CSR Process Simulations Can Help Municipalities Meet Stringent Nutrient Removal Requirements

Continuous Flow Sequencing Reactor (CSR) Basin with Moving Bridge, Submerged Diffusers, and Stationary Diffusers

White Paper
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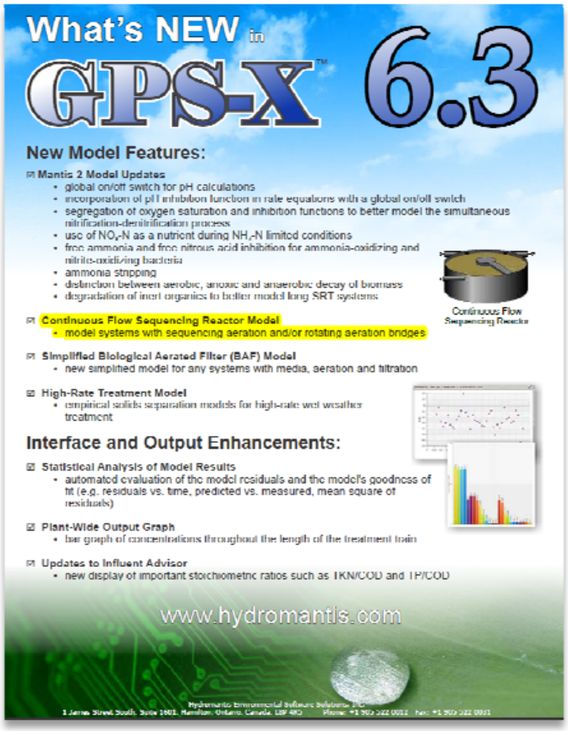
The complexity of biological activities and the number of process variables important to nutrient removal in advanced activated sludge wastewater treatment plants require the use of process simulation. Process simulation can help engineers evaluating different treatment processes and designing the best biological nutrient removal (BNR) process. It can help operators optimizing their plant performance at the same time reducing their operating cost associated with aeration and methanol addition. In this paper, a new process model for the continuous-flow sequencing reactor (CSR), which was developed by Hydromantis for their GPS-X process simulator, will be described. Also, model development and calibration of the Roth Lane WWTP (which uses CSR process) will be first presented followed by running simulations to predict plant performance at different flow and loading conditions.

CSR Process Model Description

The CSR Process developed by Schreiber, LLC (Trussville, Alabama), is a cyclic aeration process that uses fine-bubble membrane diffusers suspended from a peripherally driven rotating bridge and accessible stationary diffusers attached to the tank's wall. As the bridge rotates, it moves the submerged diffuser assemblies stirring the reactor's mixed liquor as well as providing aeration. The control process automatically cycle aeration on and off to create oxic, anoxic, and anaerobic conditions within the reactor's biomass. Sequencing these conditions in the same order allows nitrification, denitrification, and biological phosphorus removal in a single reactor. The CSR at Hampden Township's Roth Lane WWTP (*Figure 1*) has a diameter of 34 m (111.5 ft) a side water depth of 5 m (16.4 ft), and was designed based on a solid retention time (SRT) of 16 days.

Figure 1. Aerial of Hampden Township's Roth Lane WWTP in Mechanicsburg, PA



What's NEW in GPS-X™ 6.3

New Model Features:

☑ **Mantis 2 Model Updates**
  - global on/off switch for pH calculations
  - incorporation of pH inhibition function in rate equations with a global on/off switch
  - segregation of oxygen saturation and inhibition functions to better model the simultaneous nitrification-denitrification process
  - use of NO_x-N as a nutrient during NH_4-N limited conditions
  - free ammonia and free nitrous acid inhibition for ammonia-oxidizing and nitrite-oxidizing bacteria
  - ammonia stripping
  - distinction between aerobic, anoxic and anaerobic decay of biomass
  - degradation of inert organics to better model long SRT systems

