Combining Stress Testing and Dynamic Linking of Whole-Plant Simulators and Computational Fluid Dynamics for the Evaluation of Wastewater Treatment Plant Wet Weather Capacity

Alonso Griborio, Joe Rohrbacher, Paul Pitt, Ron Latimer, and James Gellner

Over the past few years, utilization of advanced activated sludge process simulation models such as BioWin™, GPS-X, STOAT, and WEST has increased significantly. These process simulation models are powerful tools for evaluation, optimization, and design of wastewater treatment plants, especially biological and enhanced nutrient removal (BNR/ENR) plants. These models include the ability to simulate the whole-plant process under both steady state and dynamic conditions. The whole-plant simulators include elements to simulate primary and secondary clarifier performance; however, these clarifier models are idealized one-dimensional models and do not account for hydrodynamics, flocculation and internal features, or environmental impacts such as temperature; and therefore are limited in their ability to represent clarifiers with various design elements such as inlets, flocculating wells, and baffles. As a result, the process simulation models are limited in terms of accurately predicting secondary clarifier performance.

A more comprehensive approach for modeling clarifiers is the use of computational fluid dynamics (CFD) models. The CFD models can incorporate hydrodynamics, flocculation, turbulence, and temperature in a clarifier settling model and allow for optimization of clarifier design. Although the more advanced clarifier models have yet to be incorporated into a whole-plant simulator model, the two can be used together in order to accurately predict final effluent quality to develop wet weather operating strategies and to confirm the design of the system. This article covers the state of the art in dynamic process simulation modeling, clarifier modeling using dynamic CFD simulations, and the linking of the two to perform dynamic modeling of the activated sludge/secondary clarifier system. Through the use of cases studies, this article also illustrates the benefits of conducting stress testing for both plant rating and data collection for the calibration of the combined models.

Methodology

Two case studies illustrate the combined use of whole-plant simulators and CFD models and the benefits of stress testing:

Case Study 1: Kentucky Wastewater Treatment Plant

Case study 1 illustrates the application of stress testing and the linked use of BioWin and the CFD clarifier model "2Dc" model for the evaluation of the weather capacity of the 46.5 mgd Kentucky plant. A wet weather event was applied transitioning from 46.5 to 100 mgd. BioWin was used to predict the MLSS concentration with and without the application of step feed, and the 2Dc model was applied to predict the clarifier capacity under different scenarios.

The 46.5 mgd (maximum month flow) Kentucky plant is a conventional activated sludge treatment plant with effluent carbonaceous biological oxygen demand ($cBOD_5$), total suspended solids (TSS), and ammonia nitrogen (NH_3) limits for discharge to the Ohio River. Table 1 shows a summary of the effluent permit. Major unit processes include screening, grit removal, primary clarifiers, fine bubble conventional activated sludge, secondary/final clarifiers, and sodium hypochlorite/sodium bisufite disinfection. The plant has an annual average flow (AAF) rate of 34.4 mgd, a maximum month flow (MMF) rate of 46.5 mgd, and experiences peak wet weather flow rates of approximately 95 mgd. The plant secondary treatment system is currently rated at 60 mgd. In the future, it will be necessary to treat approximately 100 mgd to accommodate the potential wet weather flows expected in the system. The plant has the ability to step feed up to 100 percent of the primary effluent to the midpoint of the aeration basins.

There are six final clarifiers currently installed at the Kentucky plant. All six secondary clarifiers have an octagonal shape at the top and transition to a circular configuration at the base. The effective diameter is 131 ft and the side water depth (SWD) is 14 ft for all units. All secondary clarifiers are provided with influent feed well, inboard effluent launders, Stamford (density current) baffles and organ pipe type suction mechanism. Figure 1 shows an aerial view

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Alonso Griborio (Hollywood, Fla.) is a senior principal engineer, Joe Rohrbacher (Charleston, S.C.) is an associate, Ron Latimer (Atlanta, Ga.) and James Gellner (Cincinnati, Ohio) are senior associates, and Paul Pitt (New York, N.Y.) is vice president and wastewater process design director, all at Hazen and Sawyer.

