ESTIMATION OF COSTS OF PHOSPHORUS REMOVAL IN WASTEWATER TREATMENT FACILITIES: ADAPTATION OF EXISTING FACILITIES

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By

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ABSTRACT

As part of a wider enquiry into the feasibility of offset banking schemes as a means to implement pollutant trading within Georgia watersheds, this is the second of two reports addressing the issue of estimating costs for upgrades in the performance of phosphorus removal in point-source wastewater treatment facilities. Earlier, preliminary results are presented in Jiang *et al* (2004) (Working Paper # 2004-010 of the Georgia Water Planning and Policy Center). The present study is much more detailed and employs an advanced software package (WEST®, Hemmis nv, Kortrijk, Belgium) for simulating a variety of treatment plant designs operating under typical Georgia conditions. Specifically, upgrades in performance, in a single step, from a plant working at an effluent limit of less than 2.0 mg/l phosphorus to one working with limits variously ranging between less than 1.0 mg/l to less than 0.05 mg/l phosphorus are simulated and the resulting costs of the upgrade estimated.

Five capacities of plant are considered, from 1 MGD to 100 MGD. Three strategic, alternative designs for the facility are considered: the basic activated sludge (AS) process with chemical addition, the Anoxic/Oxic (A/O) arrangement of the AS process, and the Anaerobic/Aerobic/Oxic (A/A/O) arrangement of the AS process. Upgrades in performance are consistent with the logical alternatives for adapting these options. Cost comparisons are made primarily on the basis of the incremental cost of the upgrade, i.e., from the base-case, reference plant to that performing at the higher level, as expressed through the incremental Total Annual Economic Cost (TAEC; in $) and the marginal unit cost of phosphorus removal, expressed in ($/kg).

For the most stringent upgrade, for example, to a plant generating an effluent with less than 0.05 mg/l phosphorus, these marginal costs — the cost of the *additional* phosphorus removed as a result of the upgrade — amount to something of the order of 150-425 $/kg, with the upper bound being associated with the smallest plant configuration (1 MGD).

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1. INTRODUCTION

In our previous report (Jiang *et al*, 2004) we presented estimates of the costs of removing phosphorus from municipal wastewater under the assumption that the treatment facilities would be constructed *de novo*, i.e., from scratch. That foregoing report, as is the present report, was motivated by the prospect of lowering nutrient levels in rivers and lakes using an offset banking scheme for pollutant trading between point and nonpoint sources of pollution (Cummings *et al*, 2003). In most situations, however, instead of building new facilities for reducing point sources of pollution, we need to adapt the already existing facilities – operating at a level of x % removal of P, say – to a higher level of y % removal. Since a number of paths of adaptation are possible, it is clear some should be more cost-effective than others. In particular, at the extremes, a path of adaptation based on *no* reconstruction and maximal adaptation of operational policies – a “0 percent reconstruction” policy – may have costs of a very different size and nature to a path based entirely on reconstruction with no operational innovations – a “100 percent reconstruction policy”. While we shall not explore such issues herein, they are clearly of very considerable significance with respect to the potential for the more widespread introduction of instrumentation, control, and automation (ICA) in the water industry (Ingildsen and Olsson, 2001; Beck, 2005).

Our current goal, however, is to examine merely a small number of adaptations (all under the policy of essentially 100 percent reconstruction) that will transfer the performance of a given design of facility, for a variety of capacities, from x % to y % removal rates and to generate the resulting costs of such transitions. While one might examine this problem using data available on some of the actual transitions implemented in practice (Schulz *et al*, 2003), or possibly by scaling up from various pilot plant configurations (Gnirss *et al*, 2003), an approach based on extensive simulation is adopted herein (see also Alex *et al*, 1999). Simulation has an important advantage over pilot-scale experiments, since the influence of a very wide range of design features and operating conditions can be rapidly evaluated on a consistent basis (Hao *et al*, 2001). To be specific, we shall base our studies on the WEST simulation platform (Hemmis nv, Kortrijk, Belgium).

2. SIMULATION METHOD

From the several alternatives supported within WEST, Activated Sludge Model No.2d (ASM 2d) (Henze *et al*, 1999) has been selected for our present purpose, because it simulates both biological phosphorus removal and the removal of phosphate through precipitation by metal addition. Given previous detailed and comprehensive studies of the Athens #2 Wastewater Treatment Plant (Liu and Beck, 2000; Liu, 2000), the simulated designs for the wastewater treatment facilities can be driven by crude sewage variations typical for Georgia. In this preliminary study, we have chosen to use data covering a short fourteen-day period reflecting, to all intents and purposes, dry weather conditions. Furthermore, we have used the data as collected, without attempting to extract from them any smoothed estimate of the dry-weather diurnal/weekly patterns (as illustrated, for example, in Beck and Lin, 2003). In future studies we note, therefore, that it would be appropriate to broaden the coverage to include the more typical mix of wet- and dry-weather operating conditions and for periods spanning seasonal variations. Further characterization of the influent wastewater, as required for the state variables of the plant model, is performed according to the research conducted by Insel *et al* (2003) and Hao *et al* (2001) and is listed in Table 1.

Values assigned to the parameters of ASM 2d are derived from the research of Insel *et al* (2003). The behavior of the clarifier is simulated with the double-exponential settling function in a 10-layer model (Takacs *et al*, 1991). For evaluating the performance of a wastewater treatment plant (WWTP), a standard procedure has already been developed by the COST 624 Working Group (http://www.ensic.u-nancy.fr/COSTWWTP). According to this procedure, a 100-day period of simulated behavior should be used to allow the state variables of the model to reach a state of "equilibrium" prior to the model then being driven by the observed record of variations in the crude sewage quantity and quality during dry weather. In our research, it was found that 30 days are sufficient for most of the system configurations to reach the required equilibrium, and their performance then evaluated, as shown in Figure 1.

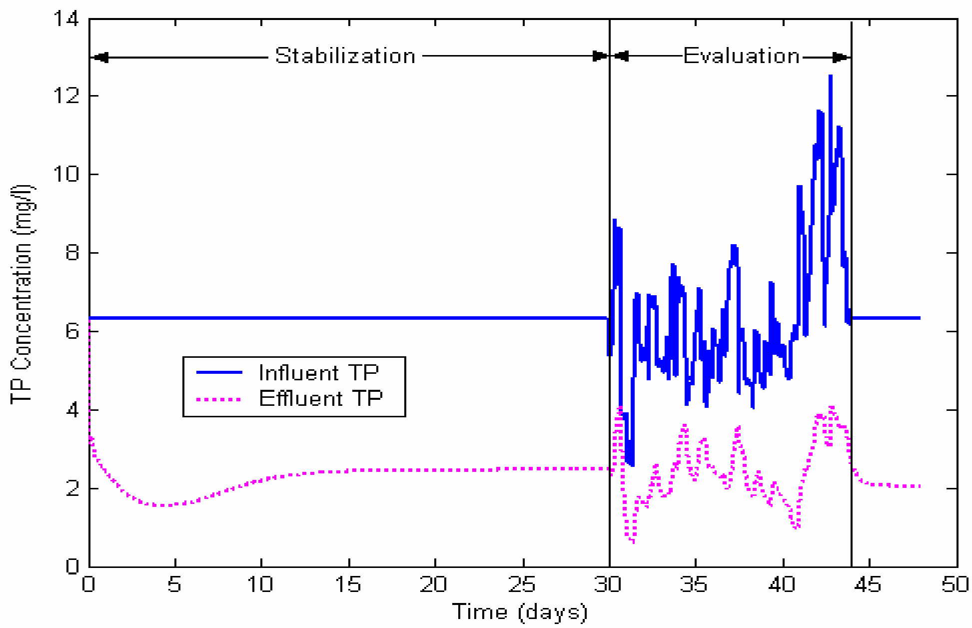

Figure 1. Two stages in the "benchmarking" simulation of the reference activated sludge process

The activated sludge (AS) process is a basic unit process of municipal wastewater treatment and is accordingly selected herein as the base-case reference process from which upgrading of performance and adaptation will take place. The costs estimated in this report are the costs involved in that adaptation, as we have said, and therefore they exclude all the costs of the basic AS system having been installed in the first place. These now prior – previously, *de novo* – costs for the AS design can be found in our previous report (Jiang *et al*, 2004). We note that it is quite possible for some plants with different operating policies to achieve performance in practice that is superior to the quality of the effluent simulated in Figure 1, which in part is a function of the way in which values have been assigned to the parameters (coefficients) of the underlying model. We acknowledge this limitation (it is one of many) and may, in future studies, return to an assessment of the extent to which the results of the present study are sensitive to this choice for the performance of the base-case plant configuration.

Table 1 The flux-based average influent characterization for Athens No.2 WWTP

Parameters	**Unit**	**Concentration**
Total COD, COD_{tot}	mgCOD/l	349
BOD_5	mgO_2/l	228
Total inert COD, C_I	mgCOD/l	59.5
Particulate COD, X_I	mgCOD/l	36.9
Soluble inert COD, S_I	mgCOD/l	22.6
Biodegradable COD, C_S	mgCOD/l	289.4
Fermentable COD, S_F	mgCOD/l	62.0
Acetate, S_A	mgCOD/l	56.4
Slowly biodegradable COD, X_S	mgCOD/l	171
Ortho-P, S_{PO4_P}	mgP/l	2.97
Total Phosphorus, TP	mgP/l	6.34
Ammonium,NH_4_N	mgN/l	16.1
TSS	mgSS/l	186

To enhance phosphorus removal, and therefore to generate estimates of the costs of adaptation, two configurations of biological phosphorus removal will be employed, the Anoxic/Oxic (A/O) or Anaerobic/Anoxic/Oxic (A/A/O) processes, and one design using chemical addition. Furthermore, accompanying additional unit processes, such as a clarifier, sand filter, or ultra-filter, will be incorporated, as appropriate, to remove particulate matter from the effluent and hence remove the attaching phosphorus (since particulate-associated phosphorus dominates in the higher-performing designs). Detailed descriptions of these unit processes can be found in Jiang *et al* (2004).

3. COST ESTIMATION METHOD

The costs of upgrading facility performance include both a capital cost and an operations and maintenance (O & M) cost. As in our previous work (Jiang *et al*, 2004), procedures for generating the former are derived from *Construction Costs for Municipal Wastewater Treatment Plants* (USEPA, 1980) and *Estimating Treatment Costs* (USEPA, 1979), modified as indicated below. The O & M cost is estimated using the algorithm of EPA (1998) and includes component costs for energy, chemicals, sludge disposal, labor, maintenance, and insurance.

3.1 Energy

Overall consumption of energy can be broken down into three parts, namely, aeration energy (AE), pumping energy (PE), and mixing energy (ME), and is directly derived from the simulation results. AE is calculated from the Kla (oxygen transfer) coefficient associated with the aeration basin (the oxic component) of the biological treatment unit, according to the following relation (Alex *et al*, 2000), where the numerical coefficients are modified according to the research conducted by SBW Consulting, Inc. (2002):

$$AE = \frac{24}{T} \int_{t=t_1}^{t=t_2} \sum_{i=1}^{n} [4.032(Kla)_i^2 + 78.408*(Kla)_i]dt$$

where Kla is the oxygen transfer coefficient (h^{-1}), t_1 and t_2 are the starting time and ending time of the evaluation, T is the length of the evaluation interval (days), and n is the number of aeration tanks. PE is calculated according to another relation drawn from Alex *et al* (2000),

$$PE = \frac{0.04}{T} \int_{t=t_1}^{t=t_2} [Q_a(t) + Q_r(t) + Q_w(t)]dt$$

in which Q_a is the flow of internal recirculation (m^3/d), Q_r is the flow of return sludge (m^3/d), and Q_w is the flow of waste sludge (m^3/d). ME is calculated as follows,

$$ME = 24 *UE*(V_{anaer} + V_{anox})$$

where UE is the unit energy consumption of mixing, which is 0.014 kw/m^3 for a hydrolytic tank (Zakkour *et al*, 2001); and V_{anaer} and V_{anox} are the volumes of anaerobic tank and anoxic tank respectively (m^3).

3.2 Chemicals

The chemicals consumed in the various treatment units include the alum added to the aeration basin, the polymers added to the clarifier, and the cleaning agent used in the ultra-filtration process. The amount of alum addition is calculated directly from the simulation results as

$$M_{Al} = \frac{1}{T}\int_{t=t_1}^{t=t_2} X_{Al}*Q_{Al}(t)dt$$

in which X_{Al} is the concentration of $Al_2(SO_4)_3$ solution (g/m^3), Q_{Al} is the $Al_2(SO_4)_3$ feed flow, in m^3/d. The unit cost of $Al_2(SO_4)_3$ is derived from the current market price (http://search.chem.cn), and will turn out to be an important factor meriting further discussion (below). The amount of polymer consumption is derived from *Water Works Engineering* (Qasim *et al*, 2000). The cost of cleaning agents is estimated on the basis of data presented by Drouiche *et al* (2001).

3.3 Sludge Disposal

The amount of sludge needing to be disposed of is calculated directly from the simulation results with the relation developed by the COST 624 Working Group (http://www.ensic.u-nancy.fr/COSTWWTP):

$$M_{sludge} = \frac{1}{T}[TSS(t_2) - TSS(t_1) + \int_{t=t_1}^{t=t_2} X_u*Q_w(t)dt]$$

in which $TSS(t_1)$ and $TSS(t_2)$ are the amount of sludge in the system at the starting time and ending time of the evaluation. X_u is the sludge concentration in the underflow of the settler. For the filtration and ultra-filtration process, the sludge in the backwash stream is also added to the amount of sludge disposal.

In the previous study (Jiang *et al*, 2004) the sludge was divided into two categories: the biological sludge produced by the growth of organisms, and the mixture of this biological sludge with the chemical sludge produced from metal addition. According to the applicable regulations in Georgia, the latter can be disposed of in a municipal solid waste landfill, as long as the sludge is not a regulated hazardous waste and it passes the paint-filter test (Cown, 2004). Since the alum sludge produced from water treatment is not identified on any of USEPA's lists of hazardous substances (Koorse, 1993), and no long-term (30 months) effects of alum sludge application on groundwater and soil water quality and pine growth have been observed (Geertsema *et al*, 1994), it appears that the addition of alum for phosphorus removal does not adversely affect the agricultural value of the resulting sludge compared to non-chemical sludge (USEPA, 1987). Thus, it is reasonable to assume that the mixture of biological sludge and alum sludge can still be handled in the same way as the regular sludge. However, since the dewatering cost is another important component of the cost of (on-site) sludge handling, this too is incorporated into the sludge disposal cost estimated herein. This dewatering cost is derived from the research conducted by the Organization for Economic Co-operation and Development (1974), updated with the method of Qasim *et al* (1992).

3.4 Other Considerations

Besides energy consumption, chemicals, and sludge disposal, there are three other factors to be considered for estimating the O & M cost: labor, maintenance, and insurance. The amounts of labor are estimated from *Estimating Water Treatment Costs* (USEPA, 1979), while the wage for skilled labor is derived from the Engineering News-Record (ENR) indexes. Maintenance and insurance are estimated according to *Detailed Costing Document for the Centralized Wastewater Treatment Industry* (USEPA, 1998). Details of these estimation procedures can be found in our earlier report (Jiang *et al*, 2004).

