of the hungry man at the banquet who, not knowing the time of his next meal, stuffs excess food into his pockets (just in case). In the additional anaerobic compartment (compare Figure 3 with Figure 2), organisms in the waste form anaerobic byproducts of fermentation, such as succinates, volatile fatty acids (VFAs), and acetates. The VFAs are further converted to poly-hydroxy-alkanoates (PHA) with glycogen as an NADH source and poly-P as an energy source. During this process glycogen is consumed and phosphate is released into the liquid stream. Subsequently, in the aerobic compartment, the PAOs take the anaerobic byproducts and reincorporate them into their cellular material. PHA is consumed, whereas glycogen and poly-P are regenerated. Since phosphorus uptake appears to be

slightly greater than the release due to the growth process, more phosphorus is removed from the wastewater than would otherwise be the case.

In such luxury uptake processes the net rate of phosphate removal is strongly affected by the BOD concentration in the influent crude sewage. If this is too low, phosphate uptake will decrease accordingly, and the total phosphorus concentration in the effluent may exceed the desired regulatory limit.

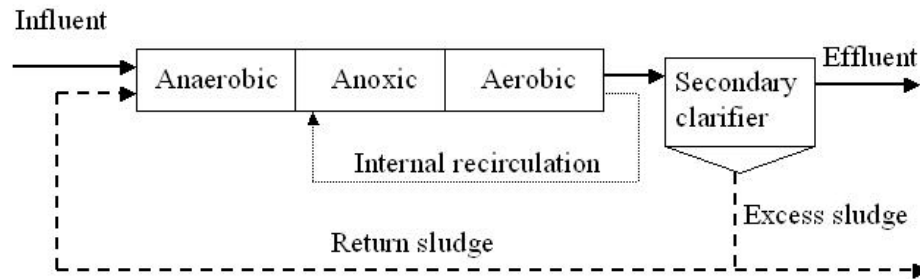
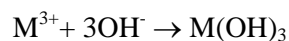
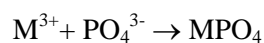


Figure 3. Three-stage activated sludge process

2.4 Three-stage Activated Sludge with Metal Addition (AAO + M)

While biological luxury uptake may be maximized, in most cases it is not sufficient to reduce the phosphorus content in the effluent below 1 mg/L of total phosphorus (Matsch and Drnevich, 1987). It may be necessary to add metal ions to the wastewater in order to remove additional phosphorus by the physical-chemical means of precipitation, as in the fourth design of Figure 4. Most commonly, iron as ferric chloride and aluminum in the form of aluminum sulfate are used, although phosphorus can also be removed by precipitation with calcium as lime. The precipitation reaction with iron (Fe^{3+}) or aluminum (Al^{3+}) in the trivalent state can be expressed as follows



The necessary addition of the metal salts can be executed in the primary clarifier, the aeration basin or secondary clarifier, or even in a tertiary clarifier, if available. If the use of metal ions (chemicals) is to be minimized, their addition at the end of the aeration basin may be most cost-effective.

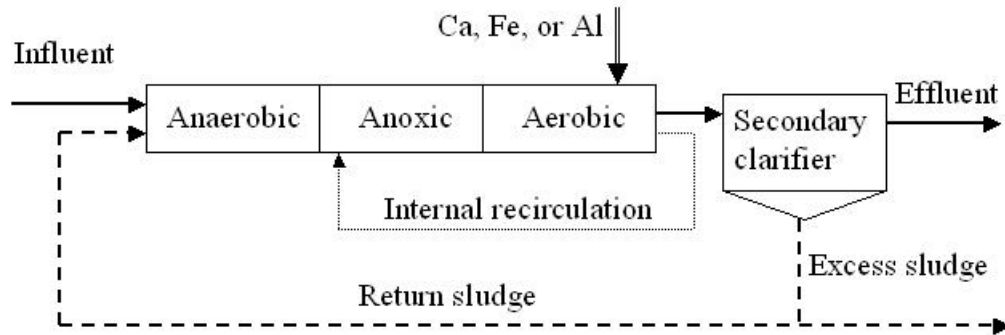


Figure 4. Three-stage activated sludge process with metal addition

2.5 Three-stage Activated Sludge with Metal Addition and Tertiary Clarifier (AAO + M + S)

If a more stringent limit for phosphorus (0.5 mg/L) is to be met, a tertiary clarifier or other type of final solids removal device (Figure 5) may be needed to further eliminate the solids in the effluent. At such low levels of phosphorus, it is the phosphorus in a particulate form that tends to be dominant. Clarifiers are often used for this purpose, because they are energy efficient and do not require the type of maintenance or attention needed by filtration systems. It should be noted that clarifiers are also often less sensitive to changes in hydraulic flows than filter systems and, in terms of backwash or sludge volume, they produce 1% - 3% of their throughput as sludge, compared with filtration systems, which generally have 5% - 10% of their throughput removed as backwash and rinse waters, with the implied additional costs of treatment and disposal.

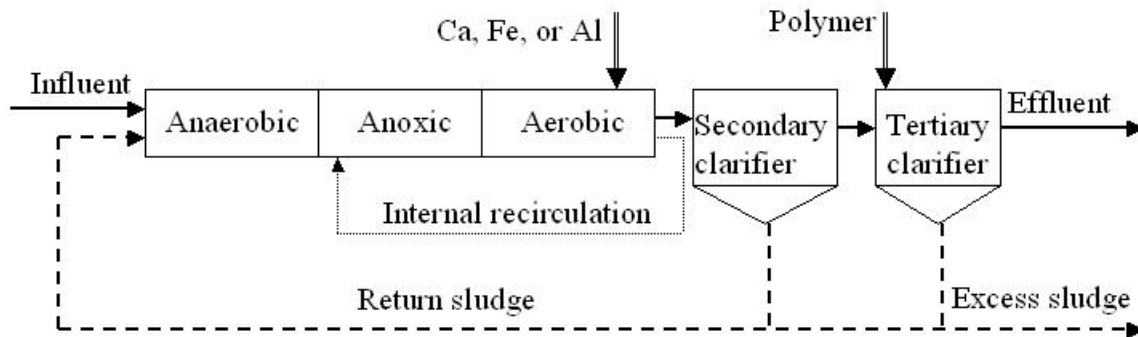


Figure 5. Three-stage activated sludge process with metal addition and tertiary clarifier

Enhanced solids removal and, therefore, enhanced removal of particulate-associated phosphorus, can be attained by the addition of low levels (generally under 5 mg/L) of polymers of high molecular weight to the wastewaters. A number of such substances can be used to increase the removal of the fine-grained suspended particulates (to which the phosphorus is attached). Given tertiary sedimentation/clarification, the concentration of total suspended solids in the effluent can be reduced below 5 mg/L, while the concentration of total phosphorus can be reduced to below 0.5 mg/L.

2.6 Three-stage Activated Sludge with Metal Addition, Tertiary Clarifier and Filtration

(AAO + M + S + F)

Some small particles and their attaching phosphorus may still remain in the effluent, even after the tertiary clarifier. However, if a filter is installed (as in the design of Figure 6), the solids present in the effluent can be reduced yet further, with thus a concomitant decrease in the effluent total phosphorus concentration. Following tertiary sedimentation and filtration the concentration of total suspended solids can be reduced to 1 mg/L and the total phosphorus concentration to below 0.15 mg/L. In effect, rather than being of significance in its own right, the tertiary clarifier in this fifth design alternative serves as a pretreatment device for the filter, by removing solids and thereby extending the length of the filter run (between backwashing). For this application, the addition of aluminum or calcium salts as precipitants is

preferred over that of iron, in order to avoid the growth of filter “slimes”, which make filtration difficult and increase backwash requirements.