Table 1. Kentucky Wastewater Treatment Plant – Effluent Permit Limits

Parameter	Monthly Average	Weekly Average
$cBOD_5$ (mg/L)	25	37.5
TSS (mg/L)	30	45
NH_3-N (mg/L)	20	30
DO	> 2 (mg/L), (daily)	
pH	[6,9], daily	
Total Residual Chlorine (mg/L)	---	0.076
Fecal Coliform (cts/100 mL)	200	400

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of the six final clarifiers at the plant. All six existing secondary clarifiers will be reused and retrofitted and a new 131 ft diameter secondary clarifier is proposed to be added as part of the plant improvement project.

There are three components to the process methodology used for the wet weather capacity determination of the plant: biological process simulation, field testing (stress and settling testing), and computational fluid dynamics (CFD) modeling.

Biological Process Simulation. The modeling objective for the plant was to simulate a dynamic response of the exiting biological process from steady state conditions at 46.5 mgd and applying a wet weather event of 100 mgd for a duration of two days using a step feed strategy of the primary clarifier effluent. Steady state conditions prior to the storm event were at maximum month flow and load under winter temperature conditions with a targeted operating MLSS of less than 3,000 mg/L. The step feed location was placed at 50 percent of the aeration basin volume and 100 percent step feed was employed during the wet weather event. Return activated sludge (RAS) rates were 50 percent of the influent flow rate. Ensuring existing biological treatment was achieved with the existing seasonal nitrification limits; the resulting mixed liquor suspended solids (MLSS) was 2,000 mg/L during the two-day storm event and 100 mgd final clarifier effluent flow, when step feed was applied. Figure 2 shows the BioWin process flow diagram.

Clarifier Stress Testing and Settling Column Testing. Clarifier stressing testing involves hydraulically stressing the existing final clarifiers such that the dynamic clarifier performance may be monitored. This is achieved by taking units offline until the targeted surface over flow rate (SOR) and solids loading rates (SLRs) are reached. Operating performance is continuously monitored until the clarifier reaches a determined “failure” point, such as high effluent TSS or high blanket level, at which point the stress testing is ended and the offline units are returned to service. Parameters monitored for each operating clarifier include: sludge blanket levels, MLSS, effluent suspended solids (ESS), RAS, TSS, sludge volume index (SVI), flow rates, dispersed suspended solids (DSS), and flocculated suspended solids (FSS).

CFD Modeling. The CFD, or 2Dc, model used in this project is a quasi-three-dimensional clarifier model developed at the University of New Orleans (McCorquodale et al. 2005, Griborio and McCorquodale 2006). The calibrated CFD model was used to identify improvements to the existing clarifier infrastructure that would increase clarifier performance and capacity. The model was then used to evaluate clarifier performance under different scenarios of flows, settling and loading conditions, and units out of service. Simulations using the BioWin wet weather predicted condition allowed for the determination of effluent suspended solids performance and potential optimization opportunities in the clarifier design.