3.5 Cost Updating

In the previous study (Jiang *et al*, 2004) a single index (the Engineering News Record (ENR) Construction Cost Index) was used to adjust costs for inflation. However, there is much evidence to indicate that these time-honored indexes are often inadequate for application to water utility construction (Qasim *et al*, 1992). Thus, as presented by Qasim *et al* (1992), the total construction costs are divided into eight components, namely excavation and site work, manufactured equipment, concrete, steel, labor, piping and valves, electrical equipment and instrumentation, and housing. The Bureau of Labor Statistics (BLS) and ENR indexes (Table 2) are used variously to update these components, and the sum of the updated components becomes the updated costs.

Table 2 BLS and ENR indexes used for the cost updating

Cost component	Index	October 1978 value of index	Updated May 2004 value of index
Excavation and site work	ENR skilled labor wage index	2486	6672
Manufactured equipment	BLS general purpose machinery and equipment	72.9	158.3
Concrete	BLS concrete ingredients	71.6	168.3
Steel	BLS steel mill products	75.0	135.4
Labor	ENR skilled labor wage index	2486	6672
Pipes and valves	BLS miscellaneous general purpose equipment	70.5	176.4
Electrical equipment and instrumentation	BLS electrical machinery and equipment	72.3	114.5
Housing	ENR building cost index	1654	3956

3.6 Two Key Estimates of Costs

Costs of upgrading plant performance will be summarized in the following according to two key forms of estimates, the unit cost expressed as $/kg TP removed and the incremental Total Annual Economic Cost (TAEC). For clarity, these indicators are defined as follows.

First, the Total Annual Economic Cost is the sum of the annualized capital cost (in order to achieve the adaptation of the plant from the reference AS base-case) and the annualized O & M costs (Tsagarakis *et al*, 2003).

$$TAEC = C_{ca} * CRF + C_a$$

where C_{ca} is the capital cost (not including land cost in this research). C_a is the annualized O & M cost. CRF is the Capital Recovery Factor, which is calculated by the following relation (Tsagarakis *et al*, 2003),

$$CRF = \frac{r(1+r)^t}{(1+r)^t - 1}$$

where r is the Opportunity Cost of Capital (OCC); and t is the economic life. For WWTP facilities, the economic life is generally taken to be 20 years and the CRF is 8.72% when the OCC is equal to 6% (Tsagarakis *et al*, 2003).

From this estimate of the TAEC, the unit cost of TP removal is simply derived as the TAEC divided by the *increase* of annual TP removal as a result of the adaptation, i.e.,

$$C_u = \frac{TAEC}{M_{TP,1} - M_{TP,0}}$$

where C_u is the unit cost of TP removal, $M_{TP,1}$ is the annual TP removal after adaptation, and $M_{TP,0}$ is the annual TP removal of the base-case AS process. The amount of annual TP removal is calculated directly from the simulation results according to the following formula,

$$M_{TP} = \frac{1}{T} \int_{t=t_1}^{t=t_2} (TP_{in} - TP_{out}) * Q_0(t)dt$$

where TP_{in} and TP_{out} are the TP concentrations in the influent and effluent, respectively, and Q_0 is the influent flow rate (m^3/d).

4. ASSUMPTIONS AND SOME KEY DESIGN CHOICES

In any study such as this, a very great number of assumptions must be made, concerning, for example, the values assigned to the physical and economic parameters of the model, choices of plant configurations, the sizing of tanks, the duration and form of the crude sewage input sequence, the nature of operational practices, the performance of instruments and control systems, and the working life-spans of the plant and equipment, to mention but a few. Without such assumptions our studies would not have been possible. The sensitivity of the cost estimates to a small number of the seemingly more important amongst these assumptions, whose associated parameters are clearly subject to uncertainty, is therefore explored later in a rudimentary manner herein and we acknowledge that much more, and more refined, analysis of such issues is warranted.

Some choices must be made at the outset, however. They imply that we ought ideally to implement some form of optimization of facility design, although that is well outside the scope of the present report. In such a preliminary study as this, we focus instead on a very small number of factors key to the design and, therefore, the overall performance, hence estimation of the costs of upgrading performance. In particular, when the A/O or A/A/O design is employed to remove phosphorus, the retention times of the anaerobic and anoxic tanks have a considerable influence over the performance of the entire plant. Thus, there is a need to determine a suitable retention time before the cost-effectiveness of these configurations is evaluated (the basic elements of their designs are given below in Figures 6 and 7 of Section 5).

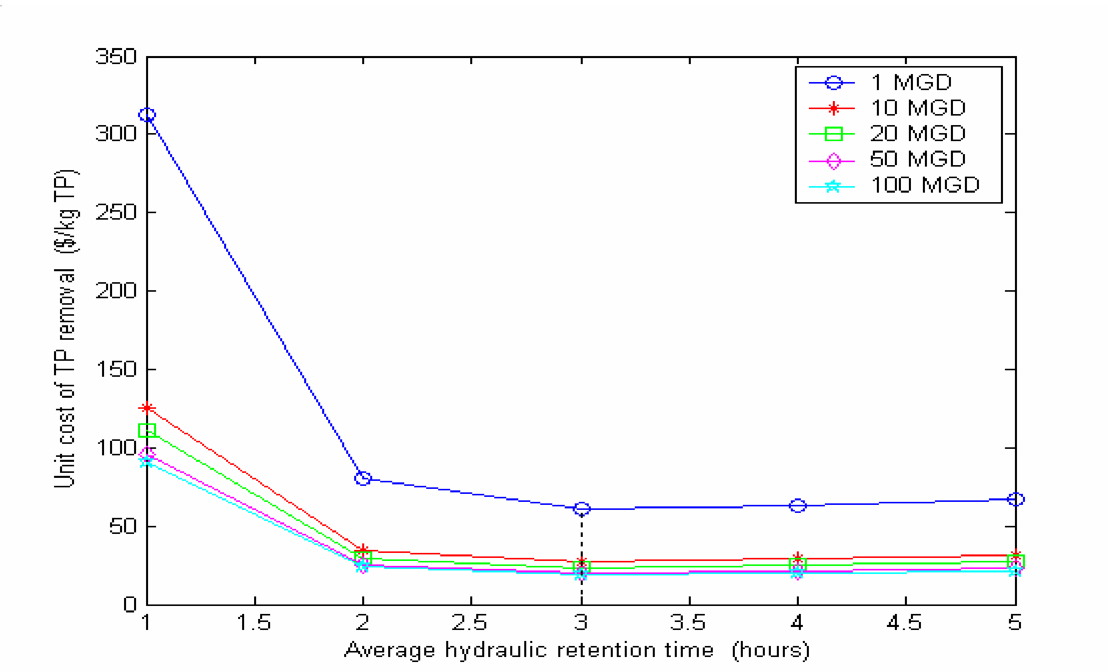

Figure 2. Influence of retention time in the anoxic tank of the A/O design on TP removal cost

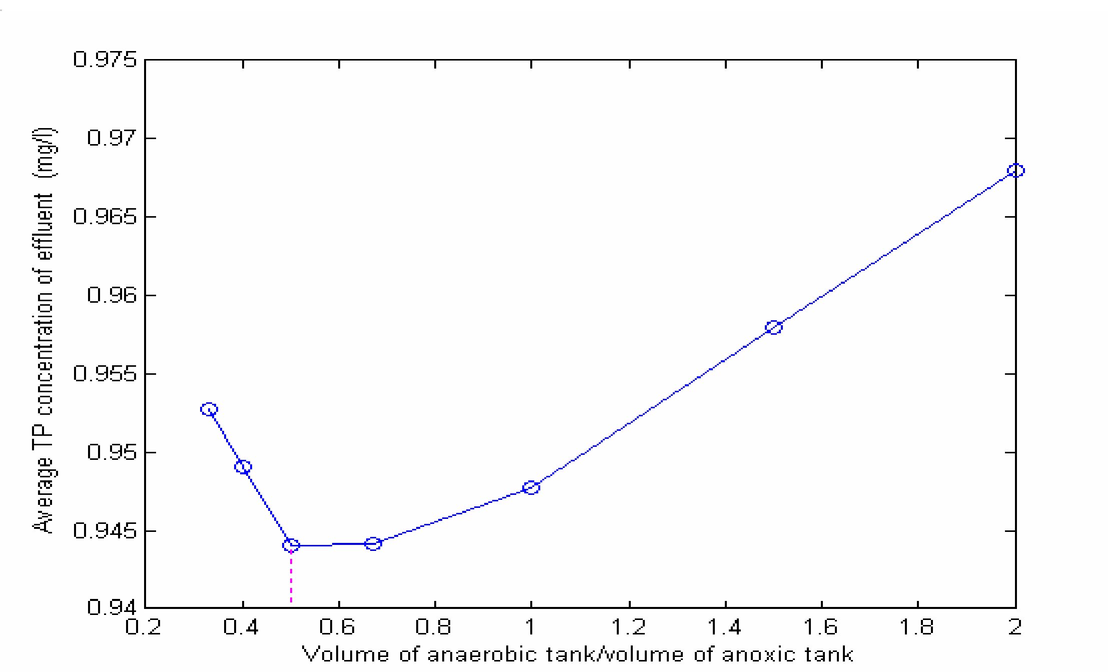

Figure 3. The influence of the ratio of the volumes of the anaerobic to anoxic tank in the A/A/O configuration on effluent performance

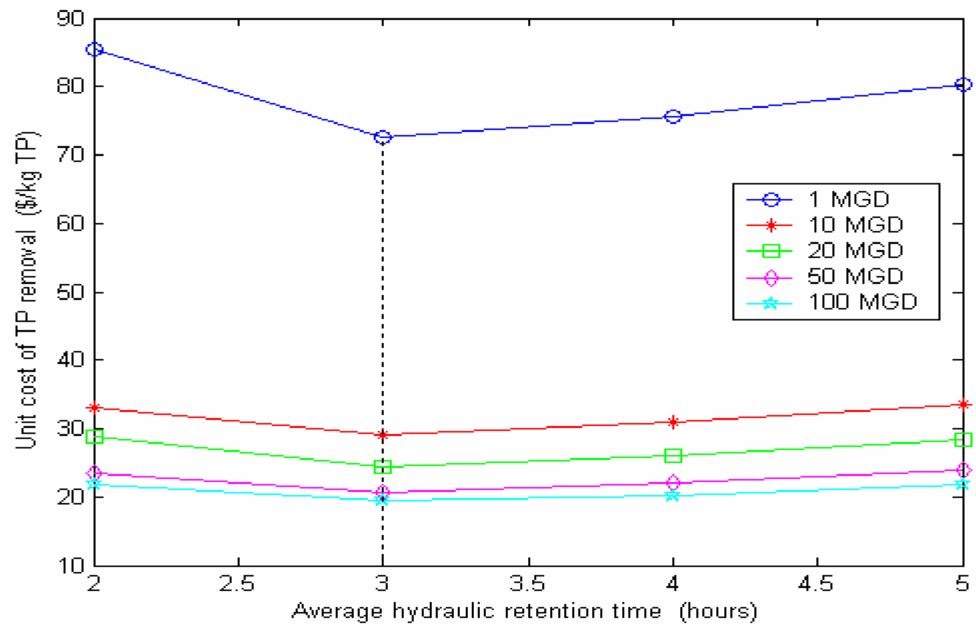

Figure 4. Influence of the combined retention times in the anaerobic and anoxic tanks of the A/A/O configuration on cost estimates

Taking first the A/O configuration of the plant, the unit cost of TP removal as a function of the hydraulic retention time in the anoxic tank is given in Figure 2. At all scales it is apparent that costs – for the requirement of operating with an effluent total P concentration of 2 mg/l – is the least when the retention time is 3 hours. Thus, we choose 3 hours as an appropriate time for this component of the A/O alternative throughout our analyses.

Turning now to the A/A/O alternative, choices for the retention times of *both* the anoxic and anaerobic tanks are key to performance. To make such choices we first need to determine a desirable ratio of the volume of the anaerobic tank to the volume of the anoxic tank. Having found above that 3 hours is a suitable retention time for the anoxic portion of the A/O process, this figure is selected for the *combined* retention time for the anaerobic and anoxic tanks in the A/A/O configuration as the basis upon which to explore a suitable ratio for the two tanks under the effluent TP limit of 2 mg/l. In total, seven values of the ratio, varying from 0.33 to 2.0 have been evaluated (see Figure 3). It is apparent that the average effluent TP concentration is lowest when the ratio is about 0.5, i.e., where the volume of the anaerobic tank is half that of the anoxic tank. This 1:2 ratio of the volumes, of the anaerobic to anoxic tank, respectively, is now fixed in order to explore how the unit costs of phosphorus removal would vary in the A/A/O design as a function of the overall retention time chosen for the two tanks combined. Four such variations on this theme were evaluated, ranging from a combined retention time of 2 hours to 5 hours, with the results shown in Figure 4 (for comparison with Figure 2 for the A/O design). Perhaps not surprisingly, they indicate a preference for 3 hours as a suitable retention time for the A/A/O alternative, which is thus the value chosen for all of the simulations herein that involve the A/A/O arrangement of the biological treatment stage.

5. RESULTS AND DISCUSSION

The key feature governing the level of performance of the wastewater treatment plant is the TP standard imposed on the plant effluent. In the present study five such limits are considered: 2 mg/l, 1 mg/l, 0.5 mg/l, 0.13 mg/l, and 0.05 mg/l. Given the influent load and quality of Table 1, the base-case activated sludge (AS) design as simulated herein is such that it cannot comply with the most lax of these standards, i.e., the 2 mg/l TP limit, for part of the evaluation period (Figure 1). This assumes, incidentally, that the plant monitoring system is sufficiently effective in detecting what is merely a transient failure to comply with required performance. To upgrade performance to reach any one of the higher standards, therefore, just three paths of adaptation are explored through simulation, all under the 100 percent reconstruction policy.

5.1 Processes With Effluent TP Limit of 2 mg/l

Of the three adaptation configurations simulated for the effluent TP below 2 mg/l, the simplest is to augment the basic AS design with a set of alum feed equipment (Figure 5). This addition includes a fiber-glass reinforced polyester (FRP) tank with 15 days of storage, and a metering pump used to pump liquid alum from the storage tank and to meter the flow as it passes directly to the aeration basin. The costs of pipes, fittings and valves are incorporated into the cost of the pumps. The flow of alum feed is adjusted according to the difference between the effluent phosphate concentration of the aeration basin and the set-point of phosphate, so that a phosphate monitor must also be purchased and incorporated into this system.

