Is an Upgrade Really Necessary?

If your treatment plant was built based on the 10 States Standards, dynamic modeling may show that it still has capacity to spare

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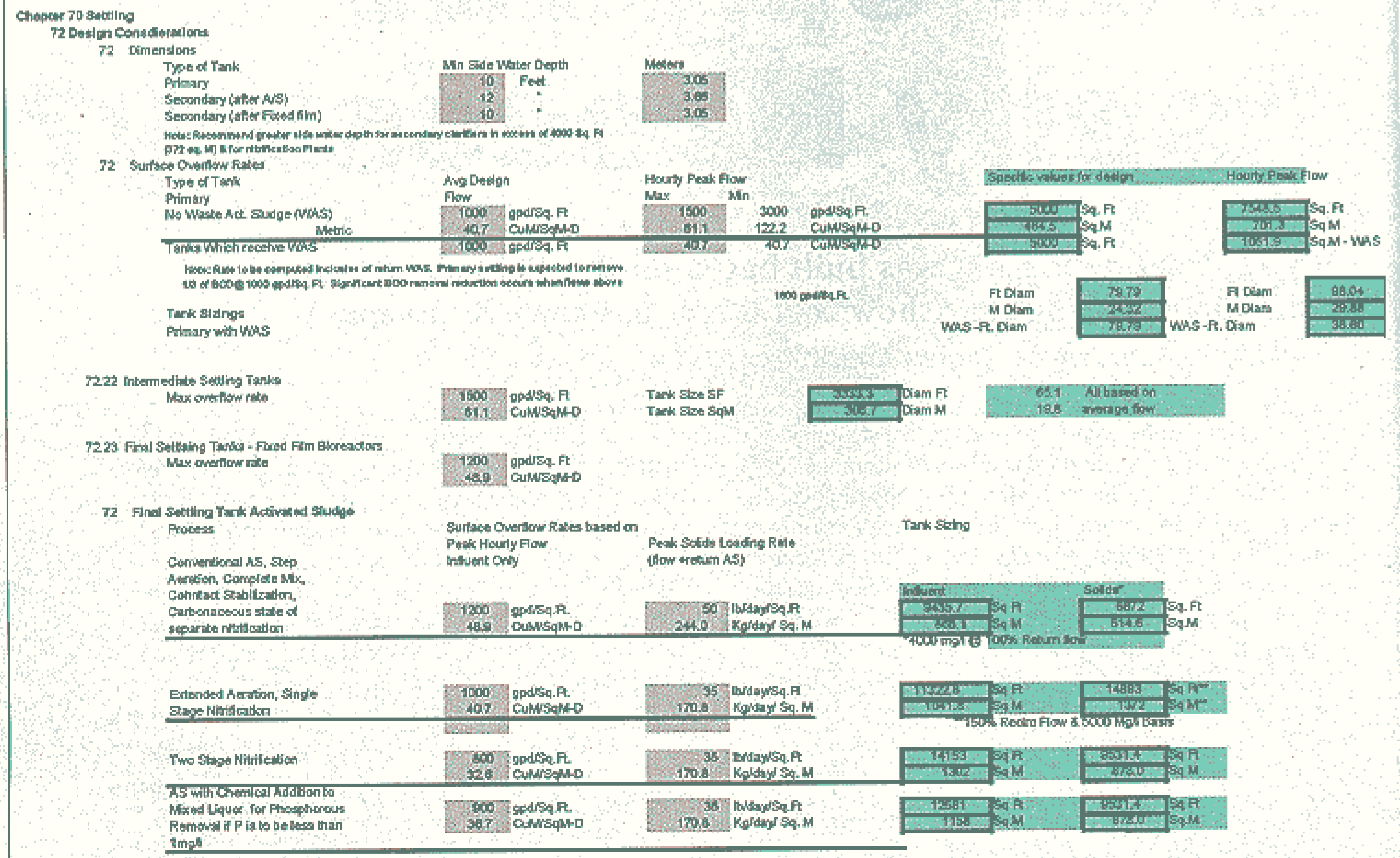
If your wastewater treatment plant was designed based on the Ten States Standards and some additional safety factors, it is extremely hydraulically and biologically underloaded. So before considering an expansion, try using dynamic modeling to evaluate your plant, because more capacity may be available through efficient use of existing facilities.