2.7 Three-stage Activated Sludge with Tertiary Clarifier and Activated Aluminum Absorption

(AAO + AI + S + C)

Activated aluminum exhibits a marked attraction for phosphate anions, even in the presence of higher concentrations of sulfate or chloride anions (Donnert *et al*, 1999). This property makes it ideal material for the removal of total phosphorus to very low levels, such as 0.10 mg/L. Several researchers (Donnert *et al*, 1999; Brattebø *et al*, 1985; Hano *et al*, 1997) have studied this process and one pilot plant using this technology has been operated successfully for 500 days. The process has not proven to be popular in practice at full scale as yet, however. We believe, therefore, that the operational cost and higher capital cost may be a deterrent to installation. The operation of the adsorption column (Figure 6) consists of three steps (Donnert *et al*, 1999): (i) adsorption of phosphorus onto the granular material; (ii) regeneration of the spent material by means of 0.5 molar NaOH (the material can be reused after rinsing with water); and (iii) recovery of phosphorus from the regeneration liquid by $\text{Ca}(\text{OH})_2$. The remaining NaOH solution can be

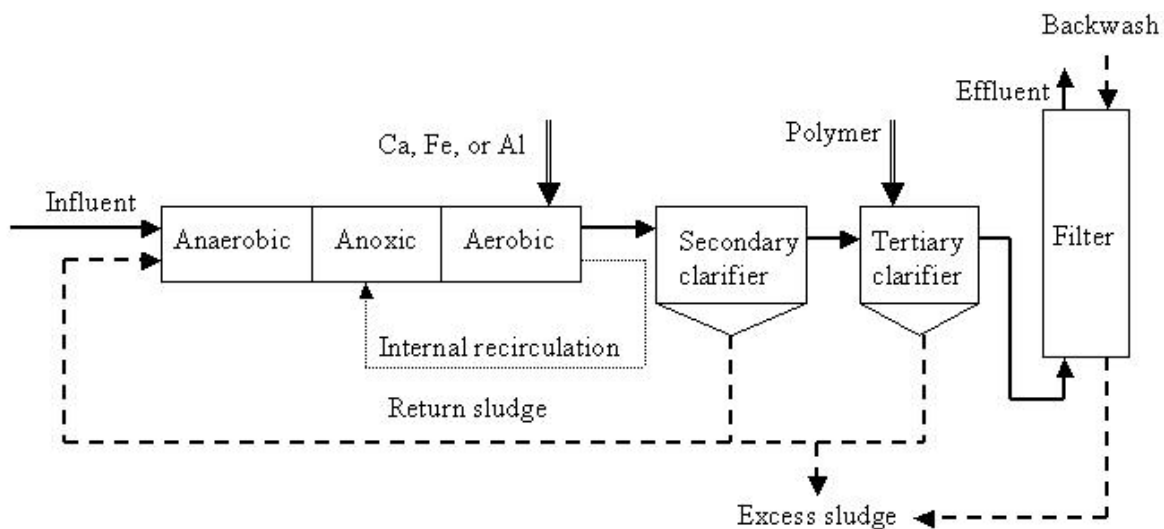
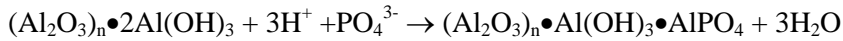


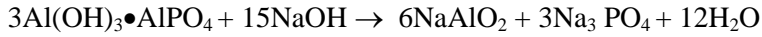
Figure 6. Three-stage activated sludge process with metal addition and tertiary clarifier and filtration

reused for regeneration.

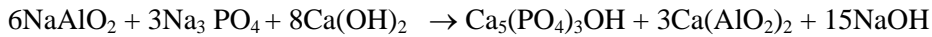
The adsorption of phosphorus takes place according to the following



while the regeneration of the granular material can be expressed by the reaction



and the precipitation of phosphorus from the regeneration liquid by $Ca(OH)_2$ as



The two reactions above show that NaOH can be reused after each precipitation process, so that the consumption of NaOH in this process is negligible.

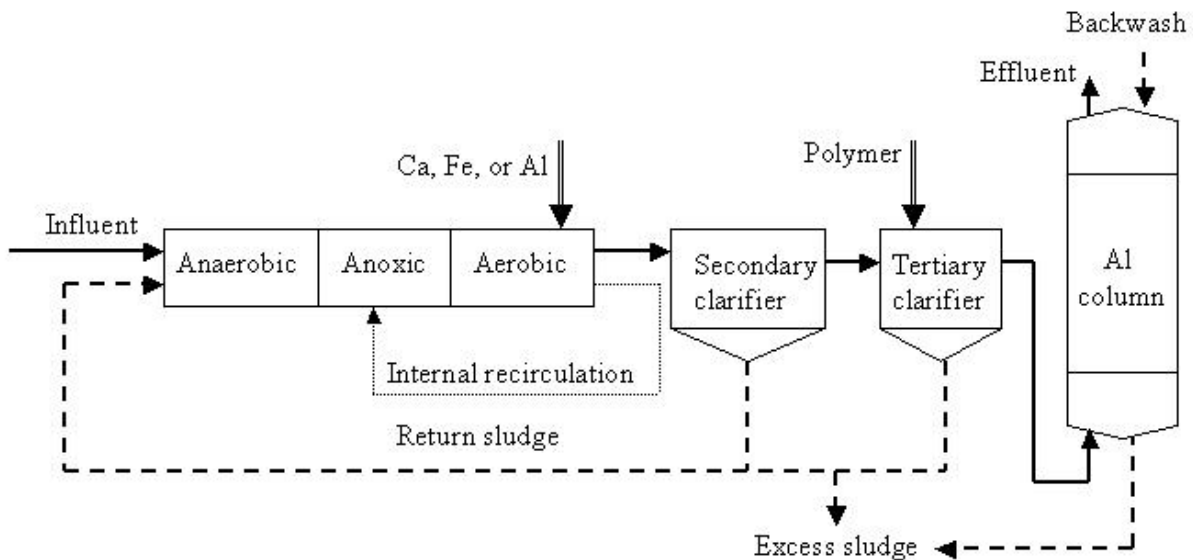


Figure 7. Three-stage activated sludge process with metal addition, tertiary clarifier and Al column

2.8 Three-stage Activated Sludge with Metal Addition, Filter, and Membrane Methods (AAO + Al + F + UF)

Utilization of ultrafiltration (UF) membranes is becoming increasingly popular, either following the final clarifier, or in lieu of the sedimentation process. The membranes are a type of micro-filter that can be

selected so that a pore size of less than 0.5 microns can be achieved². The membrane acts as a true surface filter, retaining all particles at the surface, where they can be easily removed by shear forces provided by the flow of the feed solution (Belfort, 1984). In effect, the membrane system is thereby able to achieve one hundred percent removal of suspended solids, resulting in a zero concentration in the effluent, or very close to it. The total phosphorus concentration can be lowered to 0.05 mg/L.