☑ **Continuous Flow Sequencing Reactor Model**
  - model systems with sequencing aeration and/or rotating aeration bridges

☑ **Simplified Biological Aerated Filter (BAF) Model**
  - new simplified model for any systems with media, aeration and filtration

☑ **High-Rate Treatment Model**
  - empirical solids separation models for high-rate wet weather treatment

Interface and Output Enhancements:

☑ **Statistical Analysis of Model Results**
  - automated evaluation of the model residuals and the model's goodness of fit (e.g. residuals vs. time, predicted vs. measured, mean square of residuals)

☑ **Plant-Wide Output Graph**
  - bar graph of concentrations throughout the length of the treatment train

☑ **Updates to Influent Advisor**
  - new display of important stoichiometric ratios such as TKN/COD and TP/COD

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Figure 2. GPS-X 6.3 Features and Information

The CSR process model was developed by Hydromantis (Hamilton, Ontario) for the new version of their GPS-X simulator software GPS-X version 6.3 (*Figure 2*). The model associated with the CSR process operates as a set of continuous stirred tank reactors (CSTRs) in series (to simulate a plug flow tank) with a large recycle from the last tank in the series to the first tank. The process model specifies oxygen transfer in GPS-X by using a DO Controller option, which uses the entering airflow as the manipulated variable. The CSR process model also contains a DO On/Off Controller which abruptly switches the airflow in the tank on and off depending on the specified DO high and low limits. A Timer, Nitrate controller and Ammonia controller are also included in the CSR process model providing the user with additional Aeration Controllers.

Model Development and Calibration

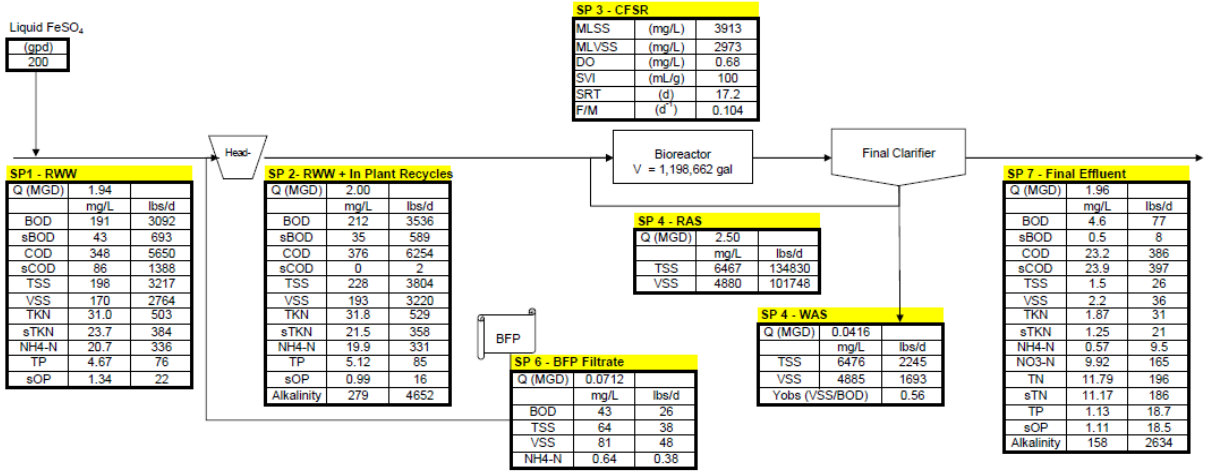
Since the Roth Lane WWTP has stringent effluent nutrient limits, utilization of a properly constructed and calibrated model using site specific wastewater characterization was critical to achieve accurate simulation results. The model development was based on the IWA Good Modeling Practice (GMP) Unified protocol, which is a five-step approach that utilizes biological wastewater modeling based on International Water Association (IWA) activated sludge models (ASM1, ASM2, ASM2d, and ASM3).