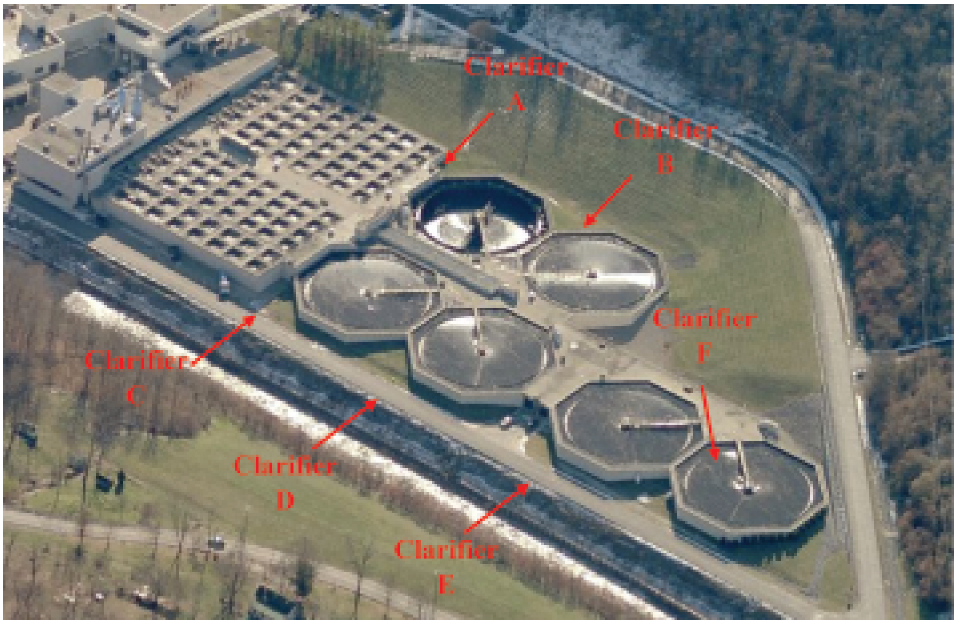

Figure 1. Aerial View of the Kentucky Wastewater Treatment Plant Final Clarifiers

Case Study 2: 15 mgd Virginia Wastewater Treatment Plant

The Virginia Wastewater Treatment Plant was originally constructed in two phases. The first phase was constructed in the late 1950s and included a grit basin, grit decanting bed, pre-aeration basins, intermediate, primary and final clarifiers, primary and secondary trickling filters, sludge drying beds, and primary and secondary digesters. The Virginia plant was then upgraded in the early 1980s to treat a design flow of 15 mgd. The facility incorporated preliminary

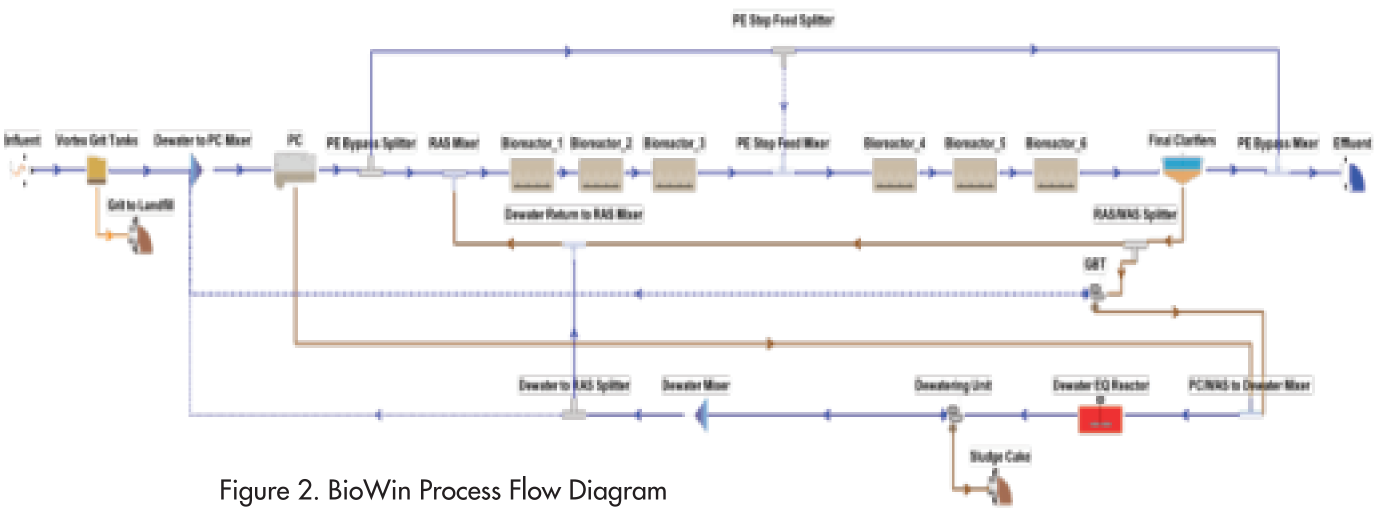

Figure 2. BioWin Process Flow Diagram

screening and grit removal, daily flow equalization, primary clarification, biological treatment, secondary clarification, chlorination/dechlorination, and tertiary flocculation and settling basins. The plant was required by the Virginia Department of Environmental Quality (DEQ) to comply with stringent nutrient requirements.

General information for the Virginia plant includes:

- 15 mgd capacity with peaks of 37.5 mgd
- Provides full nitrification and is being upgraded to comply with nutrient limits of TN = 5 mg/L and TP = 0.3 mg/L
- Two existing 130 ft diameter secondary clarifiers, 12 ft SWD, flocculation well = 19 ft diameter x 3 ft depth
- One proposed 160 ft diameter secondary clarifiers, 15 ft SWD, flocculation well = 45 ft diameter x 7 ft depth
- Typical loading conditions: MLSS ~ 2900 - 3700 mg/L; surface overflow rate (SOR) ~ 320 gpd/ft^2 (average flow), 810 gpd/ft^2 (peak flow).