2.9 Summary of Pollutant Concentrations for the Various Process Designs

To summarize, the estimated effluent qualities of the processes surveyed are given in Table 1.

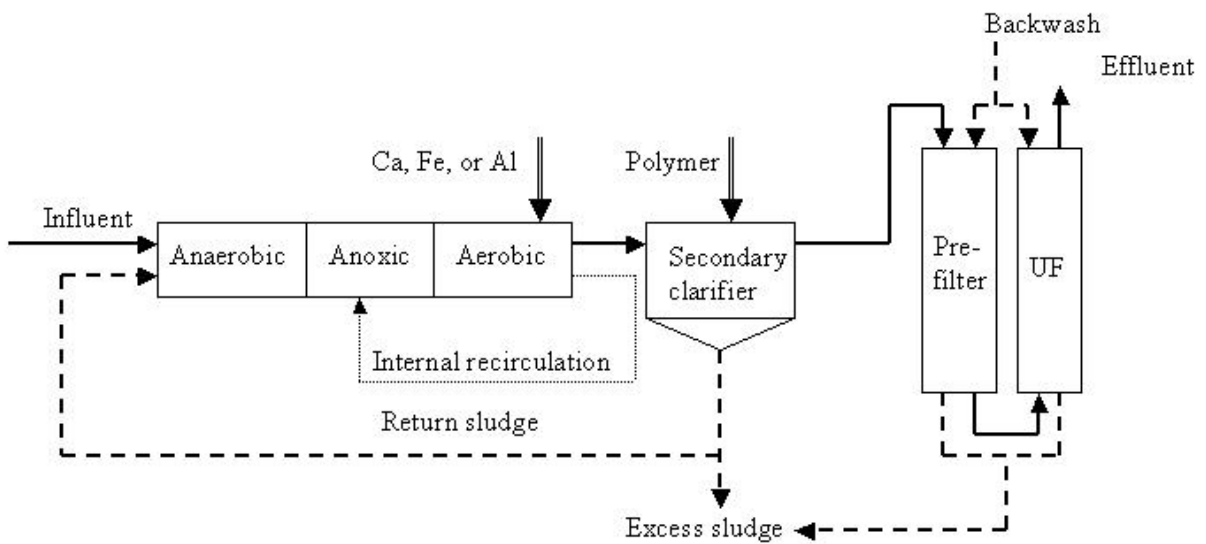


Figure 8. Three-stage activated sludge process with metal addition, filter and membrane system

Table 1 The estimated effluent quality of the eight reference designs

Process	TBOD mg/L	TSS mg/L	TP mg/L	P removal %
Influent	174	172	7.5	/
Effluent of AS	22	20	5.86	21.8
Effluent of AO	11-20	20	4.12	45.1
Effluent of AAO	11	20	2.95	60.7
Effluent of AAO + M	10	20	1.00	86.7
Effluent of AAO + M+ S	5-10	5	0.325	95.7
Effluent of AAO + M+ S + F	5	1	0.145	98.1

Effluent of AAO + M + S + C	<1	<1	0.10	98.7
Effluent of AAO + M + F + UF	<1	<1	0.05	99.3

3. COST ESTIMATION: BUILDING FACILITIES *DE NOVO*

3.1 Capital Cost

The components of cost considered as part of the overall capital cost of building an entirely new wastewater treatment plant *de novo*, and their relative magnitudes as a proportion of the total cost, are given in Table 2. These details are derived from costs for municipal wastewater treatment plants quoted in USEPA (1978), and for water treatment facilities in USEPA (1979), appropriately updated for inflation according to the Engineering News Record (ENR) construction cost index (McGraw-Hill Co., 2004). The cost of the ultrafiltration process is estimated from the research of Drouiche *et al* (2001). The resulting estimated capital costs for the eight system designs discussed in Section 2 and summarized in Table 1 are presented in Table 3 and Figure 9. Full details of the methods of generating these estimates are given in Appendix 1. Not surprisingly, our results show that the total capital costs increase with the target P removal efficiency and the design (flow) capacity of the facility (Table 3 and Figure 9). However, when the required removal efficiency exceeds 90 percent, these costs rise quickly as a consequence of the extra unit processes needed for removal of the phosphorus still remaining after (essentially) biological treatment (as in Table 1 and the preceding discussion of Section 2).

Table 2 Standard capital cost breakdown (USEPA,1998)

Factor	Component	Estimation method
Construction cost	Equipment	Technology-specific cost
	Installation	25 to 55 percent of equipment cost
	Piping	31 to 66 percent of equipment cost
	Instrumentation and Controls	6 to 30 percent of equipment cost
Indirect cost	Engineering	15 per cent of total construction cost
	Contingency	15 per cent of total construction cost

Table 3 The capital cost of the eight designs

Process	Flow MGD	Total construction cost (1978 \$*10 ⁶)	Total indirect cost (1978 \$*10 ⁶)		Total capital cost (1978 \$*10 ⁶)	Total capital cost (2004 \$*10 ⁶)
			Engineering	Contingency		
AS	1.0	2.24	0.34	0.34	2.91	7.36
	10.0	12.03	1.80	1.80	15.64	39.53
	20.0	19.95	2.99	2.99	25.94	65.56
	50.0	38.95	5.84	5.84	50.64	127.99
	100.0	64.60	9.69	9.69	83.98	212.28
AO	1.0	2.72	0.41	0.41	3.54	8.94
	10.0	14.27	2.14	2.14	18.55	46.89
	20.0	23.51	3.53	3.53	30.56	77.25
	50.0	45.48	6.82	6.82	59.12	149.45
	100.0	74.92	11.24	11.24	97.40	248.29
AAO	1.0	2.95	0.44	0.44	3.84	9.69
	10.0	16.59	2.49	2.49	21.57	54.52
	20.0	27.90	4.19	4.19	36.27	91.68
	50.0	55.47	8.32	8.32	72.11	182.28
	100.0	93.29	13.99	13.99	121.28	306.55
AAO + AI	1.0	2.97	0.45	0.45	3.86	9.76
	10.0	16.63	2.49	2.49	21.62	54.65
	20.0	27.95	4.19	4.19	36.34	91.84
	50.0	55.55	8.33	8.33	72.22	182.54
	100.0	93.42	14.01	14.01	121.45	306.98
AAO + AI + S	1.0	3.08	0.46	0.46	4.00	10.12
	10.0	17.05	2.56	2.56	22.17	56.03
	20.0	28.68	4.30	4.30	37.28	94.24
	50.0	57.39	8.61	8.61	74.61	188.58
	100.0	97.06	14.56	14.56	126.18	318.94
AAO + AI + S + F	1.0	3.30	0.50	0.50	4.29	10.84
	10.0	17.87	2.68	2.68	23.23	58.72
	20.0	30.45	4.57	4.57	39.58	100.06
	50.0	62.81	9.42	9.42	81.65	206.39
	100.0	104.81	15.72	15.72	136.25	344.41
AAO + AI + S + C	1.0	3.38	0.51	0.51	4.40	11.11
	10.0	20.05	3.01	3.01	26.07	65.88
	20.0	34.38	5.16	5.16	44.69	112.97
	50.0	72.39	10.86	10.86	94.11	237.87
	100.0	125.06	18.76	18.76	162.58	410.95
AAO + AI + F + UF	1.0	/	/	/	/	12.27
	10.0	/	/	/	/	72.79
	20.0	/	/	/	/	113.18
	50.0	/	/	/	/	277.31
	100.0	/	/	/	/	486.18