Dynamic modeling can be used to develop information about the behavior and performance of almost any wastewater treatment plant configuration and set of design conditions, including modeling the effects of infiltration, stormwater, slugs, and toxic shocks. Such models enable engineers to evaluate treatment plant designs before construction begins, investigate the effects of modified plant operations, and optimize plant performance.

Model Standards?

Developed by the Great Lakes and Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, the *Recommended Standards for Wastewater Facilities* (commonly known as the Ten States

Figure 1. Example of Design Summary Spreadsheet



Chapter 70 Settling
72 Design Considerations
72 Dimensions

Type of Tank	Min Side Water Depth		Meters
Primary	10	Feet	3.05
Secondary (after A/S)	12	"	3.66
Secondary (after Fixed film)	10	"	3.05

Note: Recommend greater side water depth for secondary clarifiers in excess of 4000 Sq. Ft (372 sq. M) & for nitrification Plants

72 Surface Overflow Rates

Type of Tank	Avg Design Flow		Hourly Peak Flow Max	Min		Specific values for design		Hourly Peak Flow	
Primary									
No Waste Act. Sludge (WAS)	1000	gpd/Sq. Ft	1500	3000	gpd/Sq.Ft.	5000	Sq. Ft	7546.5	Sq. Ft
Metric	40.7	CuM/SqM-D	61.1	122.2	CuM/SqM-D	464.5	Sq.M	701.3	Sq.M
Tanks Which receive WAS	1000	gpd/Sq. Ft	40.7	40.7	CuM/SqM-D	5000	Sq. Ft	1061.9	Sq.M - WAS

Note: Rate to be computed includes of return WAS. Primary settling is expected to remove 1/3 of BOD@ 1000 gpd/Sq. Ft. Significant BOD removal reduction occurs when flows above 1600 gpd/Sq.Ft.

Tank Sizings
Primary with WAS

Ft Diam	79.79		Ft Diam	98.04
M Diam	24.32		M Diam	29.88
WAS -Ft. Diam	79.79	WAS -Ft. Diam		36.80

72.22 Intermediate Settling Tanks

Max overflow rate							
1500	gpd/Sq. Ft	Tank Size SF	3533.3	Diam Ft	65.1	All based on
61.1	CuM/SqM-D	Tank Size SqM	306.7	Diam M	19.8	average flow

72.23 Final Settling Tanks - Fixed Film Bioreactors

Max overflow rate 1200 gpd/Sq. Ft
48.9 CuM/SqM-D

72 Final Settling Tank Activated Sludge

Process	Surface Overflow Rates based on Peak Hourly Flow Influent Only		Peak Solids Loading Rate (flow +return AS)		Tank Sizing Influent		Solids*	
Conventional AS, Step Aeration, Complete Mix, Cohntact Stabilization, Carbonaceous state of separate nitrification	1200 48.9	gpd/Sq.Ft. CuM/SqM-D	50 244.0	lb/day/Sq.Ft Kg/day/ Sq. M	9435.7 866.1	Sq Ft Sq M	6672 614.6	Sq. Ft Sq.M
Extended Aeration, Single Stage Nitrification	1000 40.7	gpd/Sq.Ft. CuM/SqM-D	35 170.8	lb/day/Sq.Ft Kg/day/ Sq. M	11322.8 1041.8	Sq Ft Sq M	14883 1372	Sq Ft** Sq M**
Two Stage Nitrification	800 32.6	gpd/Sq.Ft. CuM/SqM-D	35 170.8	lb/day/Sq.Ft Kg/day/ Sq. M	14153 1302	Sq Ft Sq M	9531.4 876.0	Sq Ft Sq M
AS with Chemical Addition to Mixed Liquor for Phosphorous Removal if P is to be less than 1mg/l	900 36.7	gpd/Sq.Ft. CuM/SqM-D	35 170.8	lb/day/Sq.Ft Kg/day/ Sq. M	12581 1158	Sq Ft Sq M	9531.4 876.0	Sq Ft Sq M

*4000 mg/l @ 100% Return flow

**150% Recirc Flow & 5000 Mg/l Basis

Standards) originally was adopted by Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, New York, Ohio, Pennsylvania, and Wisconsin, and since has been adopted formally or informally by many state regulatory agencies. Wastewater treatment plant designs based on this design code often receive minimal scrutiny from regulators because of the Standards' proven effectiveness. Many consultants also add their own design safety factors and expansion allowances to the Ten States Standards, unaware that this code already has a built-in cushion.