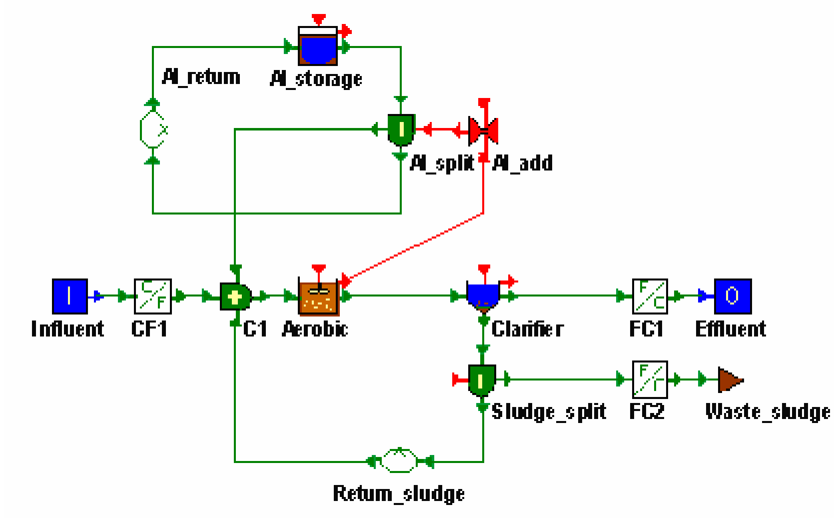

Figure 5. Implementation of AS with Al addition (AS + Al) in WEST

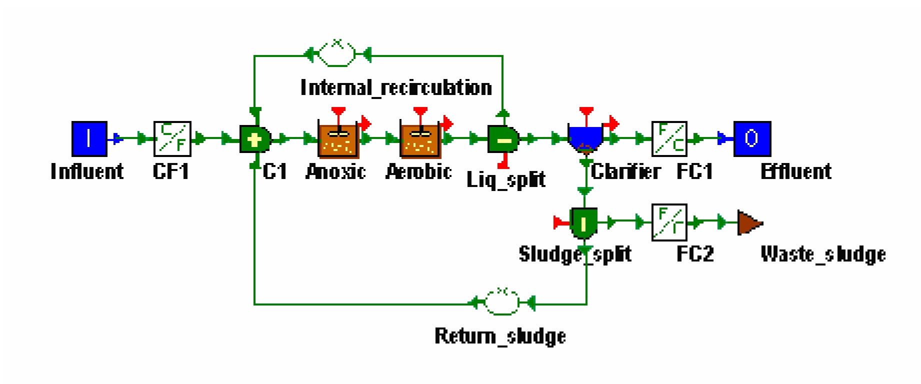

Figure 6. Implementation of the A/O design in WEST

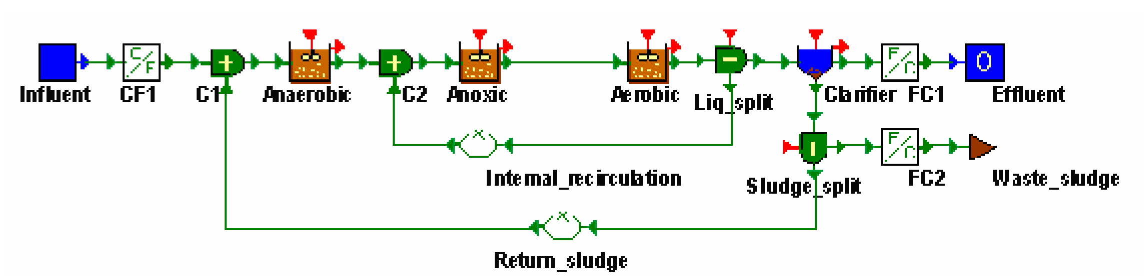

Figure 7. Implementation of the A/A/O design in WEST

Table 3 Cost estimation for the three adaptation configurations (TP limit 2 mg/l)

Capacity MGD			1	10	20	50	100
AS +Al	Capital cost 10^4\$		18.4	22.1	25.1	31.8	39.9
	O & M cost 10^4\$	Energy	0.04	0.13	0.19	0.32	0.50
		Labor	0.67	0.67	0.67	0.70	0.74
		Chemical	0.68	6.76	13.5	33.8	67.6
		Sludge disposal	0.41	4.13	8.26	20.7	41.3
		Maintenance & Insurance	1.10	1.33	1.51	1.91	2.39
	TAEC 10^4\$/y		4.51	15.0	26.3	60.2	116
	TP removed MT/y		1.47	14.7	29.3	73.4	147
	Unit cost for TP removal \$/kg		30.8	10.2	8.98	8.20	7.91
A/O	Capital cost 10^4\$		44.2	189	305	585	994
	O & M cost 10^4\$	Energy	1.38	13.8	27.6	69.0	138
		Labor	3.13	5.92	8.64	17.9	35.0
		Chemical	0	0	0	0	0
		Sludge disposal	0.26	2.56	5.12	12.8	25.6
		Maintenance & Insurance	2.65	11.3	18.3	35.1	59.7
	TAEC 10^4\$/y		11.3	50.1	86.3	186	345
	TP removed MT /y		1.84	18.4	36.8	92.1	184
	Unit cost for TP removal \$/kg		61.2	27.2	23.4	20.2	18.7
A/A/O	Capital cost 10^4\$		56.1	208	324	596	1046
	O & M cost 10^4\$	Energy	1.56	15.6	31.3	78.2	156
		Labor	3.87	6.71	9.46	17.9	35.8
		Chemical	0	0	0	0	0
		Sludge disposal	0.29	2.88	5.77	14.4	28.8
		Maintenance & Insurance	3.36	12.5	19.4	35.7	62.7
	TAEC 10^4\$/y		14.0	55.8	94.2	198	375
	TP removed MT /y		1.93	19.3	38.5	96.3	193
	Unit cost for TP removal \$/kg		72.6	29.0	24.5	20.6	19.5

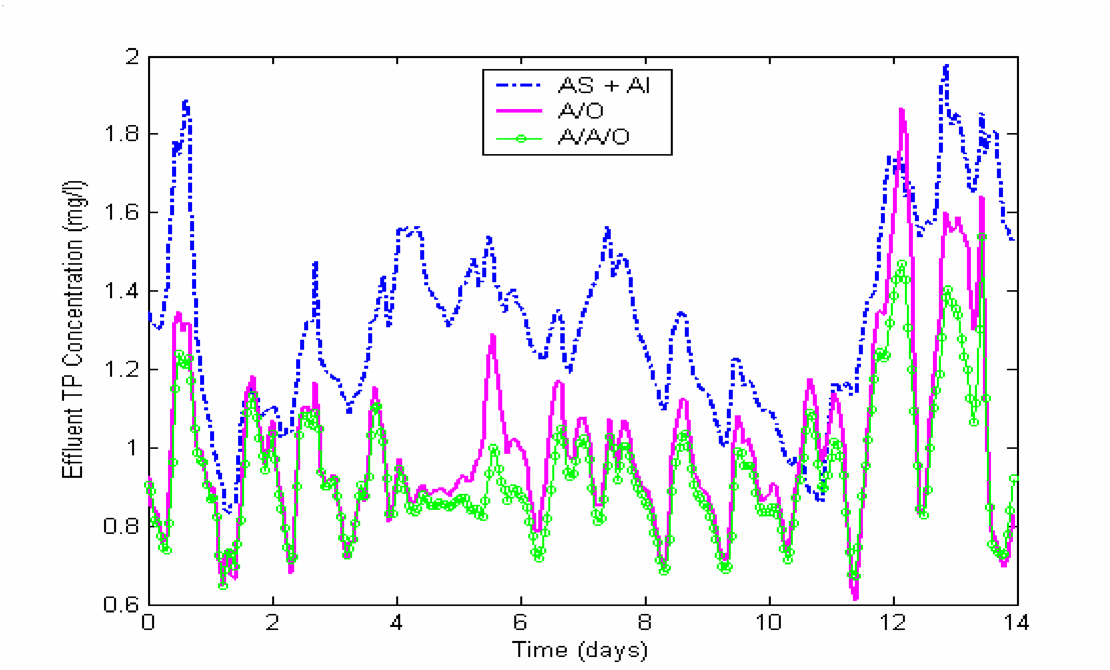

Figure 8. The simulated effluent TP concentration of the three configurations

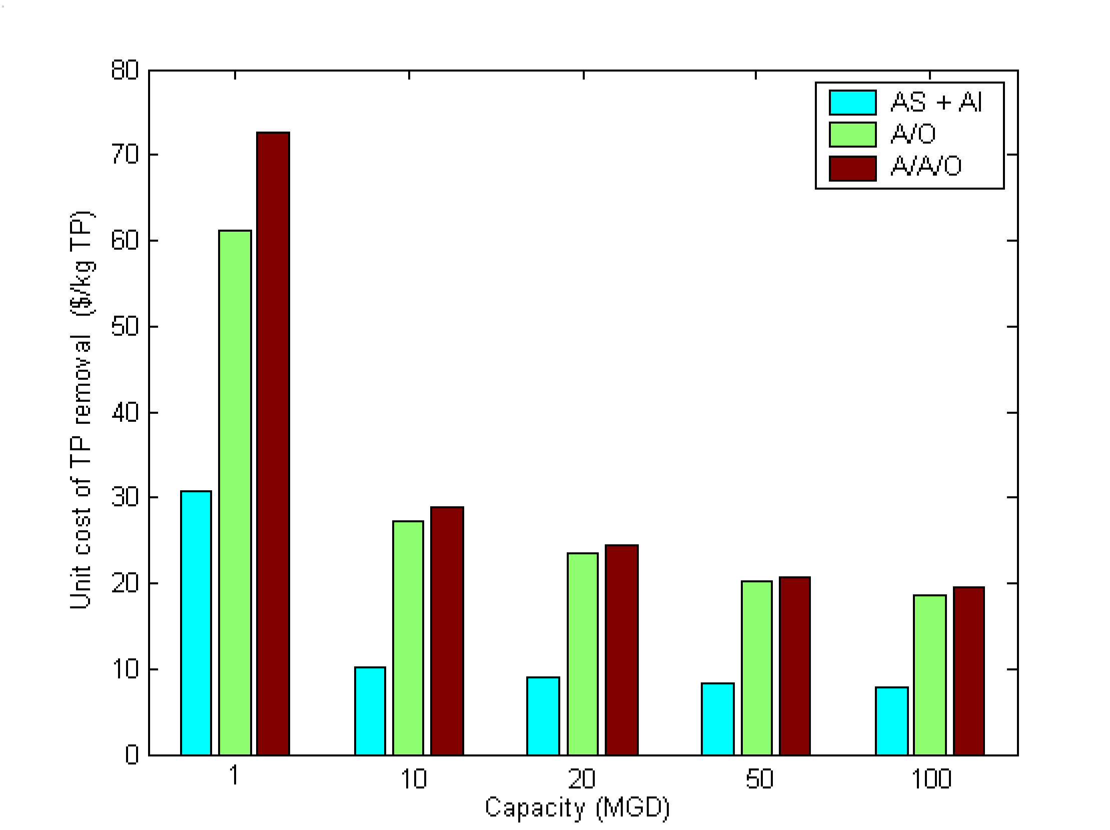

Figure 9. The unit cost of TP removal for the three adaptation configurations

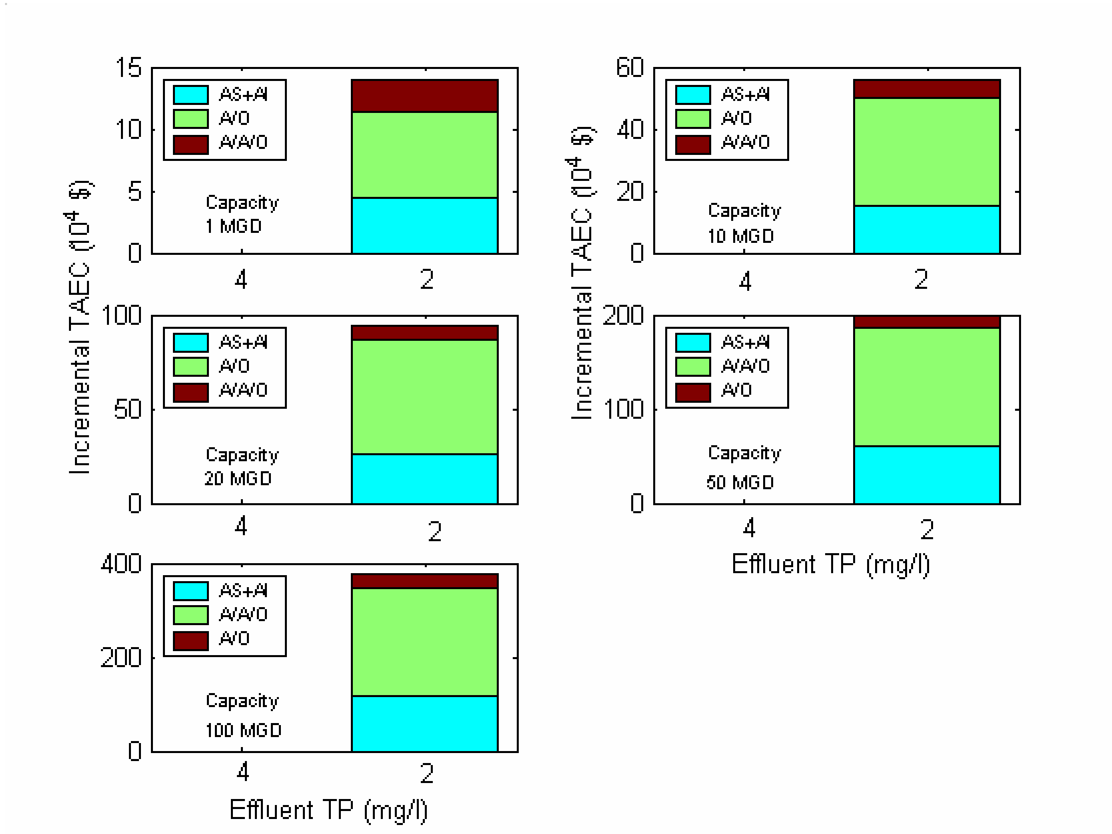

Figure 10. The incremental TAEC of the three adaptation configurations

A second alternative configuration for adaptation is the A/O design, in which an anoxic tank is added in front of the aerobic basin, together with a re-circulation pump between the two tanks (Figure 6). In this design, besides the removal of total nitrogen through denitrification, good phosphorus removal also takes place, although this latter will be adversely affected by the nitrate in the system (Barnard *et al*, 1978).

In order to overcome this problem, an anaerobic tank is added, thus to give the third alternative of the A/A/O design (Figure 7). In this alternative the fermentation stage needed for phosphorus removal and the denitrification stage take place respectively in the anaerobic tank and anoxic tank. They therefore do not interfere with each other, so that the removal of phosphorus can be achieved on a more stable and reliable basis when compared with the second alternative of the A/O configuration. This argument is confirmed by the results of Figure 8, which shows that removal of TP in the A/A/O process is more stable than in the other two options. In contrast, removal of TP in the

A/O process fluctuates continuously as a result of interference from the biochemical process of denitrification. The effluent TP concentration of the AS + Al configuration may be controlled by the amount of alum added; it can therefore be more closely manipulated than the A/A/O process, to lie, for example, just under the TP limit of 2 mg/l (with the result of a generally higher effluent TP concentration than the A/A/O design). It is also noted that the effluent TP concentration of the AS + Al alternative remains persistently high over the last three days of the record – a pattern of variation similar to that of the influent TP (see Figure 1) – whereas the effluent TP of the A/O and A/A/O designs retains an obvious diurnal cycle with deep troughs. The reason for this may be that in the AS + Al process the addition of Al is adjusted according to the phosphate concentration in the aerobic tank, so that the effluent TP concentration is dominated by the influent TP concentration. However, in the A/O and A/A/O designs, the biomass of the PAO organisms also affects the effluent TP concentration, in addition to the variations in the influent TP concentration. When the influent TP rises, the PAOs in the A/O and A/A/O designs will increase accordingly, with the net effect that the effluent TP concentration is unlikely to be persistently high over several days.