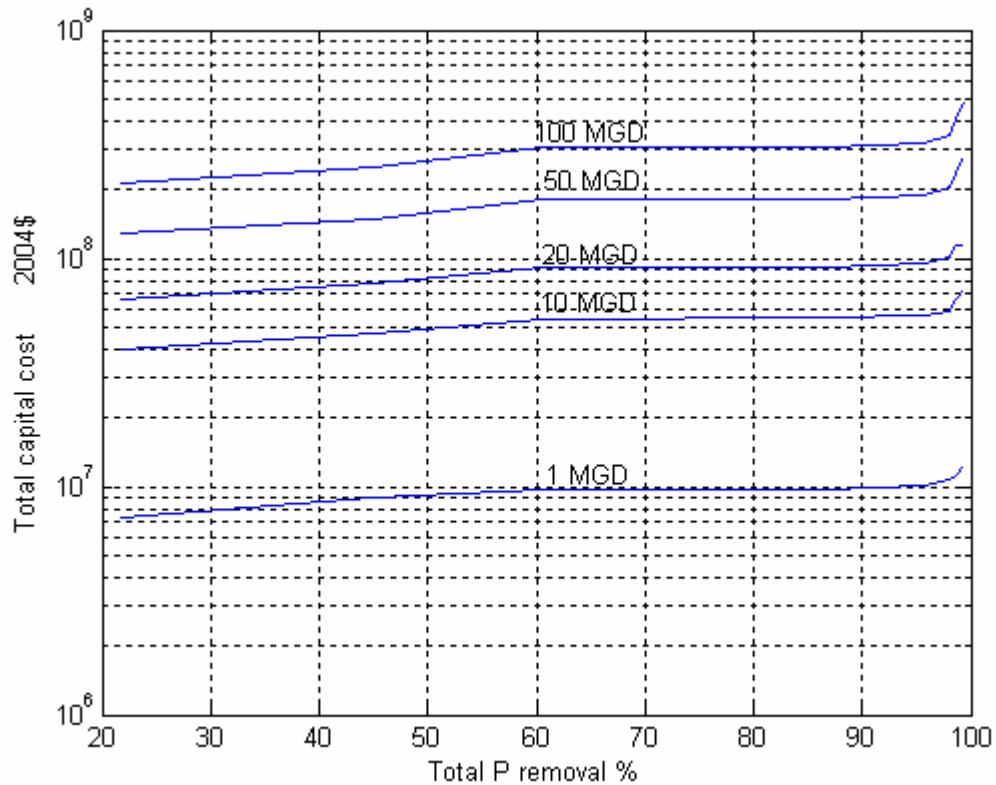


Figure 9. Capital cost curves of the eight designs

3.2 Operation and Maintenance Costs

Table 4 shows details of the constituents of operation and maintenance (O & M) costs. It is apparent that the costs of maintenance, taxes, and insurance are estimated merely as a percentage of the total capital cost. Labor costs are calculated according to the manpower needed and the average salary of common labor in 2004. According to the research conducted by the water and sanitation division of the transportation, water and urban development department of the World Bank (TWUWS, 1996), the average annual amount of water sold per unit staff member in the USA is 370,000 m³, which implies that there are 38 members of staff in a 10 MGD plant. This value is greater than the manpower requirement as set out by EPA (USEPA, 1971), however. Thus, the manpower requirements for each design are still calculated according to EPA documentation (USEPA, 1971). The energy consumption of activated sludge processes is estimated according to the results of an energy benchmarking study conducted by SBW Consulting, Inc (2002). The

energy consumption for the addition of Al, Ca(OH)₂, and polymer in clarification and filtration are taken from the report on “Estimating Water Treatment Costs” (USEPA, 1979).

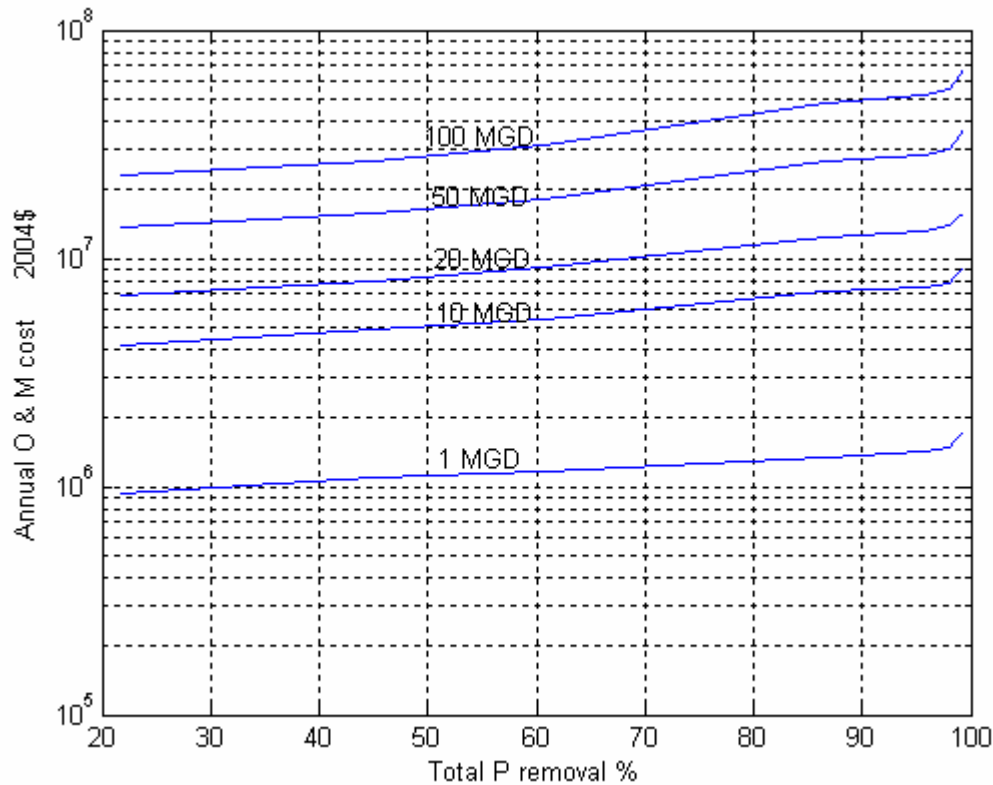


Figure 10. Annual O &M costs for the eight designs

Table 4 Standard O & M cost factor breakdown (modified after USEPA, 1998)

Factor	Estimation
Maintenance	4 per cent of total capital cost
Taxes and insurance	2 per cent of total capital cost
Labor	\$28.21/hr
Electricity	\$0.0499/ kwh
Chemicals	Al ₂ (SO ₄) ₃ •12H ₂ O \$80/ton Ca(OH) ₂ \$80.8 /ton Polymer \$3780/ton
Residuals management	Disposal costs are \$0.27/ kg solids for biological sludge and \$1.24/ kg solids for a blend of chemical and biological sludge.