Step 1 – Define Modeling Goals

The level of model accuracy and reliability in predicting WWTP performance is a function of how extensively it is calibrated, which is a function of the modeling goals. The modeling goals for Roth Lane WWTP were: (1) identify and optimize process changes required to meet lower nutrient effluent limits, and (2) predict performance under annual average daily flow and maximum monthly flow in summer and winter conditions.

Step 2 – Data Collection & CFSR Influent Characterization

A comprehensive 15-day flow-weighted sampling of data (*Figure 3*) was collected by facility staff which served three goals: (1) enabled a detailed CFSR influent characterization, (2) enabled estimating stoichiometric relationships between constituents that can be used for extrapolated influent scenarios, and (3) ensured that a large enough and detailed database is available to capture enough dynamic variation to meet the specified level of dynamic calibration.



SP1 - RWW

Q (MGD)	1.94	
	mg/L	lbs/d
BOD	191	3092
sBOD	43	693
COD	348	5650
sCOD	86	1388
TSS	198	3217
VSS	170	2764
TKN	31.0	503
sTKN	23.7	384
NH4-N	20.7	336
TP	4.67	76
sOP	1.34	22

SP 2- RWW + In Plant Recycles

Q (MGD)	2.00	
	mg/L	lbs/d
BOD	212	3536
sBOD	35	589
COD	376	6254
sCOD	0	2
TSS	228	3804
VSS	193	3220
TKN	31.8	529
sTKN	21.5	358
NH4-N	19.9	331
TP	5.12	85
sOP	0.99	16
Alkalinity	279	4652

SP 3 - CFSR

MLSS	(mg/L)	3913
MLVSS	(mg/L)	2973
DO	(mg/L)	0.68
SVI	(mL/g)	100
SRT	(d)	17.2
F/M	(d^{-1})	0.104

SP 4 - RAS

Q (MGD)	2.50	
	mg/L	lbs/d
TSS	6467	134830
VSS	4880	101748

SP 6 - BFP Filtrate

Q (MGD)	0.0712	
	mg/L	lbs/d
BOD	43	26
TSS	64	38
VSS	81	48
NH4-N	0.64	0.38

SP 4 - WAS

Q (MGD)	0.0416	
	mg/L	lbs/d
TSS	6476	2245
VSS	4885	1693
Yobs (VSS/BOD)		0.56

SP 7 - Final Effluent

Q (MGD)	1.96	
	mg/L	lbs/d
BOD	4.6	77
sBOD	0.5	8
COD	23.2	386
sCOD	23.9	397
TSS	1.5	26
VSS	2.2	36
TKN	1.87	31
sTKN	1.25	21
NH4-N	0.57	9.5
NO3-N	9.92	165
TN	11.79	196
sTN	11.17	186
TP	1.13	18.7
sOP	1.11	18.5
Alkalinity	158	2634

Figure 3. Hampden Township Roth Lane WWTP Quantified Mass Flow Diagram of 15 Days of Sampling Data

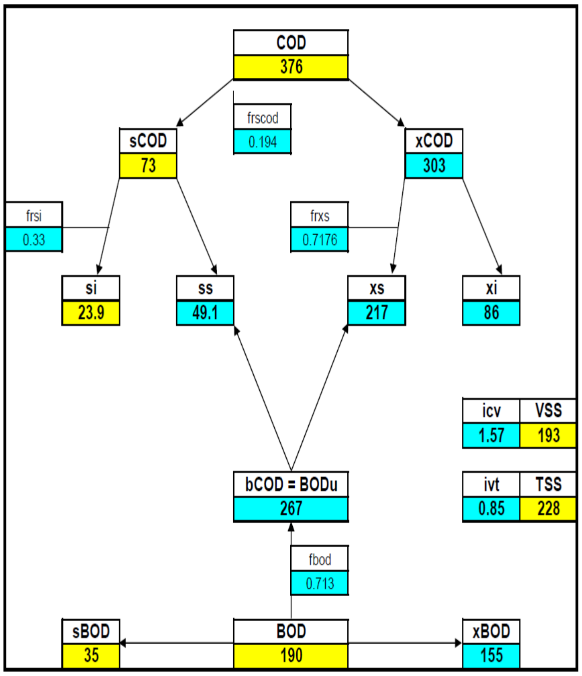


Figure 4. Roth Lane WWTP Carbonaceous Breakdown and COD Composite and State Variable.