An analysis of the secondary treatment facilities proposed for enhanced nutrient removal improvements at this 15 mgd plant was performed to determine its capability to process peak wet weather flows. A design storm was considered where the flow increased from 15 mgd to 37.5 mgd in about 24 hours and the peak flow was sustained for another 24 hours. BioWin 3.0 process simulation software was employed to model the design storm through the biological treatment facilities and to predict MLSS concentration during the storm event with and without the implementation of step feed. The secondary clarifiers were modeled using the 2Dc CFD model described in Case Study 1. The calibrated CFD model was used to evaluate the effect that step feed and non-step feed modes can have on the clarifier performance. Dynamic analyses were performed coupling these two models to determine effluent quality changes. Figure 3 shows the MLSS predicted by BioWin and the clarifier SOR used during the simulation of the storm event.

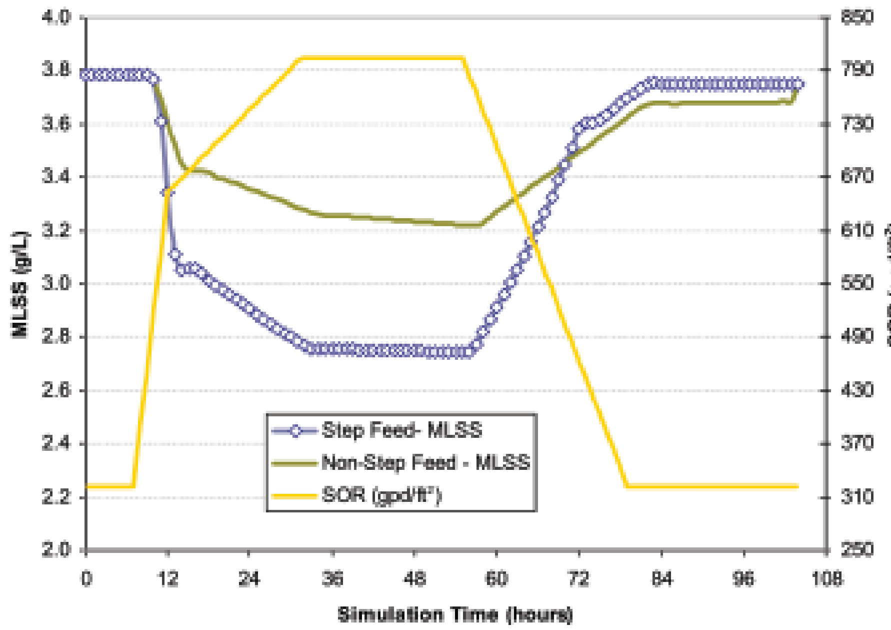

Figure 3. Storm Event Analysis – Clarifier SOR and MLSS for Step Feed and Non-Step Feed Modes

Table 2. Kentucky Wastewater Treatment Plant BioWin Wet Weather Results

Period	Peak Flow Rate (MGD)	MLSS (mg/L)	NH_3-N (mg/L)	$cBOD_5$ (mg/L)	Scenario
Maximum Month (MM)	46.5	3000	0.6	4.4	RAS 50% ASRT=5.25
Maximum Month (MM)	46.5	3000	0.5	4.2	RAS 40% ASRT=5.25
Maximum 7-Day (M7)	63.2	3000	1.4	4.9	RAS 50% No Step Feed
Maximum 7-Day (M7)	63.2	2000	6.2	3.6	RAS 50% Step Feed
Maximum Day (MD) and Peak Hour (PH)	100.0	3000	3.9	4.6	RAS 40% No Step Feed
	100.0	1900	6.8	3.2	RAS 40% Step Feed
	100.0	3000	4.0	4.8	RAS 50% No Step Feed
	100.0	2000	6.2	3.5	RAS 50% Step Feed

Results and Discussion

Case Study 1: Kentucky Wastewater Treatment Plant

The BioWin simulations at maximum month flow and load under winter temperatures provided a steady state target from which a wet weather event was applied transitioning from 46.5 to 100 mgd. During the transient simulations, the wet weather peak was applied for two days, meeting the existing treatment limits using 100 percent primary effluent step feed routed to the midpoint of the aeration basin. The MLSS at the downstream end of the aeration basin was approximately 2,000 mg/L during the peak event.