Curious to know whether the Standards were overly conservative, investigators recently prepared a wastewater treatment facility design based on this code and then evaluated its performance using dynamic computer models. They used STOAT and WEST — commercial computer programs used worldwide to design, model the performance of, and benchmark wastewater treatment plants. Both programs include a variety of wastewater treatment models, including Activated Sludge Model Number 1 (ASM1), which was first developed in 1987 by the International Water Association (formerly IAWQ; London, England) to model the performance and behavior of activated sludge systems. [Newer versions of ASM1 provide for phosphorous removal (ASM2 and ASM2d), and reflect changes in the understanding of microbial behavior (ASM3).] Investigators used ASM 1 to examine the 1997 edition of the Ten States Standards.

Modeling Parameters

Investigators started with a spreadsheet that focused on the development of parameters in Secs. 70 (Settling) and 90 (Biological Treatment) of the standards (see Figure 1, above). These sections most influence the capacity and cost of wastewater treatment systems because settling and biological treatment systems are the two elements most often expanded or modified when an activated sludge plant fails to perform. The Ten States Standards give specific numerical guidance for several design factors, including clarifier surface loading rates and aeration tank volumes. Some values must be calculated based on site-specific conditions, while others remain constant standards.

One of the Standards' principal design requirements is the application of a peaking factor based on the following equation:

$$Q_{peak} = [18 + \text{sqrt } P]/[4 + \text{sqrt } P]$$

where P is the community population in thousands.

Investigators picked a medium flow rate — population of 50 000 [equivalent to a 5-mgd (780-m^3/h, 18 742-m^3/d) flow rate, assuming 100 gal/d per person] — because it would demonstrate the models' flexibility and scalability at an intermediate level representative of many communities and existing wastewater treatment works. At this flow rate, the Standards prescribe the following general parameters:

- flow = 100 gal/d per person (0.38 m^3/d per person),
- BOD = 0.17 lb/d per person (0.077 kg/d per person),
- average waste strength (BOD_5 = 204 mg/L),
- total suspended solids (TSS) = 0.2 lb/d per person (0.0907 kg/d per person),
- average waste strength = 240 mg/L suspended solids, and
- $Q_{peak}/Q_{average} = 2.35$.

Although the Standards use BOD, virtually all activated sludge models are written using chemical oxygen demand (COD) instead. The most commonly accepted BOD–COD conversion formula is BOD_5 = 0.5 COD, so in this case COD = about 400 mg/L.

Also, the ASM1 model does not include all components of total Kjeldahl nitrogen. For example, the model does not incorporate the nonbiodegradable soluble (**S_NI**) and particulate nitrogen (**X_NI** and **X_NP**), although it does include the active mass nitrogen because of the release of biodegradable particulate nitrogen from the decay of biomass. ASM1 also includes dissolved oxygen (DO) and alkalinity to keep the charge balance in equilibrium. Its equations consider the following reactions:

- conversion of COD by aerobic growth into carbon dioxide and new biomass,
- conversion of COD by anoxic growth into carbon dioxide and new biomass,
- conversion of ammonia into nitrate,
- biomass decay, releasing COD that can be used for further biomass growth,
- breakdown of particulate COD and nitrogen into soluble forms, and
- breakdown of soluble organic nitrogen into ammonia.

Advantages of Modeling

Using dynamic models to develop and evaluate wastewater treatment plant designs allows engineers to develop data on plant behavior under various conditions and enables better contingency planning for such occurrences as shock loadings and plant upsets. Modeling also allows plant operators to develop information about the effect of specific operations on the plant. It can answer such questions as:

- "If I open (or close) that valve, what will it do to the plant?"
- "What do I do to correct (a specific) problem?"
- "How much capacity does this plant have for expansion?"

When designing a plant, many engineers build in an expansion allowance in excess of the required parameters in the 10 States Standards. This tends to be excessive because the Standards already contain a safety factor of approximately 30%. Adding an allowance for expansion or planned growth is often unnecessary and counterproductive, resulting in a design that is twice the capacity it needs to be, so performance is degraded. For example, when investigators reduced the flow of their 5-mgd (18 742-m^3/d) plant by 50%, the effluent was highly nitrified but the plant became expensive to operate (although not done for this project, both WEST and STOAT can estimate operating costs).