CSR influent characterization is very important to ensure accurate model calibration. Each parameter is broken down into soluble and particulate species or components called composite variables. Each composite variable is then broken down to its various species that make up the composite variable which are called state variables. For example, the composite variables for chemical oxygen demand (COD) are soluble COD (sCOD) and particulate COD (xCOD). (*Figure 4*) These composite variables are broken down into state variables: soluble inert COD (si), soluble substrate or biodegradable COD (ss), particulate biodegradable COD (xs), and particulate inert or non-biodegradable COD (xi). Similar to COD, nitrogen and phosphorus parameters are broken down to composite and state variables. In dynamic computer modeling, the state variables are constantly integrated over time while the composite variables are calculated by simply adding up the state variables that make them up.

Step 3 – Plant Model Set-Up

The Roth Lane plant model was originally developed by Gannett Fleming (Camp Hill, Pa.) as part of an upgrade project to meet lower nutrient effluent limits. The original model was developed in GPS-X version 6.0 using the carbon, nitrogen, and phosphorus library based on the activated sludge model version 3 (ASM3). The CSR tanks were modeled as a combination of a completely-mixed reactor and the Modelling Toolbox "timer" model to control the intermittent aeration. Chemical phosphorus removal was modeled using a chemical dosage and precipitation model that was used in conjunction with ASM3. Final clarification was modeled, also in conjunction with ASM3, with a layered, one-dimensional, solids flux model which also employed a correlation to the sludge volume index (SVI). Setting-up the original plant model based on GPS-X Version 6.0 was cumbersome and time consuming since a process model for CSR was not available. An updated plant model for the Roth Lane (*Figure 5*) facility was created in 2013 using the new CSR unit process model developed for GPS-X Version 6.3.