A 50 percent primary effluent step feed location was used to match the existing plant's ability for step feed. The six aeration tanks onsite are two pass units with step feed directly to the second pass controlled by a slide gate. Simulations results with and without the wet weather step feed strategy are shown in Table 2, for up to 100 mgd through the secondary process. The verification of the final clarifier performance at the BioWin simulated process flow, MLSS, and RAS operation is presented next.

As indicated in the methodology section, stress testing and additional field sampling were conducted in October 2008 and the results were used to calibrate the CFD and the BioWin models of the secondary treatment facilities. Figure 4 shows the CFD model output displaying the suspended solids contours and velocity vectors predicted during model calibration. Despite the low surface overflow rate, the effluent TSS is relatively high at 18 mg/L.

The modeling results indicate that the Kentucky plant secondary clarifiers exhibit a strong density current, reinforced by the re-entrainment of clarified liquid into the inlet zone. The strong

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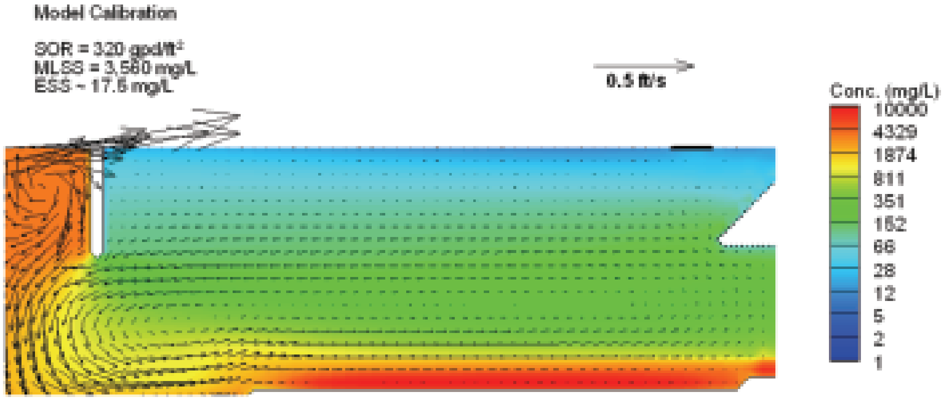

Figure 4. Suspended Solids Contours and Velocity Vectors during Model Calibration

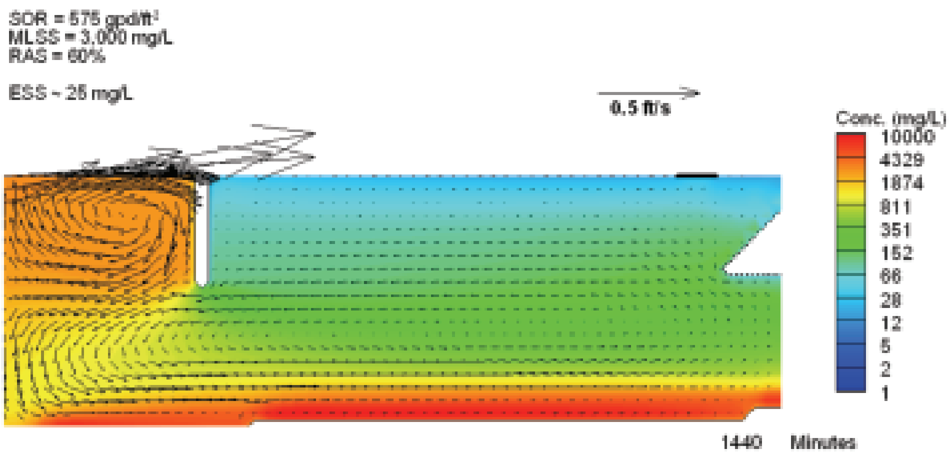

Figure 5. Suspended Solids Contours and Velocity Vectors for Retrofitted Secondary Clarifier, Flow = 46.5 mgd