The energy consumption for ultrafiltration is derived from the research conducted by Drouiche *et al* (2001) and the text on “Synthetic Membrane Processes: Fundamentals and Water Applications” (Belfort, 1984). The chemicals consumed in the various designs of treatment processes (Section 2) include the $\text{Al}_2(\text{SO}_4)_3$ added in the aeration basin, the $\text{Al}_2(\text{SO}_4)_3$ and polymer injected in tertiary clarification, Al_2O_3 consumed during the operation of an adsorption column, the $\text{Ca}(\text{OH})_2$ used in the recovery of phosphate from the regeneration solution of the adsorption column, and the dilute sulfuric acid used to clean the membrane in an ultrafiltration unit. The amounts of chemical consumption are calculated according to stoichiometry and the experimental results published in USEPA (1976) and other sources (Roques, 1995; Drouiche *et al*, 2001). The costs of sludge disposal are taken from an EPA costing document (USEPA, 1999) and updated using the ENR construction cost index, taking into account variations in such costs according to the following four types of sludge: (i) biological sludge composed of bacteria cells produced in biochemical reactions; (ii) the aluminum sludge generated in the precipitation reaction caused by Al addition; (iii) the calcium sludge formed during phosphate recovery from the regeneration solution with $\text{Ca}(\text{OH})_2$; and (iv) the waste produced in the operation of membrane systems. To summarize, the O & M cost estimates for the eight processes are presented in Table 5 and Figure 9. Full details of estimating the O & M cost are given as an example in Appendix 2. The increasing annual O & M cost, as the target level of P removal (and plant, i.e., flow capacity) increases, reflects the use of greater amounts of chemicals and energy. Noteworthy is the fact that the O & M costs for membrane systems are significantly higher than for the other systems, as a result of membrane replacement, higher energy consumption, and larger amounts of waste sludge produced.

3.3 The Total Economic Cost

Having now estimated the capital cost of construction (Table 3 and Figure 9), as well as the annual costs of operation and maintenance (Table 5 and Figure 10), we can move towards estimation of the Total Annual Economic Cost (TAEC), which will normally be the basis for deciding upon the selection of a particular process configuration to achieve a given level of removal of phosphorus. The TAEC may be calculated as follows (Tsagarkis *et al*, 2003)

Table 5 The O & M cost estimates for the eight processes (2004\$*10⁶)

Process	Flow	Maintenance	Taxes and insurance	Labor	Electricity	Chemicals	Residuals management	Total O&M cost
AS	1.0	0.29	0.15	0.41	0.05	0	0.03	0.93
	10.0	1.58	0.79	1.11	0.32	0	0.33	4.13
	20.0	2.62	1.31	1.7	0.55	0	0.66	6.84
	50.0	5.12	2.56	3.11	1.13	0	1.65	13.57
	100.0	8.49	4.25	5.16	1.95	0	3.31	23.16
AO	1.0	0.36	0.18	0.45	0.07	0	0.03	1.09
	10.0	1.88	0.94	1.24	0.45	0	0.34	4.85
	20.0	3.09	1.55	1.88	0.78	0	0.68	7.98
	50.0	5.98	2.99	3.45	1.60	0	1.71	15.73
	100.0	9.93	4.97	5.76	2.77	0	3.42	26.85
AAO	1.0	0.39	0.19	0.48	0.07	0	0.04	1.17
	10.0	2.18	1.09	1.33	0.45	0	0.38	5.43
	20.0	3.67	1.83	2.1	0.78	0	0.75	9.13
	50.0	7.29	3.65	3.85	1.62	0	1.88	18.29
	100.0	12.26	6.13	6.61	2.8	0	3.77	31.57
AAO + AI	1.0	0.39	0.2	0.49	0.07	0.005	0.2	1.35
	10.0	2.19	1.09	1.33	0.45	0.05	1.99	7.1
	20.0	3.67	1.84	2.1	0.78	0.1	3.97	12.46
	50.0	7.3	3.65	3.85	1.62	0.24	9.93	26.59
	100.0	12.28	6.14	6.61	2.81	0.48	19.85	48.17
AAO + AI + S	1.0	0.4	0.2	0.5	0.07	0.007	0.23	1.41
	10.0	2.24	1.12	1.35	0.46	0.07	2.26	7.5
	20.0	3.77	1.88	2.12	0.79	0.15	4.51	13.22
	50.0	7.54	3.77	3.89	1.62	0.37	11.29	28.48
	100.0	12.76	6.38	6.69	2.81	0.75	22.57	51.96
AAO + AI + S + F	1.0	0.43	0.22	0.52	0.08	0.007	0.23	1.49
	10.0	2.35	1.17	1.42	0.48	0.07	2.33	7.82
	20.0	4	2	2.24	0.84	0.15	4.65	13.88
	50.0	8.26	4.13	4.14	1.76	0.37	11.64	30.3
	100.0	13.78	6.89	7.26	3.08	0.75	23.27	55.03
AAO + AI + S + C	1.0	0.44	0.22	0.61	0.08	0.008	0.24	1.60
	10.0	2.64	1.32	1.53	0.51	0.08	2.37	8.44
	20.0	4.52	2.26	2.34	0.89	0.16	4.74	14.91
	50.0	9.51	4.76	4.21	1.87	0.41	11.85	32.61
	100.0	16.44	8.22	7.1	3.31	0.81	23.7	59.58
AAO + AI + F + UF	1.0	0.49	0.25	0.66	0.09	0.02	0.25	1.76
	10.0	2.91	1.46	1.50	0.62	0.19	2.5	9.18
	20.0	4.53	2.26	2.33	1.12	0.38	5	15.62
	50.0	11.09	5.55	4.25	2.46	0.95	12.5	36.80
	100.0	19.45	9.72	7.39	4.49	1.90	25	67.95