With modeling, various strategies can be implemented and evaluated. It is extremely easy to model and evaluate the implementation of a nitrogen control strategy for municipal and industrial effluents. Converting a standard wastewater treatment plant to a MLE plant can be modeled and the results evaluated in a few hours. Biological phosphate removal also can be modeled relatively easily. Both systems can support a wide variety of configurations and models where plant elements can be mixed and matched easily to meet current and projected demands.

Dynamic modeling has been extended to all parts of the treatment works as well as to the river. The effects of storm flows and high infiltration can be assessed on both the river and treatment works. Current process models include activated sludge models, clarifier models, biofilm and trickling filter models, sequencing batch reactor, and river models. Filtration, dissolved air flotation, and other models are also available, but they often require the use of laboratory testing and pilot-plant development before simulation because they contain a number of critical adjustment parameters that must be applied in order to approximate model performance. Without the adjustment parameters, the model may not predict system performance accurately.

Table 1. Values Used in Modeling

Parameter		Value Used in Modeling (mg/L)
S_I	Inert soluble matter	19
S_S	Readily biodegradable matter	94
S_O	Dissolved oxygen	0
S_NO	Nitrate and nitrite	0
S_NH	Free and saline ammonia	18
S_ND	Soluble biodegradable organic nitrogen	6
S_ALK	Alkalinity	130
X_I	Inert particulate matter	41
X_S	Slowly biodegradable matter	205
X_BH	Heterotrophic biomass	10
X_BA	Autotrophic biomass	1
X_P	Particulate products resulting from biomass decay	41
X_ND	Particulate biodegradable organic nitrogen	5.3

After researching various texts and modeling parameters, investigators developed a set of parameters (using the values in Table 1, above) that are equivalent to "standard" domestic wastewater. They then established two parallel trains configured to represent either a nitrifying system, a nitrifying system with a pre-anoxic zone, or the Modified Ludzak-Ettinger (MLE) design for nitrogen removal. MLE is a two-tank system that uses a primary anoxic zone followed by an aerobic zone, with an internal recycle taking nitrified sludge from the aerobic zone back to the anoxic zone for denitrification. The sludge is recycled from the secondary clarifier to the head end of the anoxic zone, at up to 80% recycle.

A primary clarifier was used in both cases. The primary clarifier was modeled as a Lessard and Beck primary clarifier, and the aeration tanks were modeled in two different ways: a complete-mix system (WEST; see Figure 2, below) and a plug-flow system (STOAT; see Figure 3, p. 77).

STOAT used a plug-flow system, which was modeled by using eleven internal compartments on the aeration system. A correlation that relates the internal mixing characteristics (number of compartments or stages) to the physical properties (for diffused air systems) was used. The correlation, in SI units, is

$$N = 7.4\,Q_S\,(1 + R)\,L / W\,H$$

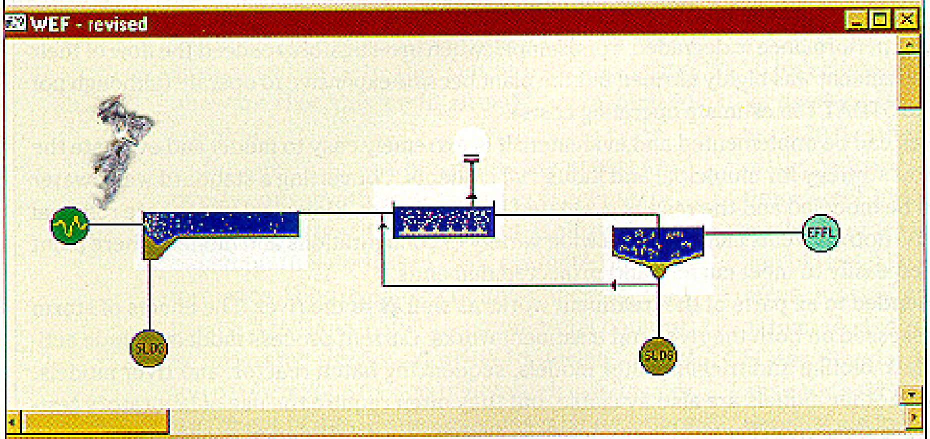
where
N = number of compartments;
Q_S = flow (m³/s);
R = RAS ratio;
L = length (m);
W = width (m); and
H = depth (m).