Cost estimates of the three configurations are summarized in Table 3 and Figures 9 and 10. Compared with the A/O and A/A/O configurations, the AS + Al process appears more economical, since the incremental TAEC and the unit cost of TP removal are only 30 to 50 percent of those of the two alternatives. As expected, the unit cost of TP removal falls with the capacity of the plant, as a result of an economy of scale. It is also noted that the unit cost of TP removal in the A/A/O process is a little higher than that of the A/O design. This is because the former has a larger capital cost, a higher energy consumption, and produces a larger mass of sludge.

5.2 Processes With Effluent TP Limit of 1 mg/l

In order to meet the TP limit of 1 mg/l, more alum is needed to precipitate out the phosphate in the AS + Al design. For the A/O and A/A/O alternatives, some alum is also needed in order to lower the effluent TP concentration (Figures 11 and 12). The resulting simulated effluent TP concentrations of the three configurations are shown in Figure 13. As for the results of the previous section, the effluent TP concentration of the A/A/O process seems more stable than the other two configurations. This may be due to the fact that A/A/O process has a stable fermentation stage, such that it can maintain a relatively higher TP removal efficiency.

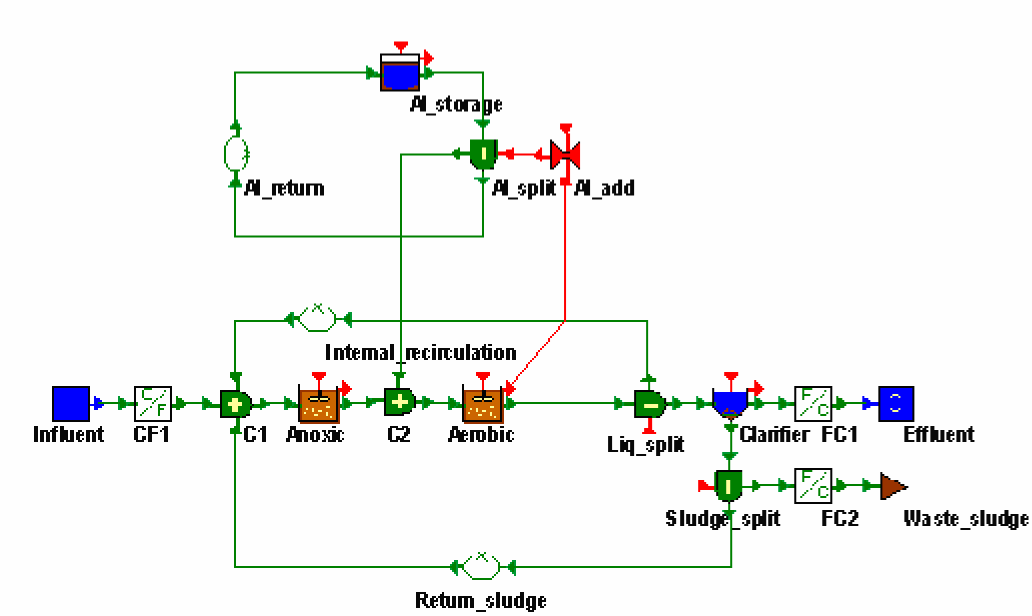

Figure 11. Implementation of the A/O with Al addition (A/O + Al) in WEST

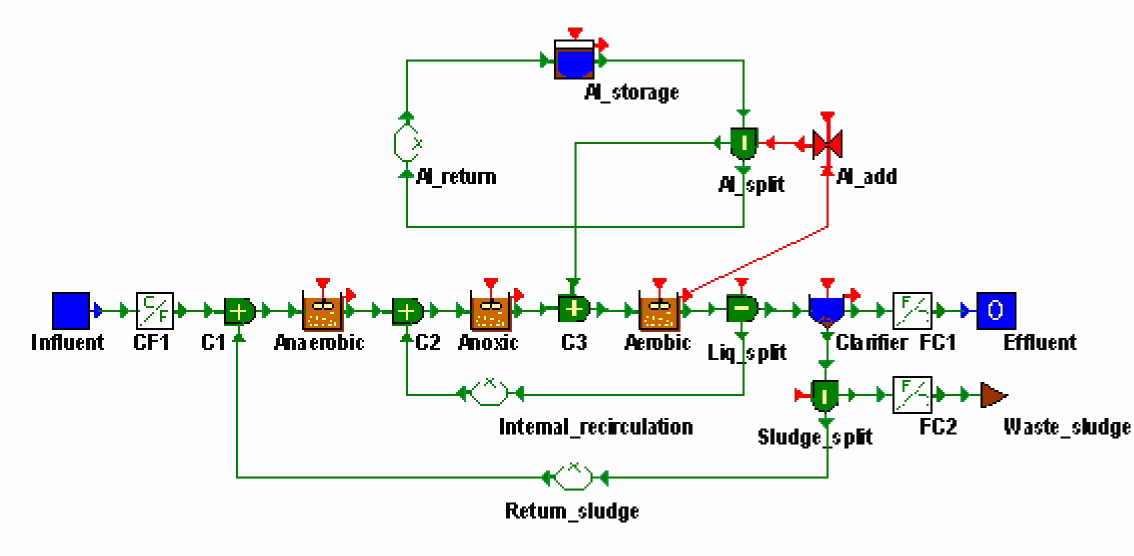

Figure 12. Implementation of the A/A/O with Al addition (A/A/O + Al) in WEST

Table 4 Cost estimation for the three adaptation configurations (TP limit 1.0 mg/l)

Capacity MGD			1	10	20	50	100
AS +Al	Capital cost 10^4\$		19.2	26.7	33.1	47.9	66.7
	O & M cost 10^4\$	Energy	0.07	0.24	0.35	0.03*	0.08*
		Labor	0.67	0.68	0.71	0.78	1.07
		Chemical	1.84	18.4	36.8	92.1	184
		Sludge disposal	1.07	10.7	21.4	53.6	107
		Maintenance & Insurance	1.15	1.60	1.99	2.87	4.00
	TAEC 10^4\$/y		6.48	34.0	64.2	154	302
	TP removed MT/y		2.28	22.8	45.6	114	228
	Unit cost for TP removal \$/kg		28.4	14.9	14.1	13.5	13.3
A/O + Al	Capital cost 10^4\$		58.7	209	327	618	1042
	O & M cost 10^4\$	Energy	1.44	14.0	27.9	69.0	138
		Labor	3.80	6.60	9.34	18.7	36.0
		Chemical	1.62	16.2	32.3	80.8	162
		Sludge disposal	1.03	10.3	20.7	51.7	103
		Maintenance & Insurance	3.52	12.5	19.6	37.1	62.5
	TAEC 10^4\$/y		14.9	77.8	138	311	592
	TP removed MT /y		2.20	22.0	44.0	110	220
	Unit cost for TP removal \$/kg		68.0	35.4	31.5	28.3	26.9
A/A/O + Al	Capital cost 10^4\$		70.6	228	346	629	1037
	O & M cost 10^4\$	Energy	1.63	15.9	31.6	78.3	157
		Labor	4.54	7.38	10.2	18.7	36.8
		Chemical	1.60	16.0	31.9	79.8	160
		Sludge disposal	1.03	10.3	20.6	51.5	103
		Maintenance & Insurance	4.24	13.7	20.8	37.7	62.2
	TAEC 10^4\$/y		19.2	83.0	145	321	609
	TP removed MT /y		2.21	22.1	44.1	110	221
	Unit cost for TP removal \$/kg		87.0	37.7	32.9	29.1	27.6

*For large plants the Al storage tank is located outdoors, thus saving on building energy costs.

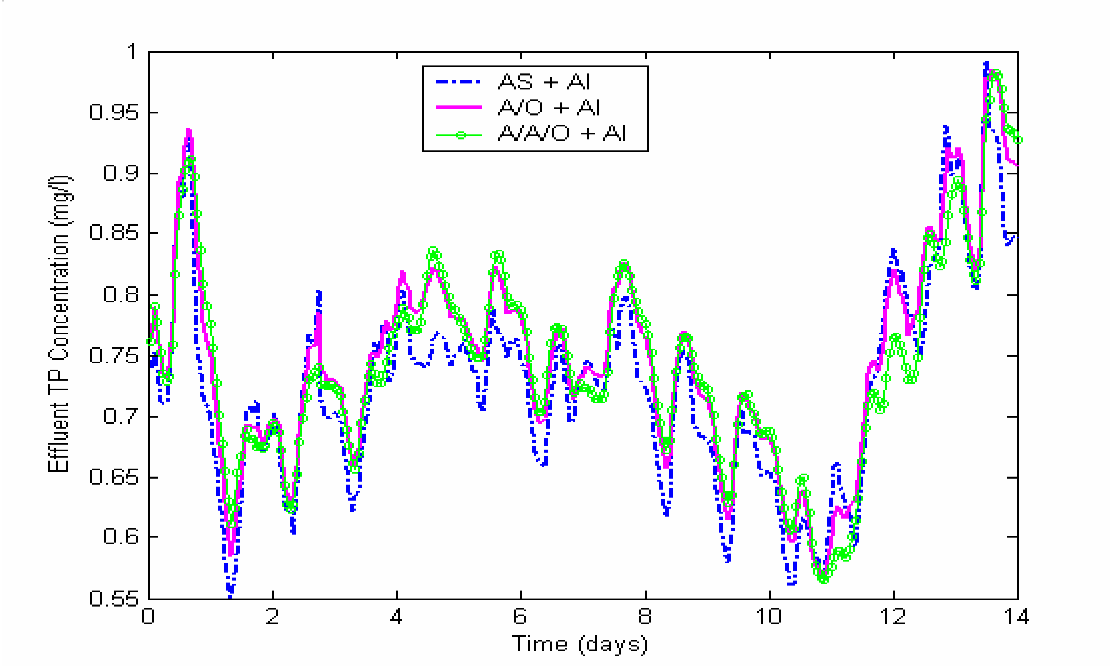

Figure 13. The simulated effluent TP concentration of the three configurations

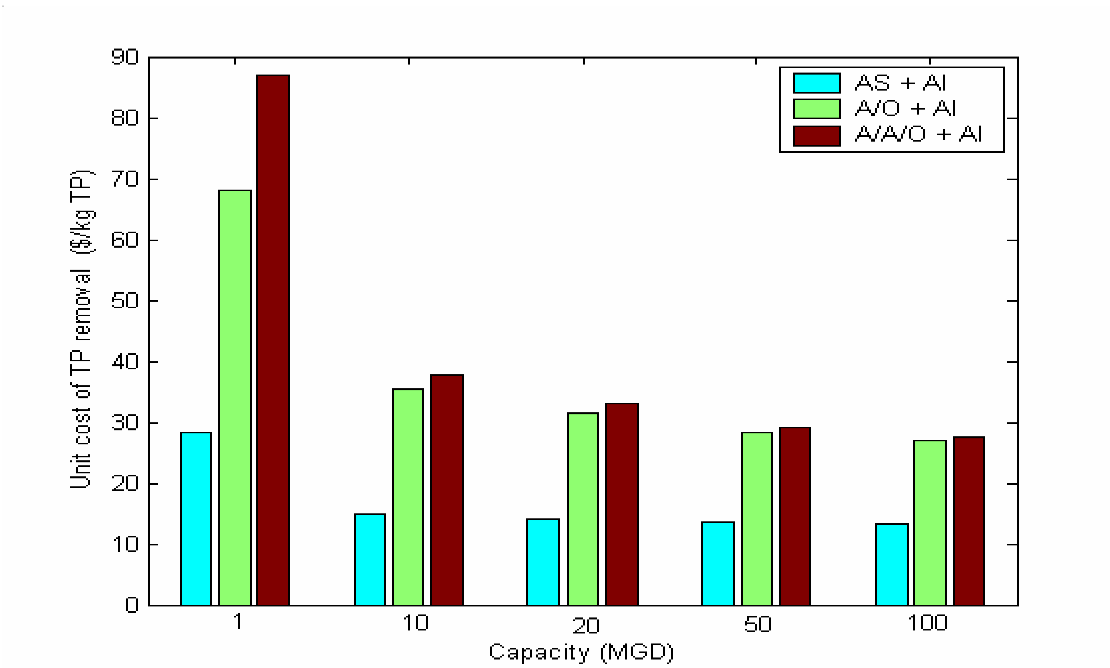

Figure 14. The unit cost of TP removal in the three adaptation configurations

The unit costs of TP removal and the incremental TAEC in the three configurations are given in Table 4 and Figures 14 and 15. As before, the costs of the AS

+ Al design are only 30 to 40 percent of those of the A/O and A/A/O designs, as a result of the substantial increase in the capital costs of these latter (relative to the previous upgrade that was considered). Again, the unit costs of TP removal in the three configurations decrease with the plant capacity. The rankings of unit costs of the three processes remain unchanged, as the increased capital costs of the A/O and A/A/O designs are too large to be offset by their relatively smaller consumptions of alum. Nevertheless, it is noted that the cost difference between the A/O and A/A/O configurations diminishes quickly as the plant capacity increases and becomes almost negligible when the plant capacity approaches 100 MGD.

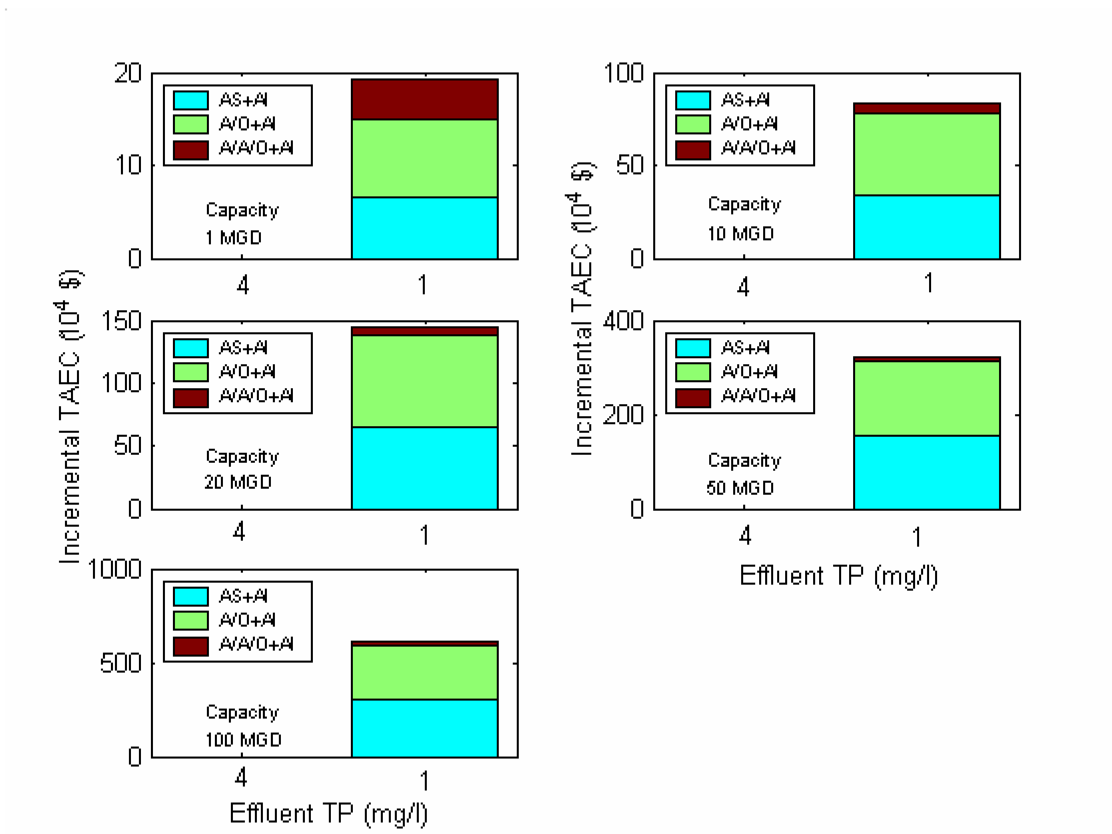

Figure 15. The incremental TAEC of the three adaptation configurations

5.3 Processes With Effluent TP Limit of 0.5 mg/l

When the effluent TP is to be lower than 0.5 mg/l, both the phosphorus in the water phase and that associated with particulate matter must be further lowered. In order to serve this purpose, more alum is added and a regular sand filter is installed to further remove solids from the effluent (Figures 16, 17, and 18). The filter must be backwashed when the solids retained within it exceed a threshold. If the backwash is performed with different rates and for different periods of duration, the performance of the filter may vary. In order to standardize the backwash procedure, we adopted the backwash duration and rate recommended by Qasim *et al* (2000) and kept them consistent throughout this research. In addition to the filter itself, some auxiliary equipment is also considered necessary: a rapid mixing and flocculation tank for the addition of polymer, filter backwash pumping facilities, a wash-water storage tank (WWST), and a wash-water surge basin.