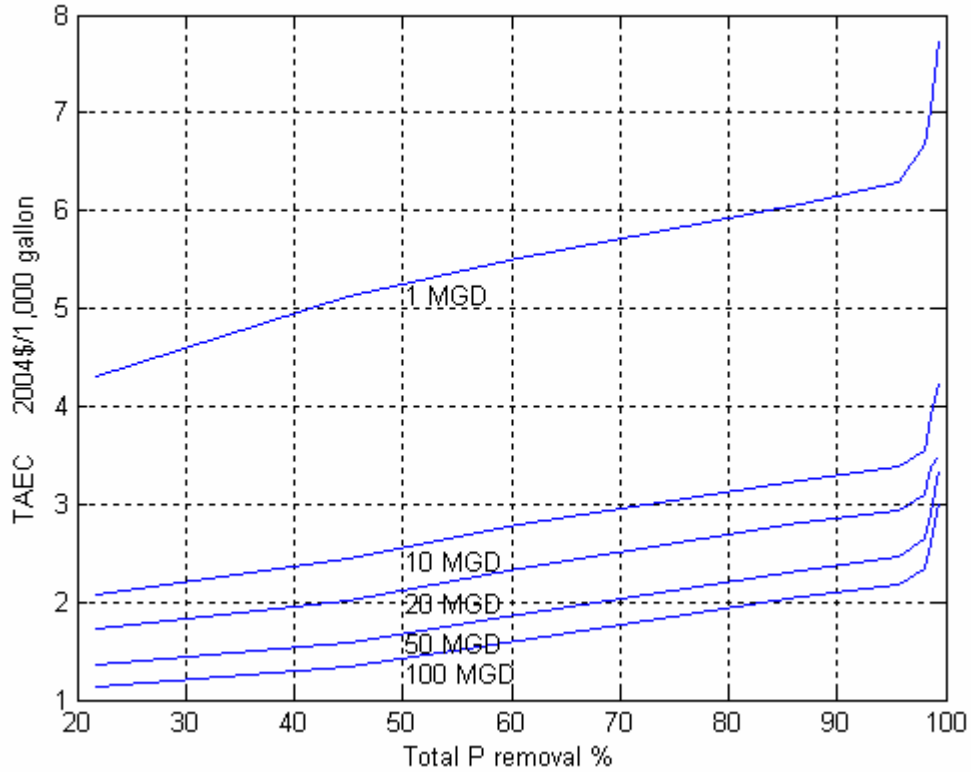


Figure 11 TAEC of the eight processes

$$TAEC = (Cca * CRF) + Ca$$

where Cca is the sum of the land cost and construction cost (see Table 3), Ca is the annual operation and maintenance cost (see Table 5), and CRF is a capital recovery factor. The land cost is not included in this report because land prices vary considerably from place to place. Given thus a CRF of 8.72 %, assuming a 20-year life-span for a wastewater treatment plant (Foess *et al*, 1998; Tsagarakis *et al*, 2003), the TAEC for the eight design configurations of Section 2 are shown in Figure 11. Figure 12 shows the relative TAEC for the designs, i.e., the unit cost of treating wastewater for facilities of different (flow) capacities relative to the reference case of a 1 MGD facility for the given configuration. Although not shown in Figure 12, for the design incorporating membrane processes, once the plant capacity exceeds 5 MGD any further economy of

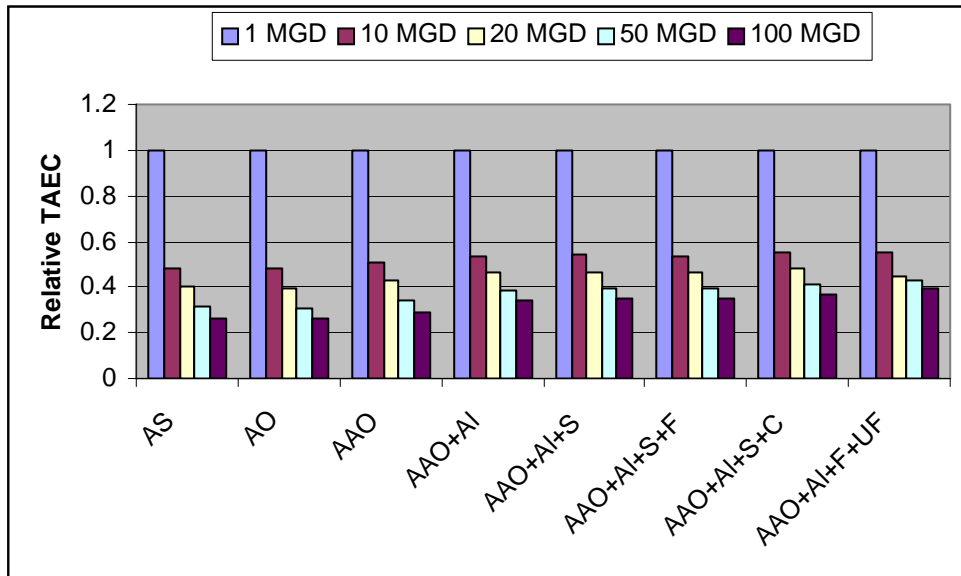


Figure 11. The relative TAEC for different capacities of WWTP

scale is very modest (Rogers, 1984). From a different perspective, where now relative TAEC is defined as the unit cost of treating wastewater by the various eight designs for the same capacity plant, relative to the reference case of the design of section 2.1 (basic activated sludge), Figure 12 indicates costs of the membrane process to be substantially higher. This is partly because the membranes are expected to have a shorter economic life and partly because of their high initial investment. It is also apparent that the TAEC of processes with higher phosphorus removal efficiencies increases at a higher rate than those with lower efficiencies. Nevertheless, it is noted that no consideration has been given to the fact that the wastewater treatment plant alone is not the entirety of the wastewater infrastructure. Where sewers and their associated pumping facilities must be installed and operated as an integral part of the upgrading of overall infrastructure performance, it would be entirely logical to include the costs of such features in the functions required for pollutant trading.

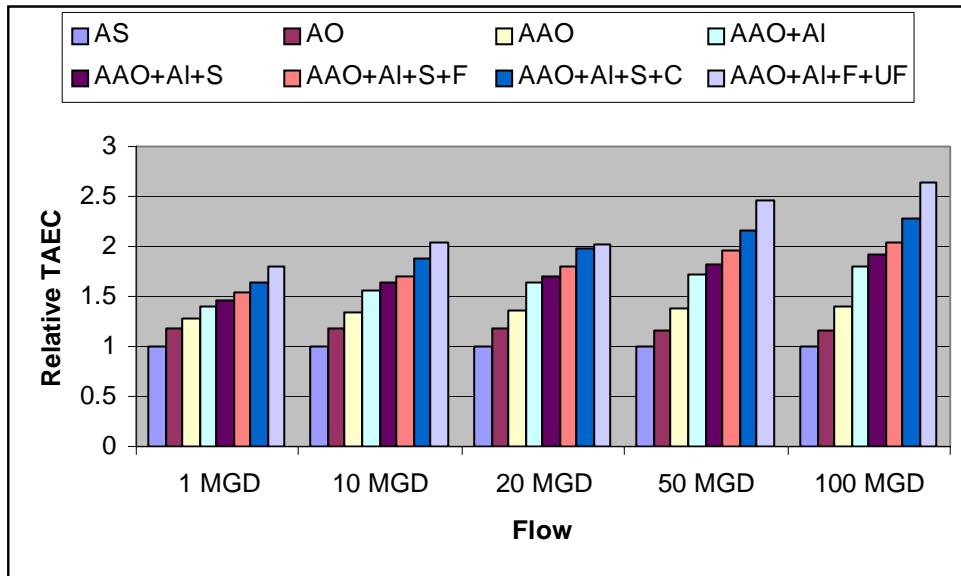


Figure 12. The relative TAEC for different processes

5. CONCLUSIONS

In the broader context of exploring offset banking as a mechanism for trading of pollutant loads between point-source and nonpoint-source discharges of phosphorus to rivers, lakes, and impoundments in a watershed (as in Keplinger *et al*, 2003), it has been necessary to develop a more appropriate means of generating the costs associated with wastewater treatment plant performance. In particular, by estimating the costs for building and operating eight candidate designs of plant, across a range of removal efficiencies, we have been able to construct cost curves for the removal of phosphorus, in principle, anywhere between 20% and 90%, for plants with capacities ranging between 1 and 100 MGD. We stress, however, that the results of this report are of a preliminary nature. Some components of some of the facility designs, though promising, may be of an essentially prototypical nature. We recognize that accounting for uncertainty will be an important consideration of the way in which the cost curves may be employed subsequently.

The cost curves of the present report refer to the construction, in effect, of an entire plant *de novo*, as opposed to curves allowing one to estimate the costs of adapting (upgrading) the

performance of an existing plant, operating at x% removal of phosphorus, to a higher level of performance, say y% removal efficiency. We believe this latter situation, of adaptation, to be the condition much more likely to be encountered in practice. A corresponding study, based on numerical results from simulation models of the various wastewater treatment system designs, is in progress and will be reported upon in due course.