Table 3. Secondary Clarifier Capacity Evaluation, SVI = 115 mL/g, MLSS = 3,000 mg/L

Q (MGD)	Units in Service	SOR (gpd/ft²)	RAS (%)	Q RAS (MGD)	ESS (mg/L)	RAS TSS (mg/L)	Observations
6 Secondary Clarifiers in Service							
34.4	6	425	60.0%	20.6	23	7900	
46.5	6	575	60.0%	27.9	25	7890	TSS Permit = 30 mg/L
63.2	6	785	60.0%	37.9	41	7860	TSS Permit = 45 mg/L
80.0	6	989	50.0%	40.0	48	8870	
85.75	6	1060	46.6%	40.0	49	9250	
100.0	6	1237	40.0%	40.0	54	10020	Sludge blanket is high ~ 10 ft
100.0	6	1237	50.0%*	50.0	59	8810	Sludge blanket is OK
7 Secondary Clarifiers in Service							
100.0	7	1060	50.0%*	50.0	45	8830	

* Total RAS flow capacity increased to 50 mgd (actual capacity 40 mgd)
ESS = Effluent TSS

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density current had low SORs, and a poorly flocculated sludge contributed to the high effluent suspended solids observed in these units. The results indicate that the existing center well diameter is small and not effective in controlling the re-entrainment. Also, the existing Stamford baffle is partially ineffective in controlling the updraft of suspended solids along the outer wall. This baffle directs solids to the inner portions of the tanks, but due to its proximity to the effluent launder, most of these solids are carried over with the upward current towards the launder.The CFD model was used to determine the optimum dimensions of the center well in order to reduce the re-entrainment of clarified liquid into the inlet zone and to better control the density current. Figure 5 shows the suspended solids contours and velocity vectors for the proposed retrofitted clarifier at design flow condition and MLSS equal to 3,000 mg/L.

Final Clarifier Performance and Capacity Evaluation

The performance and capacity of the retrofitted secondary clarifiers were evaluated for different conditions of settling properties, flows, and MLSS. The different loading conditions were evaluated for 5, 6, and 7 clarifiers in service (assuming the construction of a new secondary clarifier). The capacity analysis was conducted for two different SVIs: 115 mL/g, and 150 mL/g. The 115 mL/g SVI was selected as representative of the average settling conditions and the 150 mL/g SVIs represents the 90th percentile of the SVI data.

Capacity and Performance Evaluation Results: – SVI = 115 mL/g. Assuming an SVI of 115 mL/g, the clarifier capacity and performance were evaluated for different SORs and for two different MLSS: 3,000 mg/L and 2,000 mg/L. The MLSS equal to 3,000 mg/L represents the design MLSS and the 2,000 mg/L represents the MLSS value after step feed is implemented. Tables 3 and 4 summarize the modeling results for MLSS of 3,000 and 2,000 mg/L, respectively.

The results presented in Table 3 indicate that clarifier performance is satisfactory when the SVI and MLSS are equal to 115 mL/g and 3,000 mg/L, respectively. However, a high sludge blanket can be expected at peak flow conditions. Increasing the RAS capacity to 50 mgd would prevent buildup of the sludge blanket under these conditions. Table 4 shows the results for an SVI of 115 mL/g and MLSS of 2,000 mg/L. This MLSS corresponds to the implementation of step feed operation. According to the results presented in Table 3, step feed will not be needed at this SVI when all the clarifiers are in operation; however, it would be needed at peak flow conditions when only five clarifiers are in service.

The results demonstrate that clarifier performance and capacity are strongly related to the settling properties and the MLSS concentration. Under good settling conditions, six clarifiers in operation would be able to treat peak flows of 100 mgd. However, high sludge blanket depths could be expected. In order to reduce the risk of solids loss, it is recommended to increase the RAS flow capacity to 50 mgd to allow more flexibility for sludge blanket control. Step feed operation is another strategy that could be use to prevent excessive sludge blanket depths.

The results at poor settling conditions (SVI – 150 mL/g) indicate that step feed is needed to prevent thickening failure. The flow at which step feed needs to be implemented depends on the SVI and the number of clarifiers in service. The results demonstrate that by the combination of different wet weather strategies, like step feed and polymer addition, six clarifiers in service can effectively treat peak flows of 100 mgd, deferring the construction of a new clarifier.