The design assumed that Q_S = 780 m³/h = 0.217 m³/s, H = 3 m, L/W = 10, and R = 1. From this, N = 11 (nearest integer). STOAT used 11 compartments to model the plant as a plug-flow reactor, while WEST used two 170 000-ft³ (4814-m³) tanks, with an equivalent normal-flow residence time of 6.10 hours per tank, to model the plant as a complete-mix flow reactor. (STOAT used eleven stages because of the mixing correlation. WEST used two stages to reflect the typical mixing behavior that may be expected for a surface-aerated system or other complete-mix design.)

The WEST system used the most popular definition of ASM1, while STOAT used a slightly different interpretation (the difference has to do with the handling of the X_ND term). As a result, the models use different tank configurations and sine curves to approximate the diurnal variation, emphasizing differences in the degree of mixing — a situation that the 10 States Standards ignore. Plug-flow systems usually remove ammonia more efficiently and may produce less sludge than complete-mix systems, but are less resilient to shock loads and the effects of large diurnal variations in flow and load. Using models allows engineers to better explore such issues during design work.

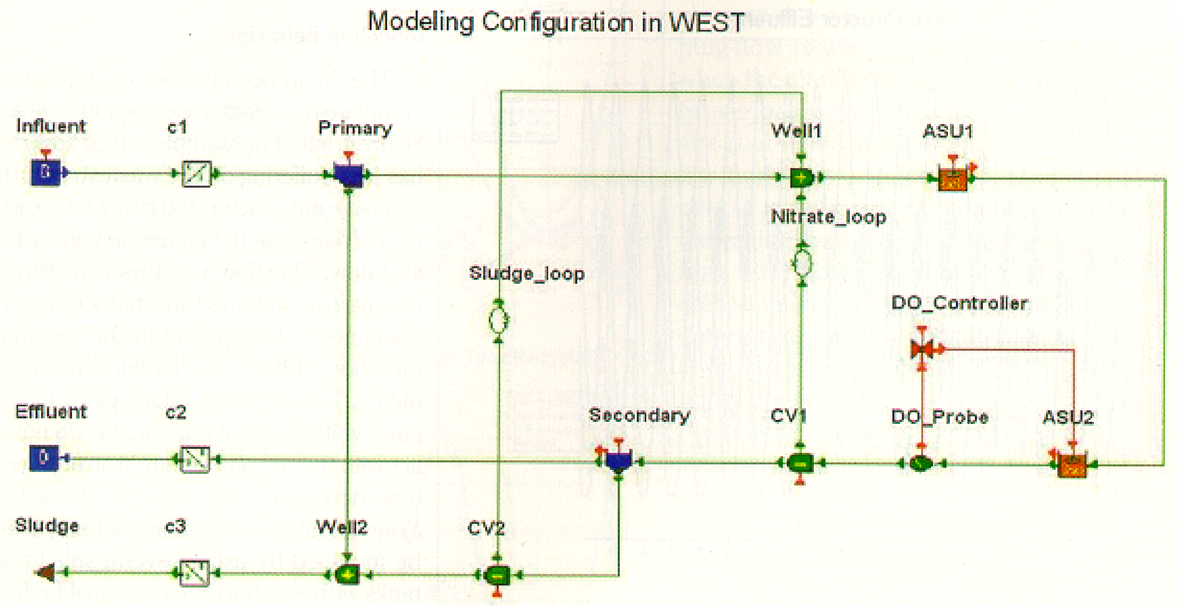
The Standards' design parameters for a 5-mgd (18 742-m³/d) plant specify a 2.265 ratio of peak hydraulic flow to average flow, a peak flow/low flow aver-

Figure 2 Modeling Configuration in STOAT



Legend: The flow proceeds from left to right. The first unit is the primary clarifier. The second is the ASU or Activated Sludge Unit. The third element is the secondary clarifier. Sludge return and recycle lines are as shown, and the valving is not shown on the flow sheet.

Figure 3. Modeling Configuration in WEST



age of 4.0. WEST and STOAT used the average flow with a variation of 60% so the hydraulic variation was not quite as severe as the Ten States Standards required, but the maximum/minimum flow ratios were 4.0. This was due to the sinusoidal characteristic of the flow generator (see Table 2, below).

During the modeling runs, investigators increased the base flow in increments of 10% until they judged that failure had occurred. The target parameters were a consistent effluent with ammonia, TSS, and total BOD concentrations of less than 5, 20, and 20 mg/L, respectively.