Looking ahead somewhat, our intention is to use the kinds of cost curves presented herein to explore the feasibility of offset banking schemes, under uncertainty, in simulated model systems of watersheds, based on the work already initiated and reported upon in Osidele *et al* (2003).

ALL FOOTNOTES

1. The level of removal is often reduced by the practice of sludge digestion. Biological treatment of wastewater produces an excess of biomass, which is separated from the liquid waste treatment train and subjected to further treatment, as sludge, prior to disposal. Digestion as a means of treatment of these biological solids (sludge), especially if carried out under anaerobic conditions, will generate a liquor rich in dissolved materials, including phosphorus. The liquor is usually returned to the head of the wastewater treatment works for additional treatment. Some wastewater treatment works choose frequently to reduce the phosphorus load to the plant by pre-treating the return sludge digestion liquors to precipitate out the phosphorus. This practice is not believed to be common in Georgia, however.
2. The size is important, because the suspended solids test (Standard Method 2540) defines suspended solids as that unable to pass through a 2.0 micron filter (whereas dissolved solids are defined as any materials passing through such a filter). Proposals are under consideration, however, that would change the test definition of suspended solids as that passing through a 0.5 micron filter. Nevertheless, since membrane filtration is equivalent to operating with a 0.45 micron filter, the total suspended solids concentration of its effluent (filtrate) would still be effectively defined as zero, or extremely close to it.

REFERENCES

- Balmer P. and Mattsson B. 1994. Wastewater treatment plant operation costs. *Wat. Sci. Tech.* 30(4):7-15.
- Battistoni P., Fava G., Pavan P., Musacco A. and Cecchi F. 1997 Phosphorus removal in anaerobic liquids by struvite crystallization without addition of chemicals : preliminary results. *Wat. Res.* 31(11):2925-2929.
- Beck, M B, Fath, B D, Parker, A K, Osidele, O O, Cowie, G M, Rasmussen, T C, Patten, B C, Norton, B G, Steinemann, A, Borrett, S R, Cox, D, Mayhew, M C, Zeng, X-Q and Zeng, W (2002b): "Developing a Concept of Adaptive Community Learning: Case Study of a Rapidly Urbanizing Watershed", *Integrated Assessment*, 3(4):299-307.
- Belfort G. 1984. Synthetic Membrane Process *Academic Press*, INC, Orlando, FL
- Bergman R.A., Porter R., Elarde J., SCHULGEN B. 2002 Membrane Pilot and demonstration-scale treatment for water reclamation at Gwinnett County, Georgia. Technological report.
- Brattebø H. and Ædegaard H. 1986. Phosphorus removal by granular activated aluminum. *Wat. Res.* 20 (8):977-986
- Cummings, Ronald G., Laura O. Taylor and M. Bruce Beck, "Developing Offset Banking Systems in Georgia," Working Paper #2003-002, Environmental Policy Program, Andrew Young School of Policy Studies, Georgia State University (Atlanta: March 2003).
- Donnert D. and Salecker M. 1999. Elimination of phosphorus from municipal and industrial waste water *Wat. Sci. Tech.* 40 (4-5):195-202.
- Foess G.W. 1998 Cost and performance evaluation of BNR processes. *Florida Water Resources Journal*, 11 (1998).
- Drouiche M., Lounici H., Belhocine D., Grib H., Piron D., and Mameri 2001, Economic study of the treatment of surface water by small ultrafiltration units. *Water SA* 27(2):199-204.
- Dryden F.O. and Stern G. 1968 *Wat. Sci. Tech* 2(2) 268 Goronszy M.C. 1992 Full-scale cyclic activated sludge system phosphorus removal. *Wat. Sci. Tech.* 26 (9-11):2253-2256.
- Gullet B., McLelland J., and Padgett D. 2003 System-wide planning for phosphorus reduction at Charlotte's three largest wastewater treatment plants. *Proceedings of South Carolina Environmental Conference*. Columbia, South Carolina, March, 2003.
- Hano T., Takanashi H., Hirata M., Urano K. and Shunji. 1997. Removal of phosphorus from wastewater by activated alumina adsorbent. *Wat. Sci. Tech.* 35 (7):39-46.
- Jardin N., Popel H.J. 1997. Waste activated sludge production of the enhanced biological phosphorus removal process. *Water Environ. Res.* 69, 375-381.
- Joko I. 1984. Phosphorus removal from wastewater by the crystallization method. *Wat. Sci. Tech.* 17 (1):121-132.
- Lee S. E., Kim K.S., Ahn J.H. and Kim C.W. 1997. Comparison of phosphorus removal Characteristics between various biological nutrient removal processes. *Wat. Sci. Tech.* 36 (12):61-68.
- Levlin E. and Hultman B 2003. Phosphorus recovery from phosphate rich Sidestreams in wastewater treatments. *Proceedings of a Polish-Swedish seminar, Report No.10. Joint Polish-Swedish Reports*, Gdansk Poland, March, 2003.
- Marcuaai M., Ciabatti I., Matteucci A., and Vernaglione G. 2003. Membrane technologies applied to textile wastewater treatment. *Ann. N.Y. Acad. Sci.* 984:53-64, 2003.
- Matsch L. C. and Drnevich R.F. 1987. Biological nutrient removal, in *Advances in Water and Waste Treatment*, Ann Arbor Sci., Mich. 1987.
- McGraw-Hill Co. 2004. McGraw-Hill Engineering News Record Construction Cost Index available at <http://enr.com>

- Metcalf & Eddy, INC. 1979. Wastewater engineering: treatment disposal reuse *McGraw-Hill Book Company*. New York.
- Mino T., Kawakami T. and Matsuo T. 1984. Location of phosphorus in activated sludge and function of intracellular polyphosphates in biological phosphorus removal process. *Wat. Sci. Tech.* 17 (1):93-106.
- Momberg G.A. and Oellermann R. a. 1992. The removal of phosphate by hydroxyapatite and struvite crystallization in South Africa. *Wat. Sci. Tech.* 26 (5-6):987-996.
- Osidele, O.O., Zeng, W. and Beck, M.B. (2003) Coping with uncertainty: a case study in sediment transport and nutrient load analysis. *Journal of Water Resources Planning and Management, American Society of Civil Engineers (ASCE)*, 129(4):345-355.
- Rensink J.H., van der Ven J., vanPamelen G., Fedder F. and Majoor E. 1997. The modified Renphosystem: a high biological nutrient removal system. *Wat. Sci. Tech.* 35 (10):137-146.
- Roques H. 1995. Chemical water treatment principles and practice. *VCH Publishers, Inc.* New York.
- Roske I. and Schonborn. C. 1994. Interactions between chemical and advanced biological phosphorus elimination. *Wat. Res.* 28 (5), 1103-1109.
- SBW Consulting, Inc. 2002. Energy benchmarking secondary wastewater treatment and ultraviolet disinfection process at various municipal wastewater treatment facilities. Technological report.
- Smolders G.J.F., Van Loosdrecht M.C.M. and Heijnen J.J. 1996. Steady-state Analysis to evaluate the phosphate removal capacity and acetate requirement of biological phosphorus removing mainstream and sidestream process configurations. *Wat. Res.* 30 (11), 2748-2760.
- Tsagarakis K. P., Mara D.D. and Angelakis A.N. 2003 Application of cost criteria for selection of municipal wastewater treatment systems. *Water, Air, and Soil Pollution* 142:187-210.
- TWUWS 1996. Water and Wastewater Utilities 2nd Edition The Water and sanitation division of transportation, water and urban development department of the World Bank, Washington, DC.
- US Department of the Army. 1978. Design of Wastewater Treatment Systems Major Facilities US Department of the Army Publication W-019.
- USEPA. 1980. Construction Costs for Municipal Wastewater Treatment Plant:1973-1978 U.S. Environmental Protection Agency, Facility Requirements Division, EPA 430-9-80-003, Washington, DC.
- USEPA. 1998. Detailed Costing document For The Centralized Waste Treatment Industry U.S. Environmental Protection Agency, Office of Water, EPA821-R-98-016, Washington, DC.
- USEPA. 1987 Design Manual: Phosphorus Removal U.S. Environmental Protection Agency, Office of Research and Development, EPA 625-1-87-001, Cincinnati, OH.
- USEPA. 1971. Estimating Costs and Manpower Requirements for Conventional Wastewater Treatment Facilities U.S. Environmental Protection Agency, Office of Research and Monitoring, EPA 17090 DAN 10/71, Kansas city, MO.
- USEPA. 1979. Estimating Water Treatment Costs U.S. Environmental Protection Agency, Office of Research and Development, EPA 600/2-79-162b, Cincinnati, OH.
- van Dijk J.C. and Braakensiek H. 1984. Phosphate removal by crystallization in a fluidized bed. *Wat. Sci. Tech.* 17 (1):33-142.
- Veldkamp R. G. 1984. Modeling phosphate sludge production. *Wat. Sci. Tech.* 17 (1):107-119.
- Wild, D. Kisliakova A. and Siegrist H. 1996. P-fixation by Mg, Ca and zeolite during stabilization of excess sludge from enhanced biological P-removal. *Wat. Sci. Tech* 31 (1-2):391-398.