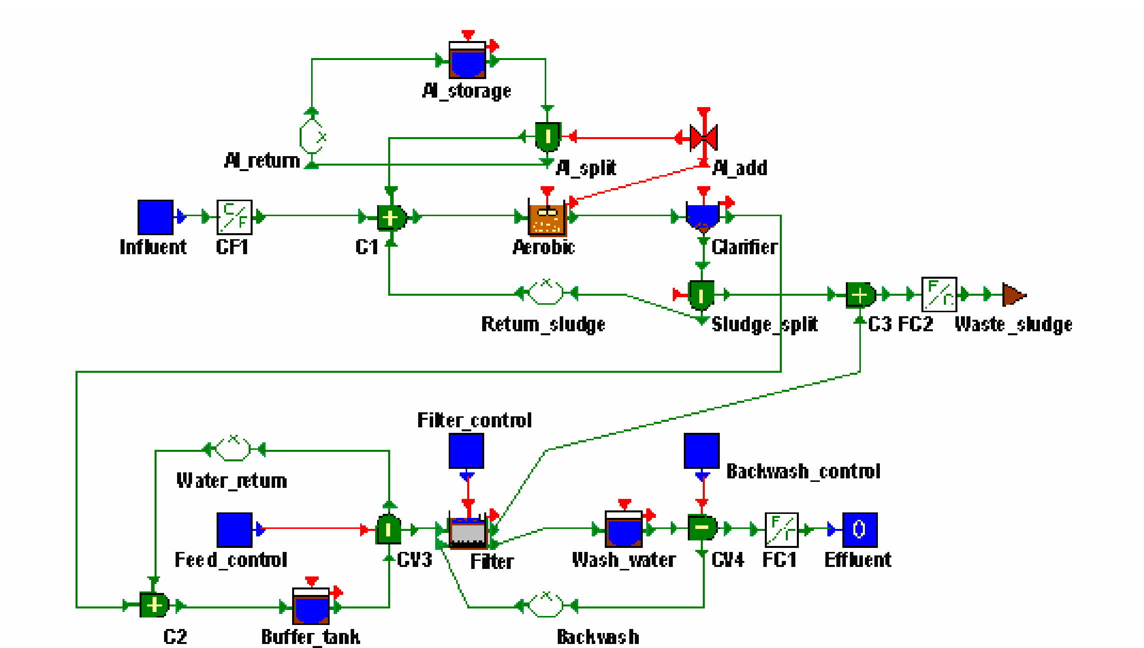

Figure 16. Implementation of AS with Al feed and filter (AS + Al + F) in WEST

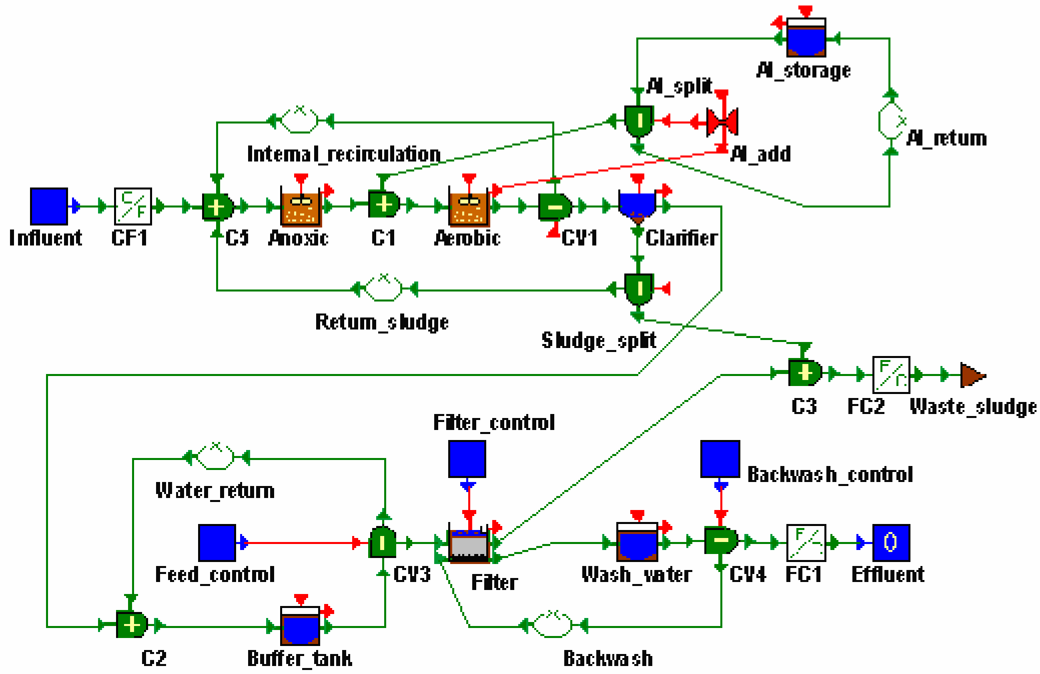

Figure 17. Implementation of A /O with Al feed and filter (A/ O + Al + F) in WEST

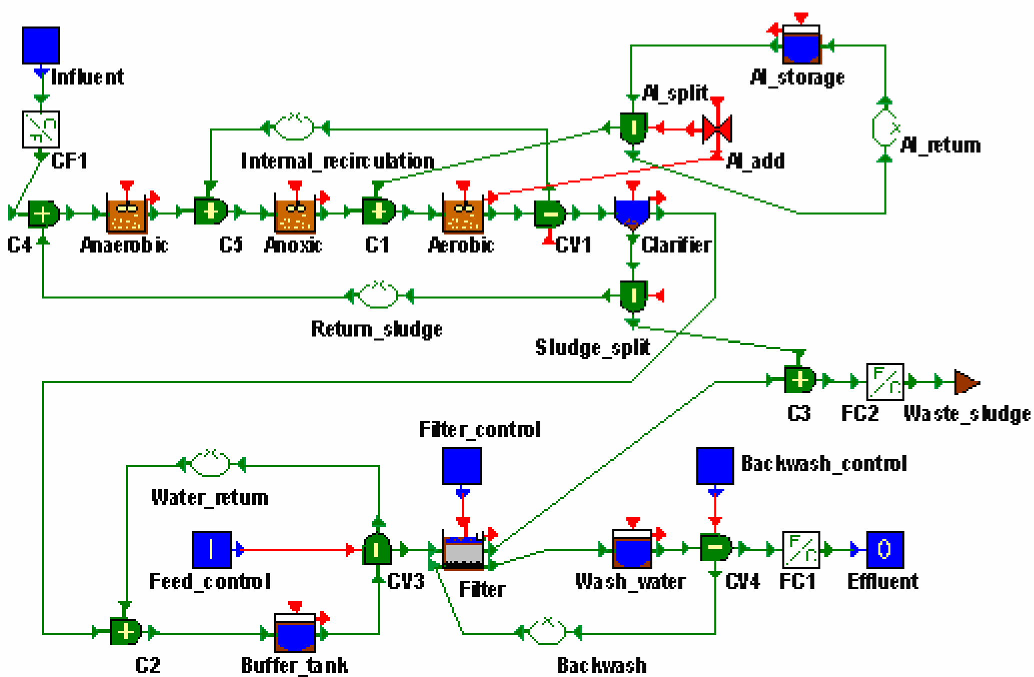

Figure 18. Implementation of A/A/O with Al feed and filter (A/ A/ O + Al + F) in WEST

Table 5 Cost estimation for the three adaptation configurations (TP limit 0.5 mg/l)

Capacity MGD			1	10	20	50	100
AS +Al + F	Capital cost 10^4\$		178	611	991	2122	4094
	O & M cost 10^4\$	Energy	0.98	7.08	14.6	36.4	71.6
		Labor	14.5	25.5	36.0	74.5	143
		Chemical	2.23	22.3	44.6	112	223
		Sludge disposal	2.60	26.0	52.1	130	260
		Maintenance & Insurance	10.7	36.7	59.4	127	246
	TAEC 10^4\$/y		46.5	171	293	665	1300
	TP removed MT/y		2.39	23.9	47.7	119	239
	Unit cost for TP removal \$/kg		195	71.6	61.4	55.8	54.5
A/O + Al +F	Capital cost 10^4\$		222	789	1285	2696	5073
	O & M cost 10^4\$	Energy	2.35	20.9	42.7	105	210
		Labor	17.6	31.4	44.6	92.3	177
		Chemical	2.08	20.8	41.6	104	208
		Sludge disposal	2.00	20.0	40.0	100	200
		Maintenance & Insurance	13.3	47.3	77.1	162	304
	TAEC 10^4\$/y		56.8	209	358	799	1542
	TP removed MT /y		2.39	23.9	47.9	120	239
	Unit cost for TP removal \$/kg		237	87.4	74.8	66.8	64.4
A/A/O + Al + F	Capital cost 10^4\$		234	808	1303	2707	5124
	O & M cost 10^4\$	Energy	2.54	22.7	46.4	115	228
		Labor	18.4	32.2	45.4	92.3	178
		Chemical	2.05	20.5	41.0	102	205
		Sludge disposal	2.00	20.0	40.0	99.9	200
		Maintenance & Insurance	1.40	48.5	78.2	162	307
	TAEC 10^4\$/y		64.8	214	365	808	1565
	TP removed MT /y		2.41	24.1	48.1	120	241
	Unit cost for TP removal \$/kg		269	89.0	75.8	67.1	65.1