Table 4. Secondary Clarifier Capacity Evaluation, SVI = 115 mL/g, MLSS = 2,000 mg/L

Q (MGD)	Units in Service	SOR (gpd/ft²)	RAS (%)	Q RAS (MGD)	ESS (mg/L)	RAS TSS (mg/L)	Observations
6 Secondary Clarifiers in Service							
34.4	6	425	40.0%	13.8	23	6960	
46.5	6	575	40.0%	18.6	28	6960	TSS Permit = 30 mg/L
63.2	6	782	40.0%	25.3	46	6900	ESS is high > 45 mg/L (permit)
80.0	6	989	40.0%	32.0	52	6900	
85.75	6	1060	40.0%	34.3	57	6880	
100.0	6	1237	40.0%	40.0	70	6840	ESS is high
7 Secondary Clarifiers in Service							
100.0	7	1060	40.0%	40.0	57	6880	
6 Secondary Clarifiers in Service - Polymer Added to Enhance Flocculation							
63.21	6	782	40.0%	25.3	40	6920	
100.0	6	1237	40.0%	40.0	60	6870	

* Total RAS flow capacity increased to 50 mgd (actual capacity 40 mgd)

Case Study 2: Virginia Wastewater Treatment Plant

Figure 6 shows the clarifiers ESS for step feed and non-step feed modes for the existing 130 ft diameter secondary clarifiers under poor settling properties. The results demonstrated that the use of step feed considerably decreases the solids loading in the secondary clarifier resulting in a lower ESS during the storm event. Without step feed, the maximum ESS is approximately 160 mg/L, while the step feed is able to reduce the ESS to approximately 55 mg/L.

Figure 7 shows the sludge blanket depth and the suspended solids contours for the step feed and non-step feed mode. The use of step feed significantly reduces the solids loading rate to the clarifiers resulting in lower sludge blanket heights and better clarifier performance. Figure 8 shows the ESS for step feed and non-step feed modes for the proposed 160 ft

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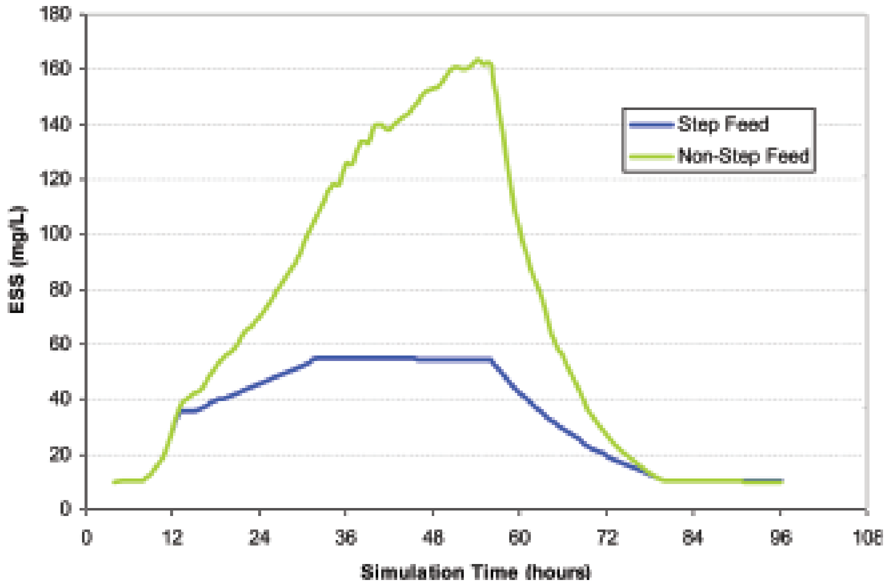

Figure 6. Existing 130 ft Diameter Secondary Clarifiers - ESS vs. Time for Storm Event – ESS for Step Feed and Non-Step Feed Modes Under Poor Settling Properties