APPENDIX 1

The Method of Estimating the Capital Cost

Estimation of the capital cost breaks down into three steps: (i) identification of the construction cost for the given design; (ii) calculation of the indirect cost as a percentage of the construction cost; and (iii) updating the result to take account of inflation in costs.

Thus, for example, to estimate the capital cost of the three-stage activated sludge process with Al addition, we find from the cost curve of secondary treatment with phosphorus removal in “Construction Costs for Municipal Wastewater Treatment Plants” (Report EPA/430/9-80-003) that the construction cost is \$2.95M for a design flow of 1 MGD. Then, from the corresponding report on “Estimating Water Treatment Costs”, specifically, from the cost curve of Al addition, we find that the construction cost is \$20k when the addition amounts to 15 lb/hr. Therefore, the total construction cost is $\$2,950,000 + \$20,000 = \$2,970,000$.

Indirect costs include an engineering cost and a contingency cost, each estimated as 15% of the total construction cost, i.e., \$445,000 each. The capital cost is the sum of the construction cost and this indirect cost, i.e., $\$2,970,000 + \$445,500 + \$445,500$, or \$3,861,000 in all.

This estimate, which is based on costs for 1978, must now be updated to reflect conditions in 2004. From the Engineering News Record construction cost index history, we find that the construction cost index for 1978 and 2004 are 2776 and 7017 respectively, so that the capital cost in 2004 dollars is $\$3,861,000 * 7016.91 / 2776$, approximately \$9,759,470.

Capital cost for other seven system designs can be estimated similarly.

APPENDIX 2

The Method of Estimating O & M Costs

This breaks down into six steps, as follows, where we illustrate the nature of the calculation for the design of the three-stage activated sludge process with Al addition.

1. Energy cost.

According to the results of SBW Consulting, Inc. (2002), the annual energy consumption for the three-stage activated sludge process with a design capacity of 1MGD is about 1,466,990 kWh. From the report on “Estimating Water Treatment Costs”, annual energy consumption for Al addition is 10,000 kWh, so that total energy consumption is accordingly 1,476,990 kWh. Given an estimated price of electricity of 0.0499 \$/kWh (the average price in Georgia for 2003) the cost of the energy consumed is \$73,702 per annum.

2. Labor cost.

According to “Estimating Costs and Manpower Requirements for Conventional Wastewater Treatment Facilities” (USEPA, 1971), the number of staff required to operate the conventional activated sludge process with a capacity of 1 MGD is 7. The labor involved in operating and maintaining the additional anaerobic and anoxic segments of the (three-stage) process is 2320 hours each year; that involved in Al addition is 63 hours. Normal payroll time consists of 2080 hours per person per year, of which effective working time is estimated to be 90%. A 2004 average salary rate is 28.21\$/hr for the associated categories of staff, so that the total labor cost is given by the product of $(2080 \cdot 7 + 2320/0.9 + 63/0.9)$ total hours of work and 28.21 \$/h salary, i.e. \$485,432.

3. Costs of chemicals

In order to meet the limit of 1 mg/L of total phosphorus in the effluent, 42.4 mg/L of $\text{Al}_2(\text{SO}_4)_3$ must be added. Thus, for a flow of 1 MGD, the amount of $\text{Al}_2(\text{SO}_4)_3 \cdot 12\text{H}_2\text{O}$ consumed on an annual basis must

therefore be $0.0424 \text{ kg/m}^3 \times 3875 \text{ m}^3/\text{day} \times 365 \text{ day}$, which equals 59,969.5 kg. Since the current price of $\text{Al}_2(\text{SO}_4)_3 \cdot 12\text{H}_2\text{O}$ is about 80\$/ton, the costs of chemicals for the given (illustrative) system design is $59969.5 \text{ kg} \times 0.08 \text{ \$/kg}$, i.e., \$4,798.

4. Costs of residuals management

The excess sludge produced in the biological portion of the system design is calculated according to guidance given in the “Design Manual for Phosphorus Removal” (USEPA, 1987). The annual amount of wasted biological sludge in the three-stage activated sludge process is thereby estimated to be 139,457 kg.

With respect to the production of chemical sludge, the addition of 42.4 mg/l of $\text{Al}_2(\text{SO}_4)_3 \cdot 12\text{H}_2\text{O}$ results in the formation of 7.65 mg/L of AlPO_4 and 6.95 mg/L of $\text{Al}(\text{OH})_3$, which gives $(7.65 \text{ mg/L} + 6.95 \text{ mg/L}) \times 3875 \text{ m}^3/\text{day} \times 365 \text{ day}/1000$, or 20,650 kg of chemical sludge.

The total mass of sludge produced on an annual basis is therefore the sum of 139,457 kg and 20,650 kg, i.e., 160,107 kg. According to the “Detailed Costing Document for the Centralized Waste Treatment Industry” (USEPA, 1998), the cost for the disposal of mixed sludge (a blend of biological and chemical sludge) is about 1.24 \$/kg solids (updated to 2004\$), so that the cost for sludge disposal is $160,107 \text{ kg} \times 1.24 \text{ \$/kg}$, i.e., \$198,533.

5. Maintenance, taxes and insurance

Again according to the “Detailed Costing Document for the Centralized Waste Treatment Industry” (USEPA, 1998), the maintenance costs are 4% of the total capital cost, whereas the costs of taxes and insurance are 2% thereof. Given the total capital cost for this system design of \$9.76M, maintenance costs are therefore \$390,400, while taxes and insurance amount to \$195,200.

6. Total O & M costs

Given the above five components, the total O & M cost sums to \$1,348,065.