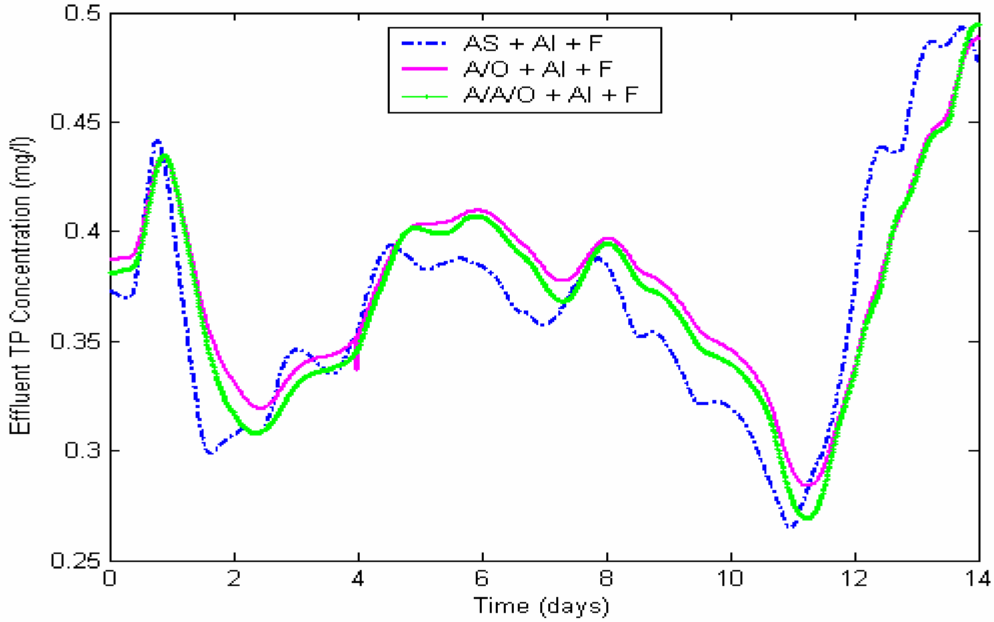

Figure 19. The simulated effluent TP concentration of the three configurations

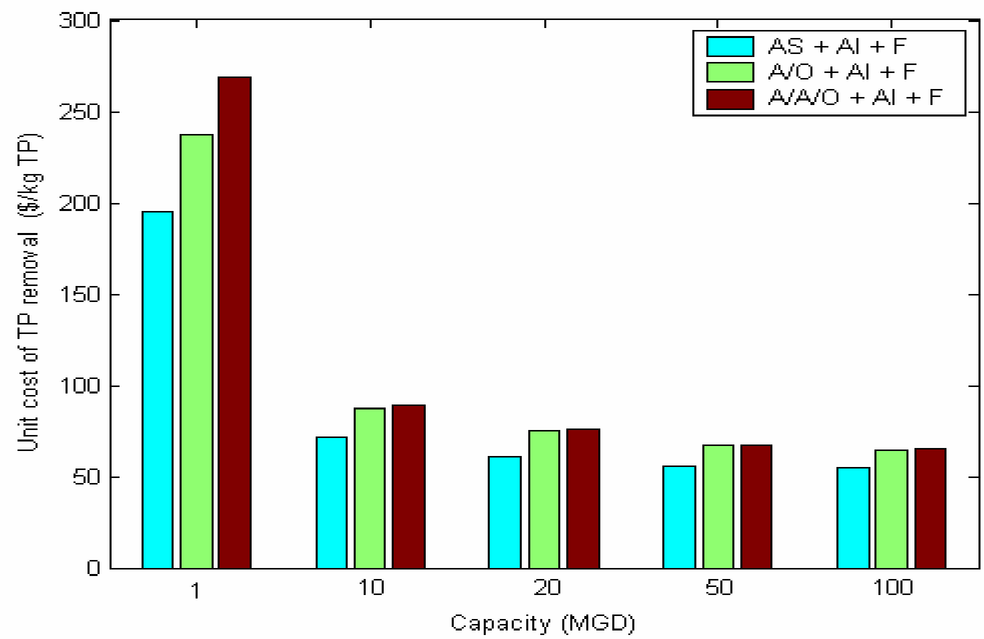

Figure 20. The unit cost of TP removal for the three adaptation configurations

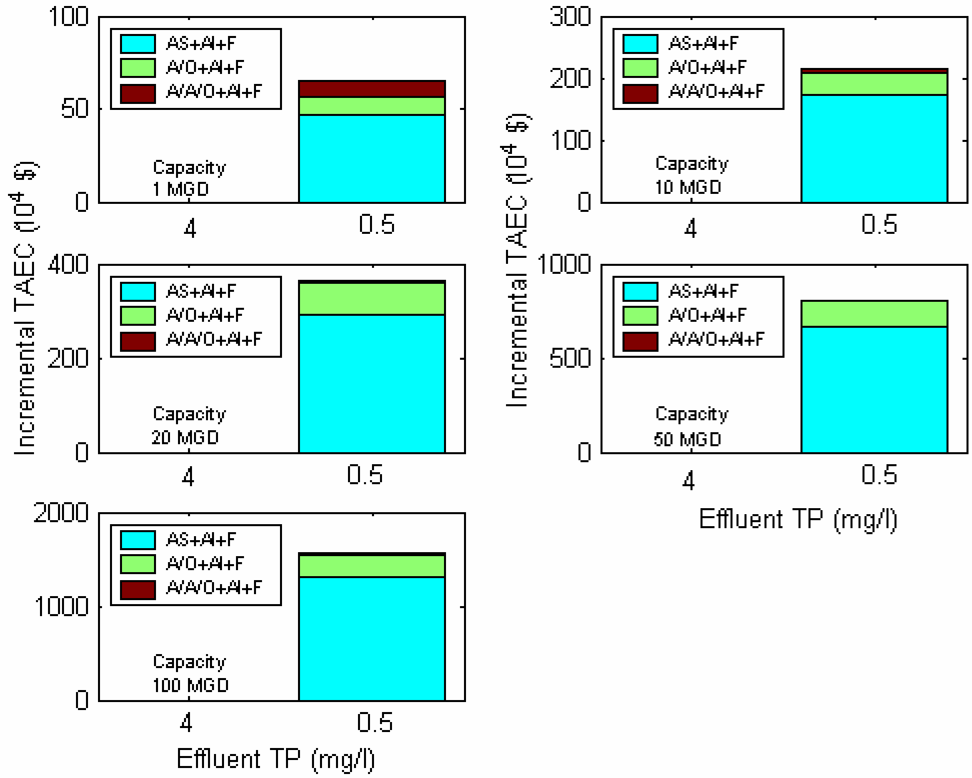

Figure 21. The incremental TAEC of the three adaptation configurations

The simulated effluent TP concentrations of Figure 19 demonstrate that the three configurations now have nearly identical performances, relative to Figures 13 and, especially, Figure 8, and noting the changes in scales across these three figures. Such similarity of performance results largely from the fact that similar amounts of alum addition are required and the removal of particulate-associated P has become critical.

The costs of the AS + Al + F configuration are still the lowest of the three options, although they have now risen to nearly 80 percent of the more costly alternatives. It is also noted that the unit cost of TP removal in the A/A/O process is still higher than that of the A/O process, although the difference nearly disappears as plant capacity increases.

5.4 Processes With Effluent TP of 0.13 mg/l

Using the same configurations as in the foregoing (for a limit of 0.5 mg/l), the addition of yet more alum will allow the plant to attain an effluent with a TP limit of 0.13

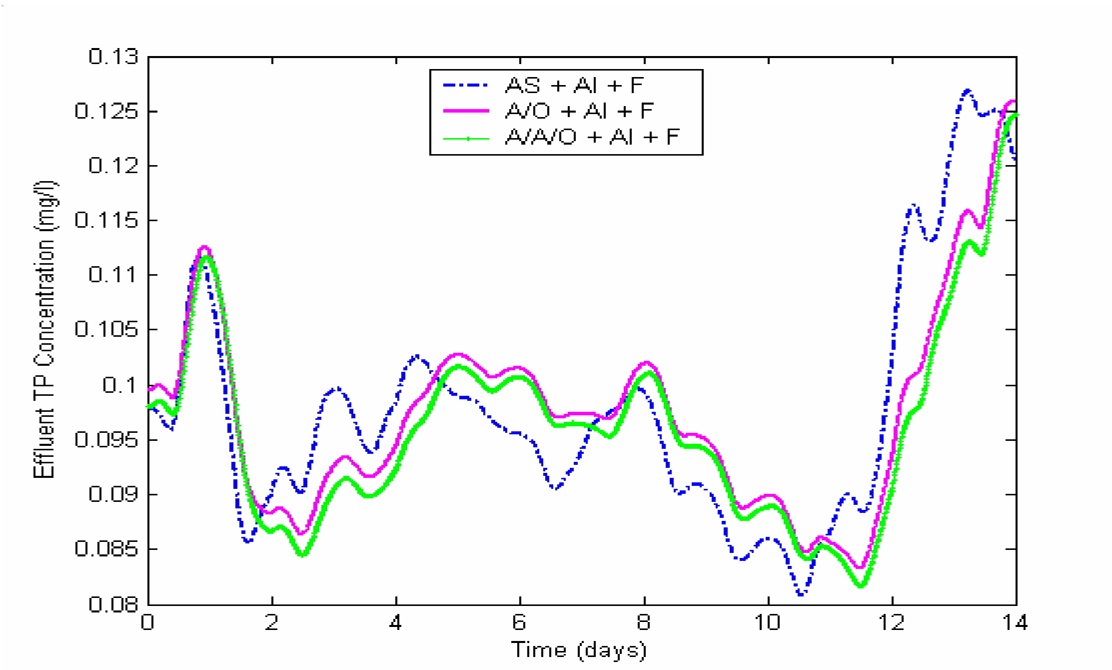

Figure 22. The simulated effluent TP concentration of the three configurations

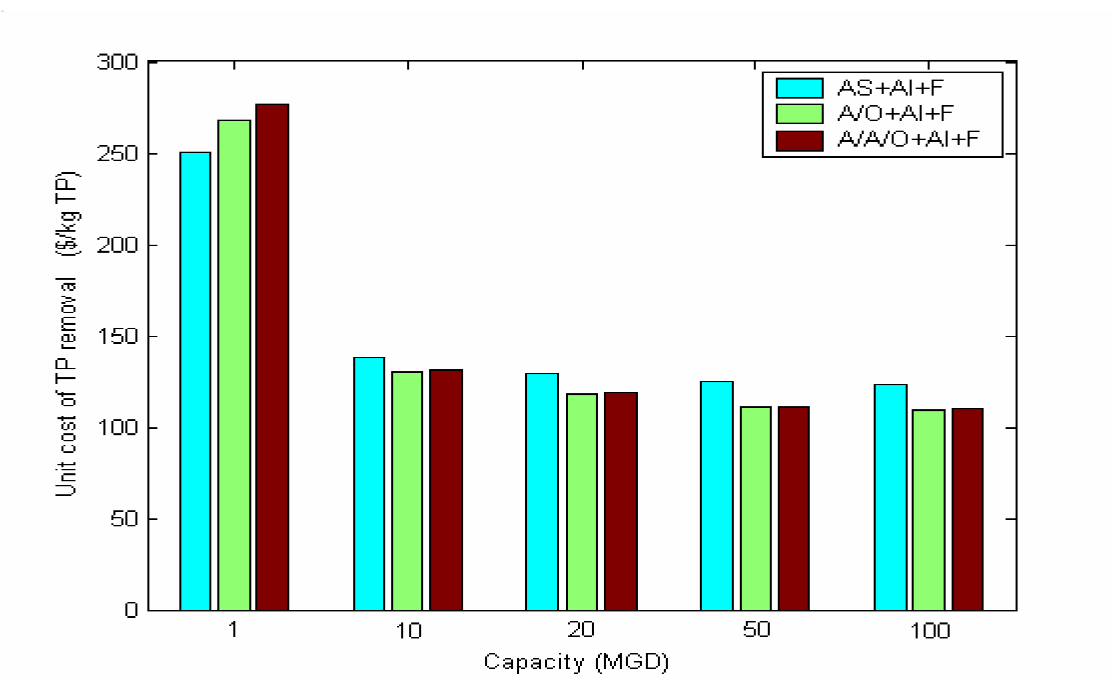

Figure 23. The unit cost of TP removal for the three adaptation configurations

Table 6 Cost estimation for the three adaptation configurations (TP limit 0.13 mg/l)

Capacity MGD			1	10	20	50	100
AS +Al + F	Capital cost 10^4\$		184	642	1043	2299	4417
	O & M cost 10^4\$	Energy	1.09	6.87	15.0	37.3	74.5
		Labor	14.5	25.8	36.4	77.1	148
		Chemical	13.8	138	275	688	1376
		Sludge disposal	10.6	106	213	532	1064
		Maintenance & Insurance	11.0	38.5	62.6	138	265
	TAEC 10^4\$/y		67.1	371	693	1672	3312
	TP removed MT/y		2.69	26.9	53.7	134	269
	Unit cost for TP removal \$/kg		250	138	129	125	123
A/O + Al + F	Capital cost 10^4\$		236	820	1326	2785	5258
	O & M cost 10^4\$	Energy	2.46	20.7	42.4	106	211
		Labor	17.6	31.6	45.8	94.2	181
		Chemical	10.1	101	202	505	1010
		Sludge disposal	7.88	78.8	158	394	788
		Maintenance & Insurance	14.1	49.2	79.5	167	315
	TAEC 10^4\$/y		72.8	353	643	1509	2964
	TP removed MT /y		2.72	27.2	54.4	136	272
	Unit cost for TP removal \$/kg		268	130	118	111	109
A/A/O + Al + F	Capital cost 10^4\$		248	839	1344	2796	5309
	O & M cost 10^4\$	Energy	2.65	22.5	46.2	115	230
		Labor	18.4	32.4	46.7	94.2	182
		Chemical	10.0	100	200	500	1001
		Sludge disposal	7.85	78.5	157	392	785
		Maintenance & Insurance	14.9	50.3	80.6	168	319
	TAEC 10^4\$/y		75.3	357	648	1514	2978
	TP removed MT /y		2.72	27.2	54.3	136	272
	Unit cost for TP removal \$/kg		277	131	119	111	110

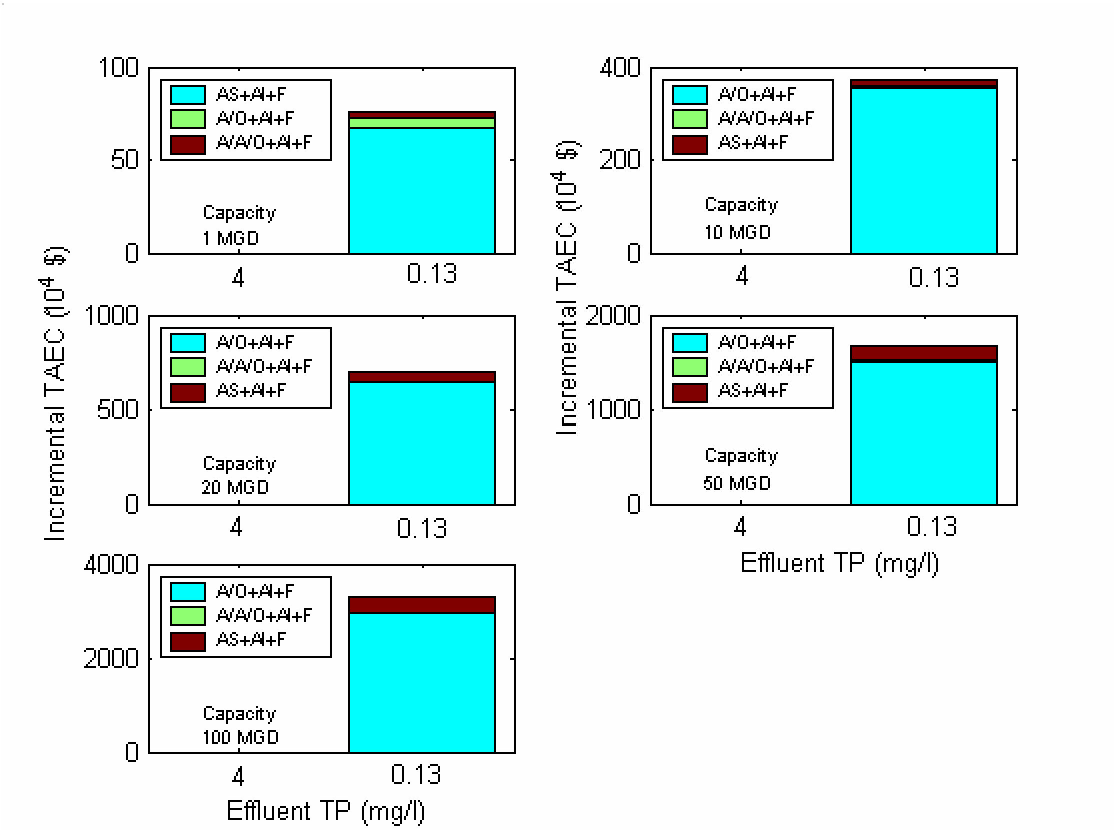

Figure 24. The incremental TAEC of the three adaptation configurations

mg/l, as indicated by the simulation results of Figure 22. The three configurations also have similar pattern of effluent TP. However, we now see that – on the basis of the unit costs of TP removal – the AS + Al + F design has lost its apparent cost-competitiveness. Indeed, as the plant capacity rises above 10 MGD, the unit cost of TP removal for the A/O + Al + F design becomes the lowest, as a result of the lower chemical and energy consumption and lower amounts of labor required.

5.5 Processes With Effluent TP Below 0.05 mg/l

Under this last, most rigorous condition, the effluent TP is to be below 0.05 mg/l, with the consequence that the effluent total suspended solids concentrations have to be reduced to below 1 mg/l. In order to exhaust the solids from the effluent, ultra-filtration is adopted in all three configurations (Figures 25, 26, and 27); this is in line with the dramatically increasing popularity of membrane treatment, the costs of which have been falling (Morin, 1994). However, because there are no models for ultrafiltration units in the WEST software platform, it has here been simulated as a modification of a sand filter model, following the work of Drouiche *et al* (2001). As in the operation of the sand filter, the backwash of the ultra-filter is also simulated as a purely physical process. The backwash with chemicals was not simulated, but the relative cost was estimated with the results of Drouiche *et al* (2001). Because the amount of alum that has to be added to the plants is significantly larger than in the previous upgrades (to the relatively lower standards), an additional clarifier was introduced into the designs for the purpose of sedimentation of the alum sludge. Furthermore, a dual-point addition was employed for the alum dosing, since this can improve the removal of phosphorus significantly, without increasing the overall alum dosage (USEPA, 1987). The costs of ultra-filtration are estimated according, in part, to the research conducted by Drouiche e*t al* (2001) and, in part, from details provided by the Ionics company (Russell, 2004).