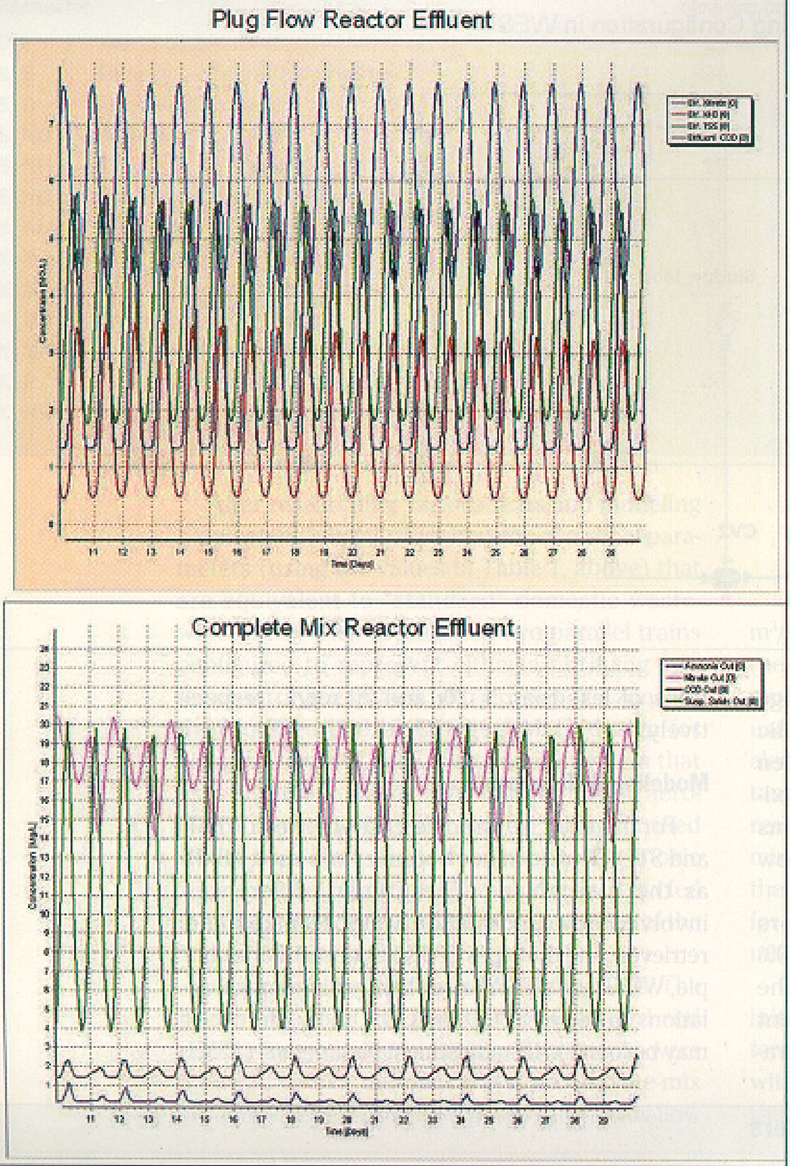
Modeling Differences

For this exercise, the differences between WEST and STOAT were minor because both used ASM1 as the base engine. The primary differences involved how information was organized and retrieved, and the types of displays used. For example, WEST and STOAT use slightly different calculations to convert BOD to COD. Other differences may be found in the adjustment parameters. (ASM1

Table 2. Summary of Design Parameters

Plant Parameter	**STOAT**	**WEST**
Waste Generator	Sine wave generator	Double sine wave generator
Amplitude above mean	60%	60%
Average Daily Flow m³/d (mgd)	18742 (5)	18742 (5)
Primary Clarifier Model	Lessard and Beck	Lessard and Beck
Primary Clarifier Surface Area (m²)	464.6	464.6
Primary Clarifier Side Water Depth	5 M	5 M
Primary Clarifier Detention Time at average flow Hours	2.97	2.97
Aeration Basin(s)	Plug Flow	Complete Mix
Number of tanks	1 with 11 compartments	2
Tank Sizes	Each compartment 437.54 m³.	Anoxic and Aerobic Tanks both sized at 4814. m³ [9628 m³ total]
Tank Detention Time (both tanks)	10.8 hours	10.8 hours
Secondary Clarifier – Model	Takacs	Takacs
Surface area m²	868.1	868.1
Side Wall Depth – (m)	5	5
Overflow Rate m³/m²/day (gpd/sf)	48.9 (1200)	48.9 (1200)

Figure 4: Comparison of Performance Between Complete-Mix and Plug-Flow Reactors



has about 30 process coefficients that can be adjusted, and the clarifier may involve another five or more adjustable coefficients. Most parameters only need to be adjusted for unusual problems, such as very soft water or industrial effluents, or are readily related to available engineering parameters, such as sludge volume index.)