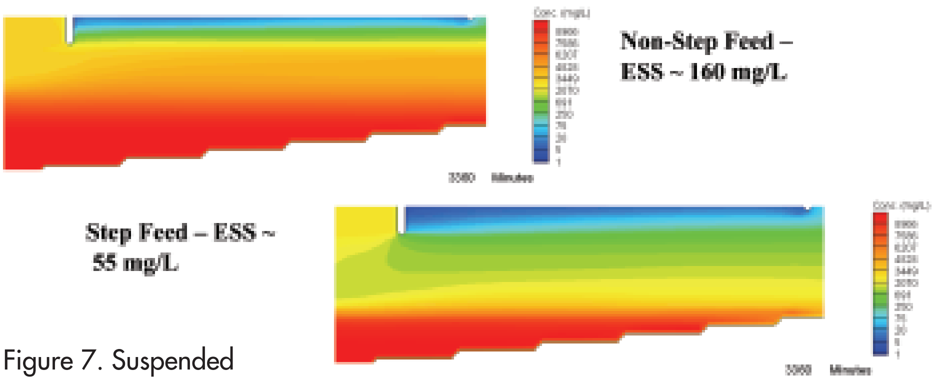

Figure 7. Suspended Solids Contours for Step Feed vs. Non Step Feed for Existing 130-ft Diameter Clarifiers Under Poor Settling Properties

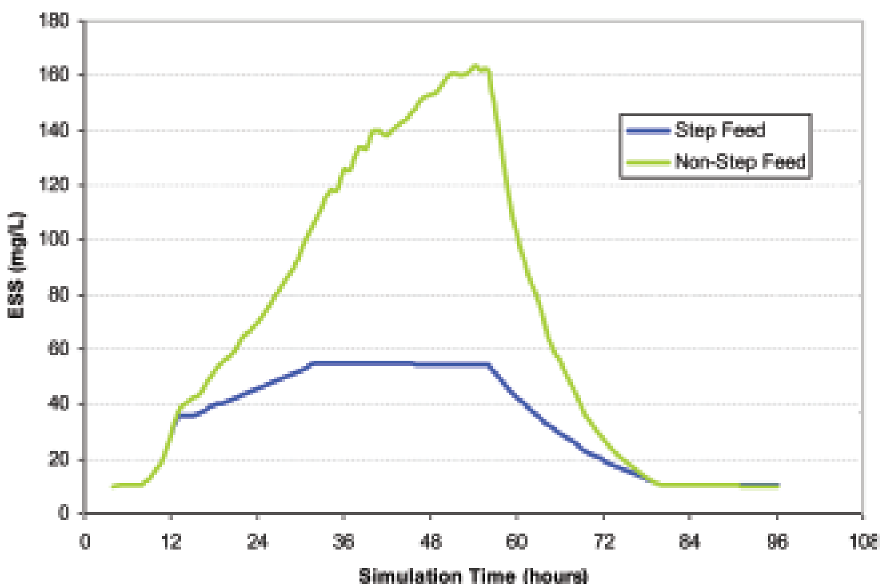

Figure 8. Proposed 160-ft Diameter Secondary Clarifiers - ESS vs. Time for Storm Event – ESS for Step Feed and Non-Step Feed Modes

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diameter new secondary clarifier. For the proposed 160 ft clarifiers, the predicted peak ESS are about 11 mg/L and 24 mg/L for step feed and non-step feed modes, respectively.

Conclusions

Step feed considerably reduces the solids loading rate to the secondary clarifiers, preventing the excessive accumulation of solids in the clarifier and resulting in lower sludge blanket depth and better clarifier performance. The use of step feed reduces the equilibrium RAS concentration, thus reducing the potential for thickening failure in the clarifier.

More stringent effluent nutrient standards require improved understanding and reliability of unit process performance. State-of-the-art tools are needed to ensure optimum performance during typical and stressed conditions. Whole plant simulators and an CFD model of the secondary clarifiers (and primaries) can be linked together for a more realistic approach. The combined use of these models provides tools for the designers and owners for evaluating various process scenarios for treatment optimization during dry and wet weather events.

The CFD modeling increases secondary clarifier performance by:

- Identifying improvements to existing infrastructure
- Development of detailed operating strategies to optimize typical and stressed clarifier conditions
- Optimizing the design of future units

The CFD modeling determines clarifier design and operational deficiencies not identified by traditional evaluation methods, validates the use of wet weather step feed and polymer addition to improve clarifier performance under stressed conditions, and results in capital and operational cost savings by optimization of existing and future facilities

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