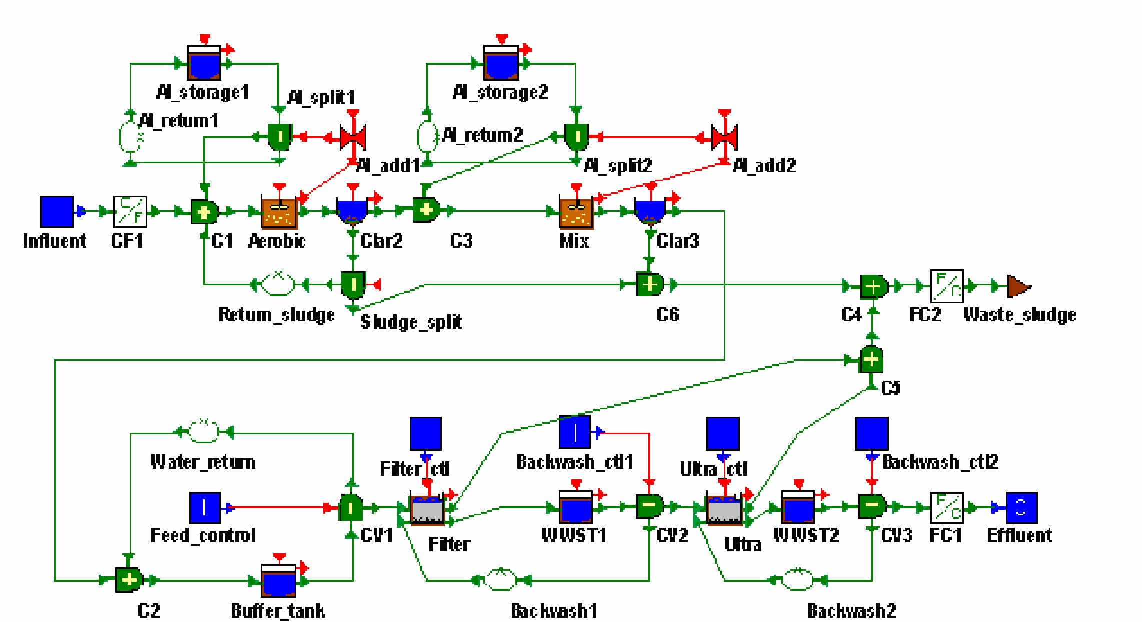

Figure 25. Implementation of AS with Al feed, tertiary clarifier, filter and ultra-filter (AS + Al + S + F + UF) in WEST

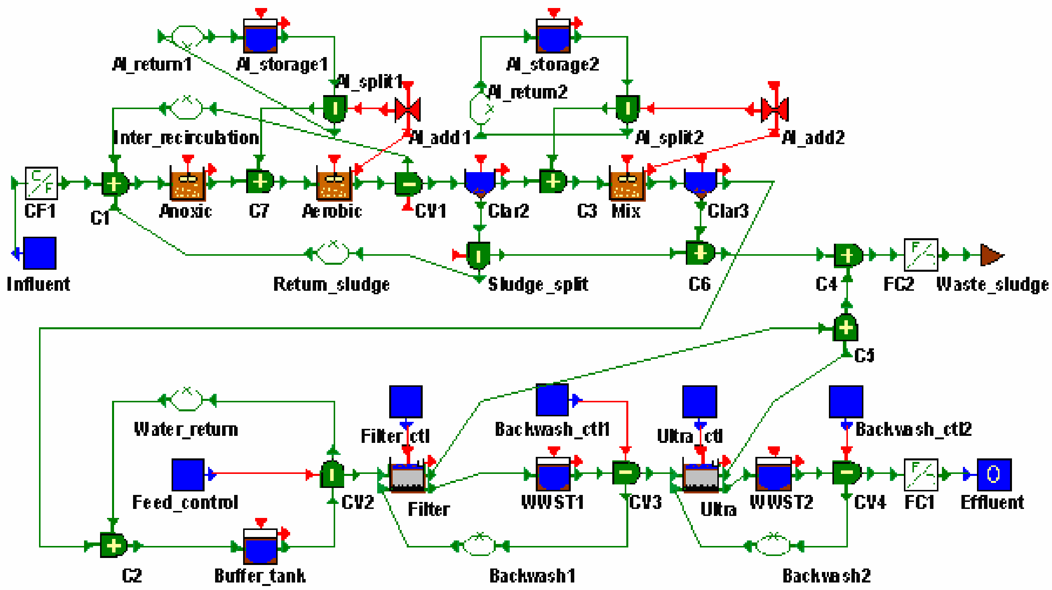

Figure 26. Implementation of A/O with Al feed, tertiary clarifier, filter and ultra-filter (A/O + Al + S + F + UF) in WEST

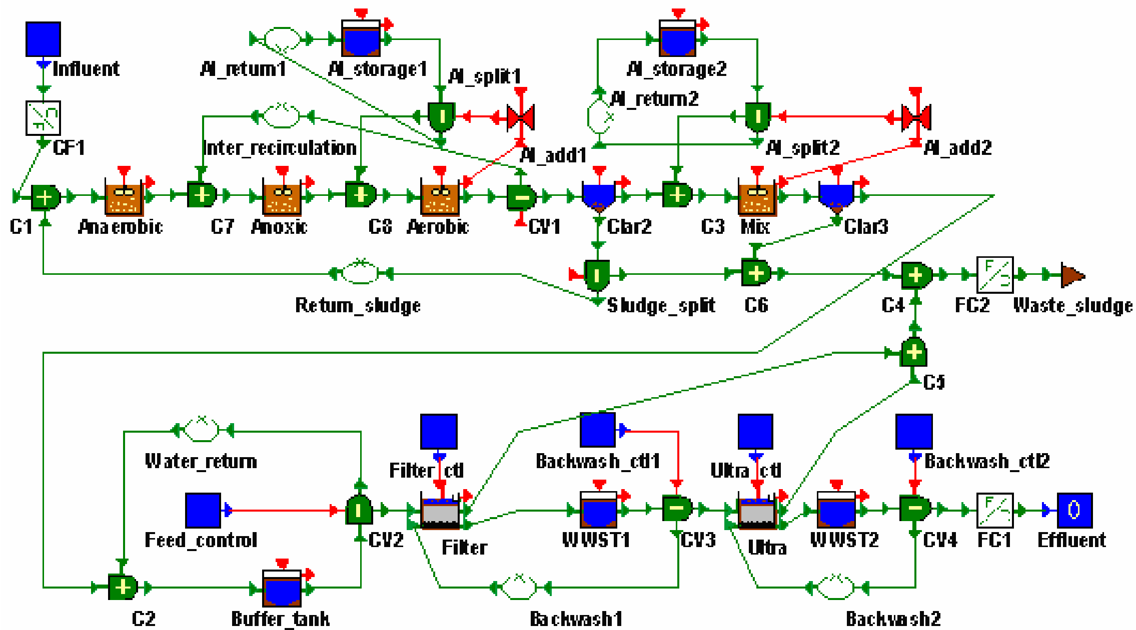

Figure 27. Implementation of A/A/O with Al feed, tertiary clarifier, filter and ultra-filter (A/A/O + Al + S + F + UF) in WEST

Table 7 Cost estimation for the three adaptation configurations (TP limit 0.05 mg/l)

Capacity MGD			1	10	20	50	100
AS + Al + S + F + UF	Capital cost 10^4\$		341	1375	2287	4468	8158
	O & M cost 10^4\$	Energy	3.92	34.2	69.1	168	335
		Labor	25.8	43.3	60.7	114	210
		Chemical	16.2	162	324	811	1621
		Sludge disposal	11.3	113	225	563	1126
		Maintenance &Insurance	20.4	82.5	137	268	489
	TAEC 10^4\$/y		107	555	1016	2314	4493
	TP removed MT/y		2.78	27.8	55.6	139	278
	Unit cost for TP removal \$/kg		387	200	183	167	162
A/O + S + Al + F + UF	Capital cost 10^4\$		384	1560	2570	5848	9110
	O & M cost 10^4\$	Energy	5.29	48.1	96.9	238	474
		Labor	28.9	49.1	69.3	133	244
		Chemical	14.9	149	298	746	1492
		Sludge disposal	9.92	99.2	198	496	992
		Maintenance &Insurance	23.1	93.6	154	302	547
	TAEC 10^4\$/y		116	575	1041	2353	4543
	TP removed MT /y		2.78	27.8	55.6	139	278
	Unit cost for TP removal \$/kg		416	207	187	169	163
A/A/O + Al + S + F + UF	Capital cost 10^4\$		396	1579	2589	5045	9161
	O & M cost 10^4\$	Energy	5.47	49.9	101	247	493
		Labor	29.7	49.9	70.2	131	248
		Chemical	14.6	146	292	729	1458
		Sludge disposal	9.71	97.1	194	486	971
		Maintenance &Insurance	23.8	94.8	155	303	550
	TAEC 10^4\$/y		118	575	1038	2335	4516
	TP removed MT /y		2.78	27.9	55.7	139	279
	Unit cost for TP removal \$/kg		423	206	186	168	162

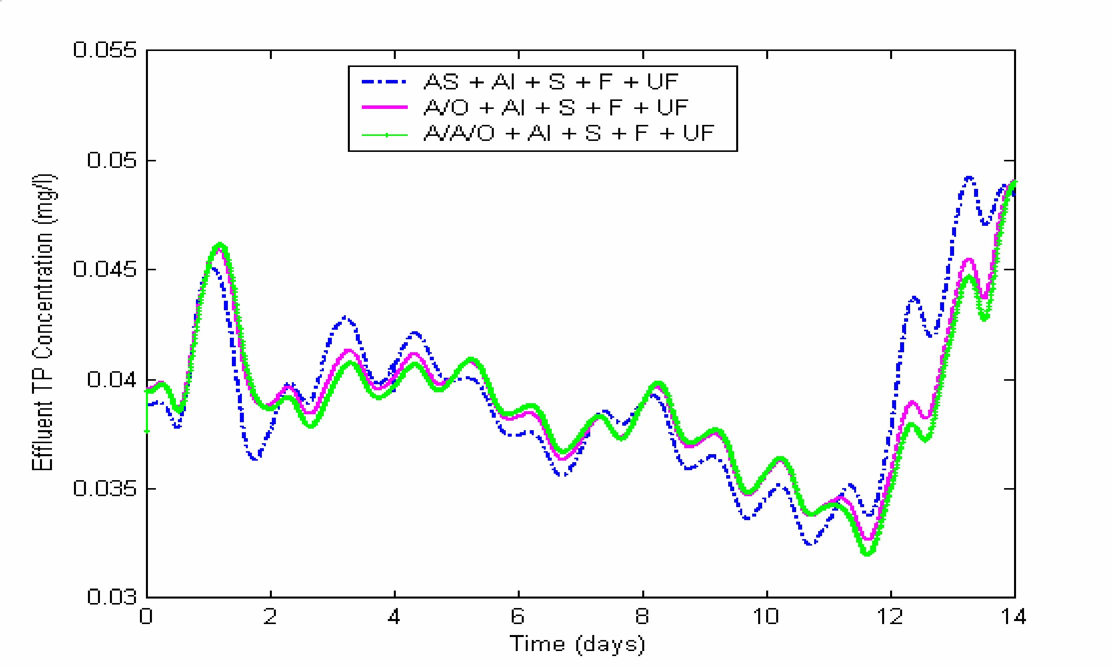

Figure 28. The simulated effluent TP concentration of the three configurations

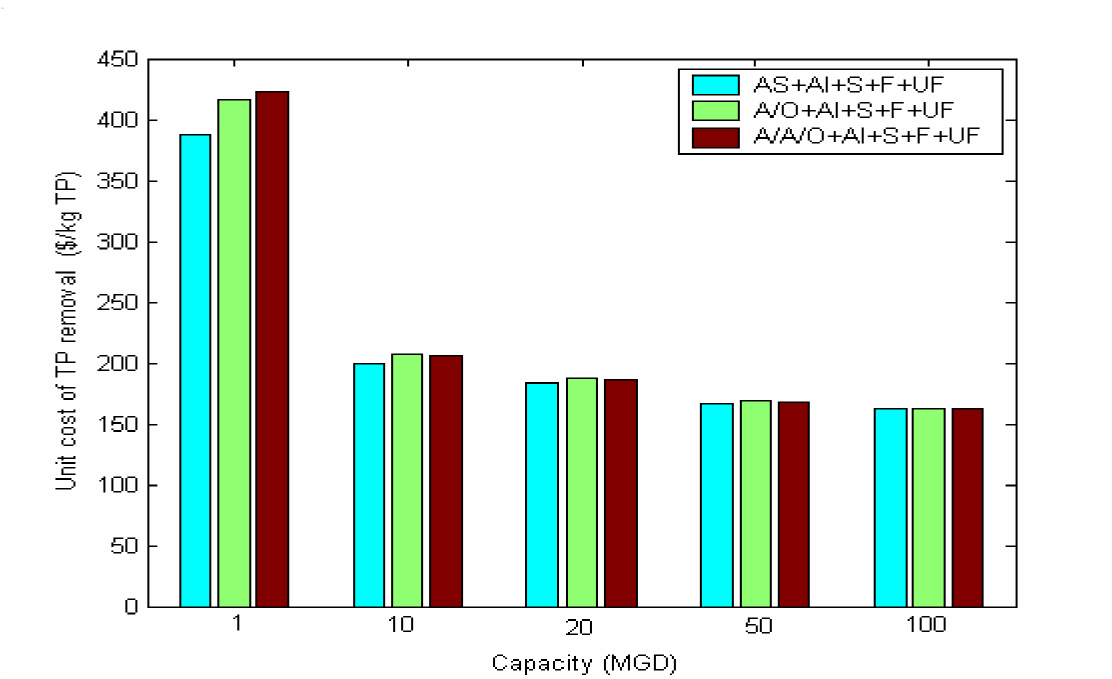

Figure 29. The unit cost of TP removal in the three adaptation configurations

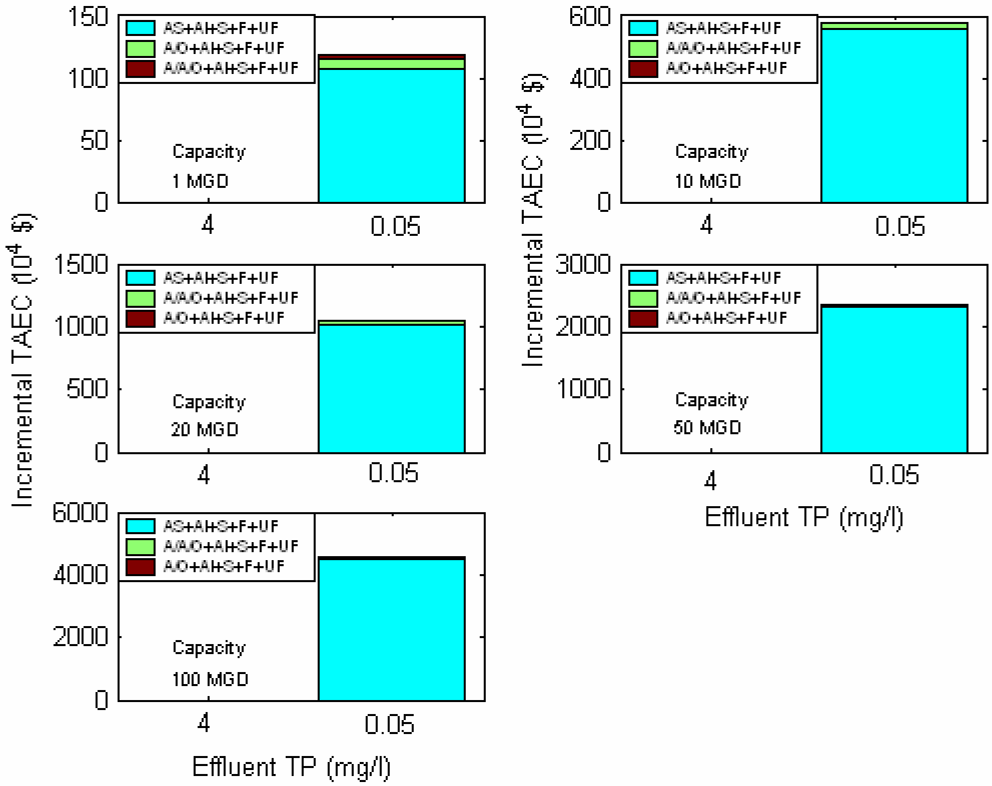

Figure 30. The incremental TAEC of the three adaptation configurations

The effluent TP concentrations of the three configurations are essentially identical, as one would expect (Figure 28). With regard to costs, judged on the basis of the unit cost of TP removal, all three strategic paths of upgrade (from the basic reference activated sludge) are more or less identical, although the AS + Al + S + F + UF process has a marginal advantage over the other alternatives when the plant capacity is lower than 20 MGD.