Modeling Behavior

The difference between a plug-flow and a complete-mix reactor can be substantial (see Figure 4, left). For example, a plug flow reactor has less buffering on the wastestream than a complete-mix reactor, and larger peaks and valleys in response to changes in concentration and flow. Plug-flow reactors generally have long narrow tanks and are characterized by an "assumed" ideal mixing in the longitudinal direction with no velocity concentration gradients. The reactions taking place in a small finite volume of the reactor, ΔV, do not interact with the concentrations in an adjacent volume. According to *Modeling of Activated Sludge Systems* (1994), a plug-flow reactor system can be modeled by using several small reactor tanks with a cumulative size equal to the total detention volume desired.

Complete-mix reactors may have the same average residence time as plug-flow reactors, but the concentration profiles and gradients are substantially different. For example, the effluent concentration as a function of average residence time is a statistical probability curve rather than the sharp straight line of a plug-flow reactor. Contamination gradients are not as sharp as with the plug-flow reactor, and the assumption is that chemical reactions apply to the entire tank volume rather than a point or finite volume.

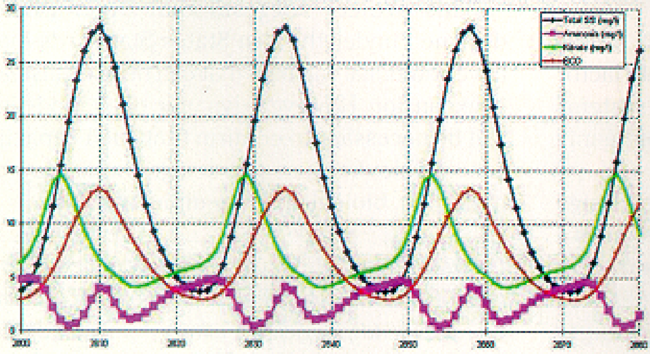
Results

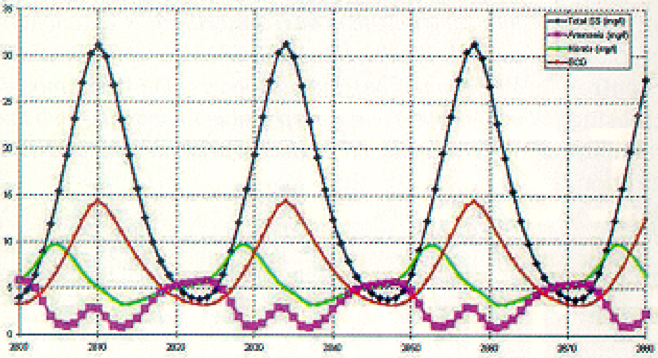
The activated sludge tanks performed adequately throughout the testing, although higher recycle rates provided overall better nitrogen removal for a given set of parameters (see Figure 5, above). For the two cases presented, TSS and BOD are slightly higher for the 100% recycle case, and nitrate was slightly lower than in the 50% recycle

Table 3. Summary of Test Mode Data with relative increase (decrease) with increasing flows

Model	Flow (+%)	BOD	NH_3	NO_3	TSS
STOAT	18742	7.84 mg/L	4.53 mg/L	2.91 mg/L	13.85 mg/L
Plug-flow	24364 (+30%)	169%	167%	(-30.2%)	175%
reactor	26238 (+40%)	222%	183%(-47.4%)	238%	
West	18742	0.827mg/L	16.15 mg/L	7.71 mg/L	
Complete-mix	24364 (+30%)	306%	(-15.3%)	153%	
flow reactor	26238 (+40%)	431%	(-23.1%)	175%	
	28113 (+50%)	627%	(-34.5%)	202%	

Figure 5. STOAT: Comparison of Effluent at 50% and 100% Recycle


50% Recycle from Secondary Aeration to Primary Anoxic Tank


100% Recycle from Secondary to Primary Anoxic Tank Recycle

case. The ammonia effluent level is approximately the same in both cases.