5.6 Summary and Overview

The incremental TAEC of all the upgrades of the preceding five sections, i.e., the upgrading of performance from the base case to any of the five tighter effluent TP standards, is summarized in Figure 31. All the configurations are simply classified into just the three strategic types considered herein, namely the AS + Al, A/O, and A/A/O designs. The ancillary devices and additional unit processes incorporated at the various levels of upgrade, such as filter, clarifier, and so forth, are not indicated in the diagram

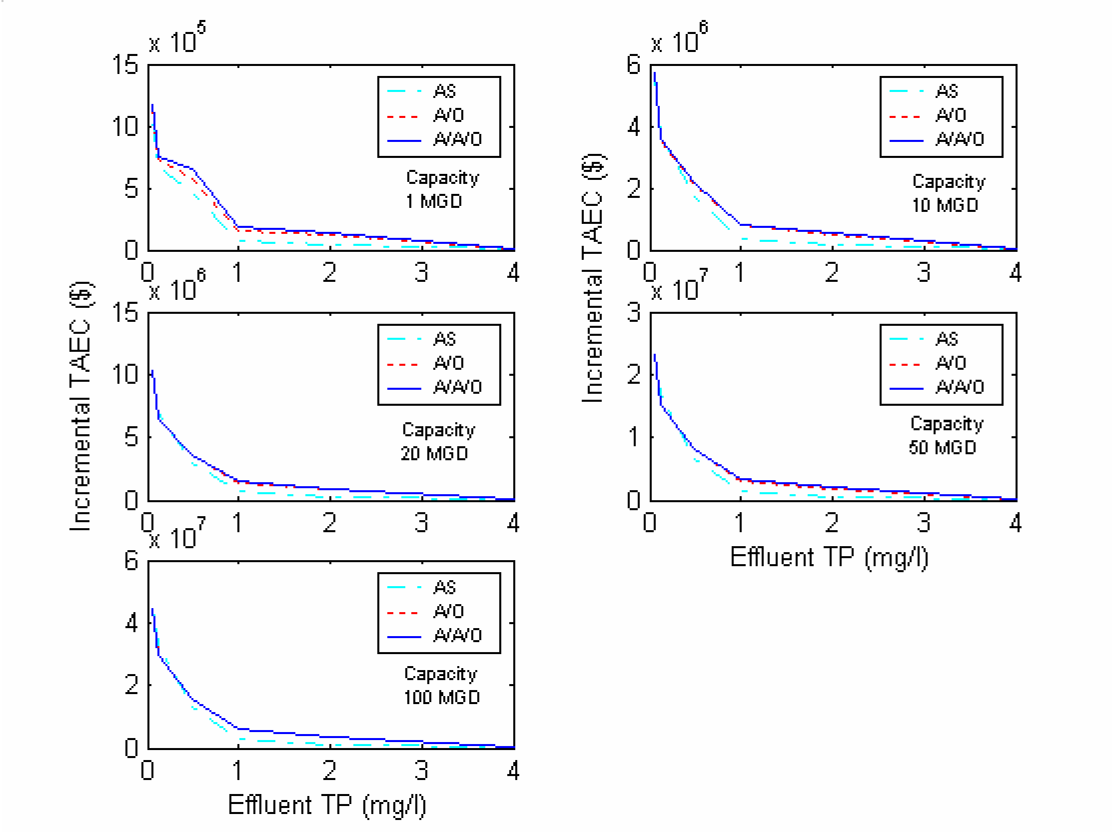

Figure 31. The incremental TAEC of all the upgrade adaptations

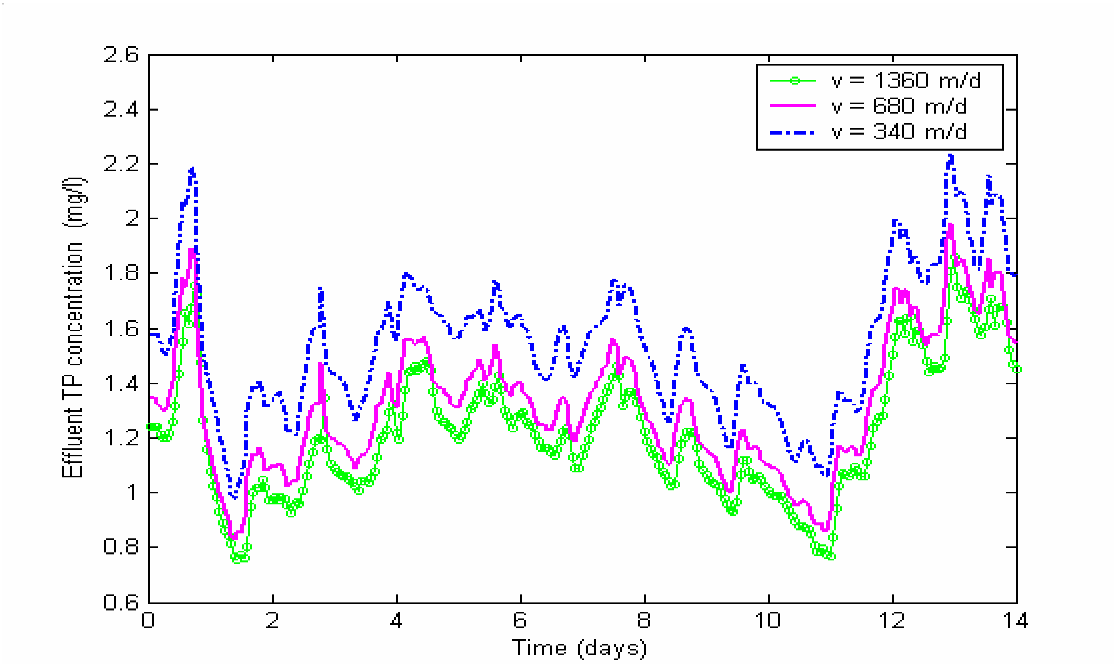

Figure 32. The effluent TP concentration for AS + Al under different sludge settling rates

for reasons of clarity. It is apparent that the incremental TAEC increases with increasing plant capacity, but this increase is not proportional to capacity, as a result of economies of scale. Another trend is for the incremental TAEC to increase with the increasing TP removal rate. However, the cost increase is clearly not proportional to the concentration decrease, such that marginal costs of removal increase dramatically. It is also noted that the difference among the three configurations diminishes as plant size increases. A significant difference between the A/O and A/A/O process is not evident at all scales.

The narrowness of the economic differences among the three options, and a potential sensitivity to changing cost structures, could be significant in terms of choosing one form of upgrade over another, in particular, when issues of model and cost uncertainties are taken into account, together with considerations of eventual operational reliability (for a much wider span of operating conditions than have been considered in this preliminary study). For example, the performance of the AS + Al alternative may vary considerably with the operation of the clarifier. If the settling of sludge in the clarifier is enhanced by adding polymer or other chemicals, the TSS concentration of the effluent will be lower, and the effluent TP concentration will also be lower (Figure 32). Thus, the TP removal will be higher and the unit TP removal cost will be lower, assuming the cost of the polymer is not excessive. In contrast, if the settling rate were to be reduced by the culture of excessive amounts of filamentous bacteria, the sludge settling would be slower, and the TP removal cost (for the same rate of removal) would increase.

Another important factor affecting the costs of TP removal is the cost of alum. It appears that currently this typically spans the range of \$0.08 to \$0.24 per kilogram, with therefore a mean cost of \$ 0.16/kg, which accordingly has been adopted herein. However, the results of a sensitivity analysis (Figure 33) show that for the larger capacity plants, the unit costs of TP removal can be of the order of +/- 50% higher for the upper and lower bounds of the unit costs of alum (in this case for the AS + Al design, when upgraded to the 2 mg/l limit). In other respects, the costs of sludge disposal may increase in the near future, as suitable landfill locations diminish. If the sludge has to be transported to more distant locations or be recycled, e.g., by acidifying the sludge and extracting the alum

(Bishop *et al*, 1991), costs could rise very rapidly and markedly so. Under such circumstances, the cost of the AS + Al design strategy may become prohibitively high, so that one might not want to commit to it now, since in 5 years' time the A/O and A/A/O alternatives might be much more promising, longer-term strategies. When selecting optimum paths of adaptation, especially when upgrading in more than just a single step, such uncertainties ought desirably to be taken into account.

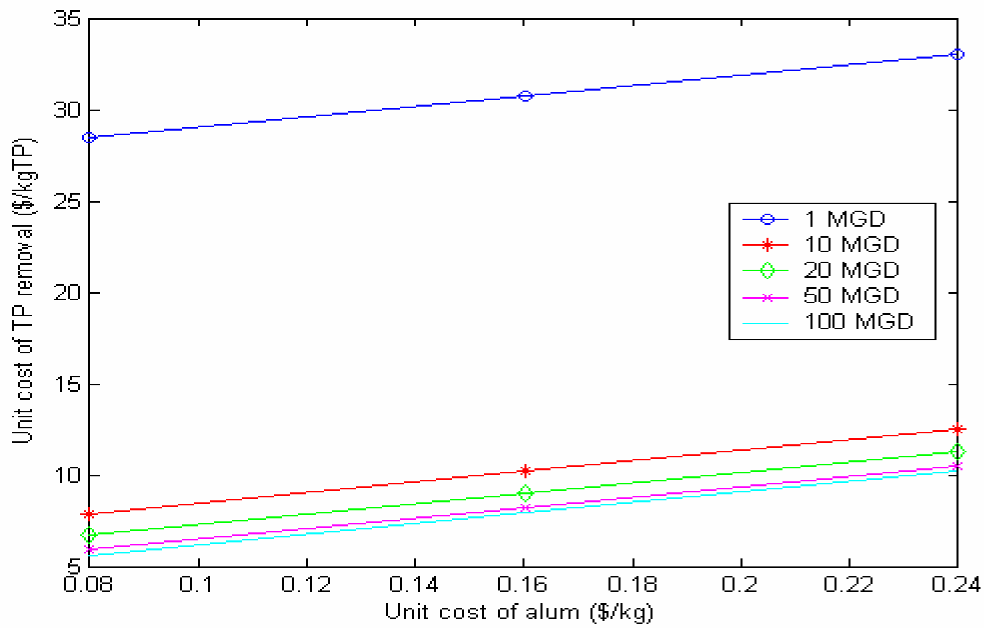

Figure 33. The unit cost of TP removal (AS + Al under TP limit of 2 mg/l)

Last, but not least, another facet of the decision of which design configuration to select is that of the objective of the treatment process. In our present research, only phosphorus removal has been considered. If it were the case that nitrogen likewise was to be successfully removed at the same time, the AS + Al configuration might appear to be relatively costly, since it cannot in general achieve the same higher rates of nitrogen removal (through biological nitrification-denitrification) as the A/O and A/A/O designs.

6. CONCLUSIONS

In this, our second report on estimating the costs of phosphorus removal in point-source discharges, the costs of adapting existing wastewater treatment facilities to various higher levels of performance have been computed on the basis of simulation exercises.

For these exercises we have employed the WEST software platform, which has greatly accelerated completion of this preliminary phase of our studies. Our computations have employed industry-standard models of the relevant unit processes of wastewater treatment, suitably calibrated and implemented according to typical Georgia facility operations. We have also followed the "benchmarking" procedures recommended for using such models for our research.

A basic activated-sludge system has been taken as the reference plant for current operations. From this basis, several different possible paths of adaptation to higher levels of performance, ranging across total phosphorus (TP) concentrations in the plant effluent of between 0.05 and 2 mg/l, have been simulated and their costs estimated. Thus, under TP limits of between 0.5 and 2.0 mg/l, the AS + Al (with or without ancillary devices) is the most economical. These results are in agreement with the findings of Schulz *et al* (2002), who demonstrated that the unit costs of phosphorus removal are lower in plants with chemical precipitation, due mainly to the higher capital costs of installing the anaerobic tank volume required for upgrading the companion biological processes of P removal. However, under the TP limit of 0.13 mg/l, the AS + Al + F process is only economical for a small plant (1 MGD), whereas the A/O + Al + F and A/A/O + Al + F designs are more cost-effective as the plants become larger (> 10MGD). For the most strict TP limit of 0.05 mg/l, the difference between the three configurations is marginal, although the AS + Al + S + F + UF design seems just a little more economical than the alternatives in a small plant.

Much more could be done to further the lines of research opened up herein and in our first report (Jiang *et al*, 2004). We have noted the various assumptions we have had to make, all of which require assessment, including the estimates of the crude sewage composition in Table 1, which may be a source of significant uncertainty. It is clear that the current line of research must be extended to an evaluation of the robustness of the cost estimates under uncertainty. Furthermore, as we recall the wider context in which this study is set, that of an offset banking mechanism for pollutant trading, it will especially important for cost estimates from the various published sources to be compared on a *consistent* basis. Again, in this wider setting, it is important not to lose sight of the fact that wastewater treatment systems are employed to remove constituents other than just phosphorus.

Beyond these more general observations, a number of other points should be noted with regard to the limited scope of our studies. First, all of the costs of adaptation refer to an upgrade in performance implemented in just a single step: from the base case to the specified (final) target. Second, strategic alternatives may exist outside the three considered in this report. Third, the simulation exercises ought ideally to be carried out for much longer periods, to cover both dry- and wet-weather conditions, as well as seasonal variations. Since the conditions reflected in the sequence of crude-sewage variations of the present study were those of dry weather, in the absence of process upsets, it is likely that our cost estimates may err on the side of being under-estimates. Fourth, the design for both chemical and biological phosphorus removal is capable of optimization, i.e., in respect of the different sites for alum addition, and the optimum combination of aeration, sludge wastage, and volumes of anaerobic and anoxic tanks. Last, but not least, operational practices can be optimized, such as, for example, through better control of the dissolved oxygen regime, the influent step-feed pattern, and so on. It is of great interest to examine the scope for minimizing the costs of adaptation through costly reconstruction by maximizing innovations of instrumentation, control, and automation, especially as operational costs rise and system reliability becomes more important (Beck, 2005).

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