In WEST, the comparable effluent values are:

- 50% recycle: 5.0 to 11.5 mg/L nitrate, 0.5 to 3.5 mg/L ammonia, 1.5 to 3.5 mg/L COD, and 2 to 7 mg/L TSS.
- 100% recycle: 4 to 9 mg/L nitrate, 0.5 to 3.2 mg/L ammonia, 1.5 to 5 mg/L COD, and 1.8 to 5.8 mg/L TSS.

Again, the difference in apparent modeling performance is indicative of the model being used and slight differences in some modeling techniques.

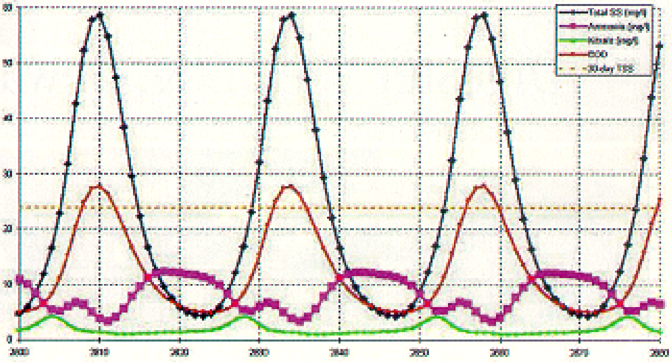
The activated sludge tanks in both models performed well through various hydraulic loadings as long as the biomass and residence time in the aeration tanks were sufficient to permit biological growth.

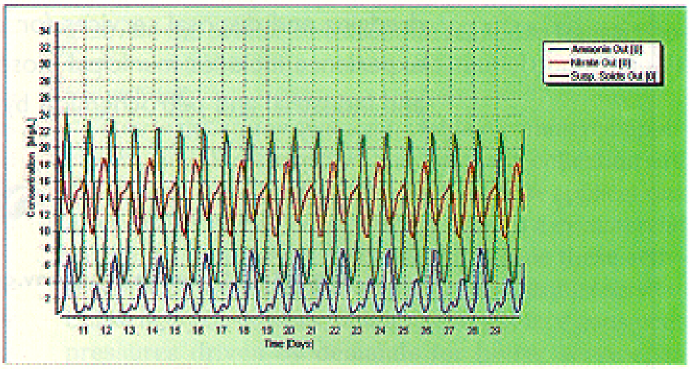
Wastewater temperature can play a significant role in plant performance. STOAT modeled the effect of changing temperature on the wastewater treatment plant. Many northern U.S. states have NPDES permits that indirectly reflect the effect of temperature by relaxing performance requirements from October through April. However, engineers now can determine the effects of cold weather and set performance standards accordingly.

For the purposes of this project, system failure occurred when average effluent BOD_5 was 20 mg/L (about 40 mg/L COD) or effluent TSS was 20 mg/L (ammonia levels were also a consideration). The plug-flow reactor typically failed when the clarifier was hydraulically overloaded by between 30% and 40% (both models could vary clarifier underflow, which increased overall clarifier performance by increasing the apparent sludge settling rate). Effluent quality in the complete-mix reactor started to deteriorate when the 30% excess flow point was passed (see Table 3, p. 78). The biological portion of the complete-mix reactor effluent quality began to deteriorate at 40% additional flow.

Inspection of the data would suggest that there are tradeoffs between the plug-flow and complete-mix models, and there are. However, one cannot compare the two sets of results directly because of the differences in WEST and STOAT.

Figure 6. Effect of a 30% Increase in Flow


STOAT: Flow +30%


WEST: Flow +30%

Significant Overdesign

Modeling confirmed that the 10 States Standards are overdesigned — the safety factor is between 30% and 50% for plug-flow systems and between 40% and 50% for complete-mix reactor systems (see Figure 6, p. 79).

Failure mode depends on the type of design used. Overall effluent deterioration becomes a factor to consider when the flow is more than 30% above average daily design flows. Enhanced clarifier performance and operating changes (such as increasing nitrate recycle ratios or secondary clarifier sludge return) will partially or totally alleviate some of the effluent deterioration conditions, within limits. Equipment changes also may be required to allow more recirculation, balanced aeration, or DO control in the aeration basins. Ultimately, increasing hydraulic and biological loadings will catch up with the plant and cause effluent deterioration.

This project suggests that older plants designed under the Ten States Standards may have additional capacity that can be used instead of expansion. However, dynamic plant modeling will be necessary to confirm that such capacity is available, because the design limits may be hydraulic, biological, or equipment-driven.

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