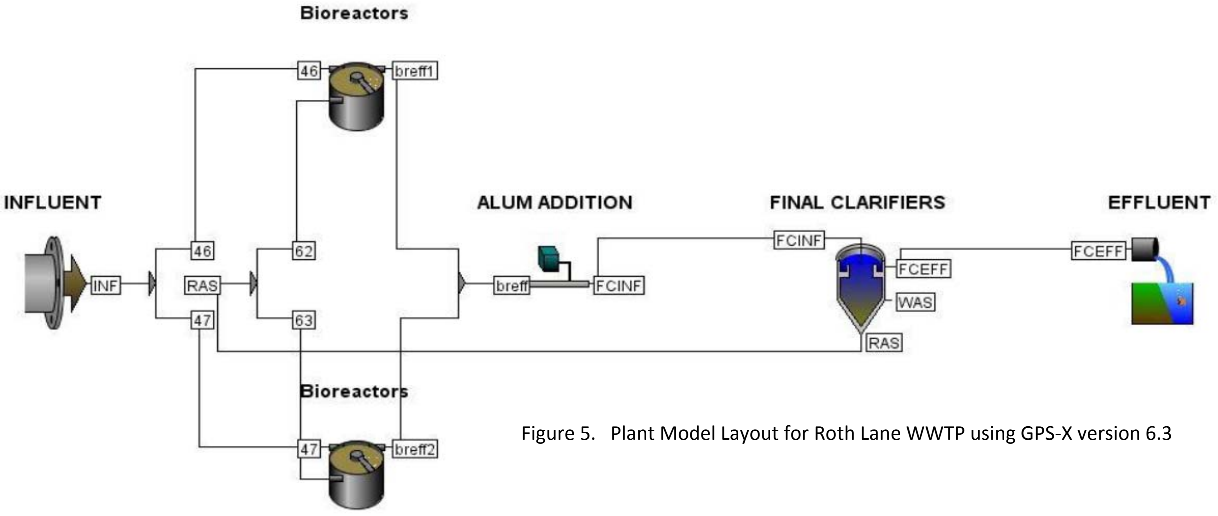
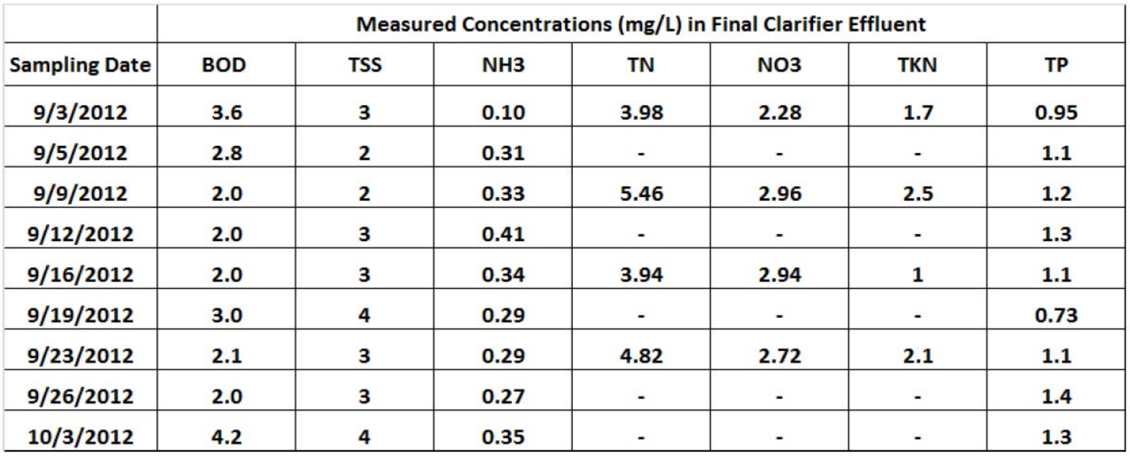


Figure 5. Plant Model Layout for Roth Lane WWTP using GPS-X version 6.3

Step 4 – Model Calibration

The updated model was calibrated using measured plant performance data (*Figure 6)* from September 1 to October 3, 2012. While the model can capture dynamic behavior at the plant on a minute-by-minute basis (as aerators turn on and off during the cycling phases of operation) the performance data at the plant was collected at much longer intervals. Composite samples for influent concentrations, MLSS and effluent concentrations were collected at intervals of a few days to two weeks. The data contained some information on dynamics at the facility; however, the scarcity of the data prevented its use for a rigorous dynamic calibration. The data does, however, contain enough information to perform a steady-state calibration of typical performance of the plant over an extended period of time. Typical average operational parameters (influent loading, RAS and WAS rates) were extracted from the data, and applied to the model.



	Measured Concentrations (mg/L) in Final Clarifier Effluent						
Sampling Date	BOD	TSS	NH3	TN	NO3	TKN	TP
9/3/2012	3.6	3	0.10	3.98	2.28	1.7	0.95
9/5/2012	2.8	2	0.31	-	-	-	1.1
9/9/2012	2.0	2	0.33	5.46	2.96	2.5	1.2
9/12/2012	2.0	3	0.41	-	-	-	1.3
9/16/2012	2.0	3	0.34	3.94	2.94	1	1.1
9/19/2012	3.0	4	0.29	-	-	-	0.73
9/23/2012	2.1	3	0.29	4.82	2.72	2.1	1.1
9/26/2012	2.0	3	0.27	-	-	-	1.4
10/3/2012	4.2	4	0.35	-	-	-	1.3

Figure 6. Plant Performance Data from Sept. 1 – Oct. 3, 2012

Step 5 – Model Simulation & Model Predictions

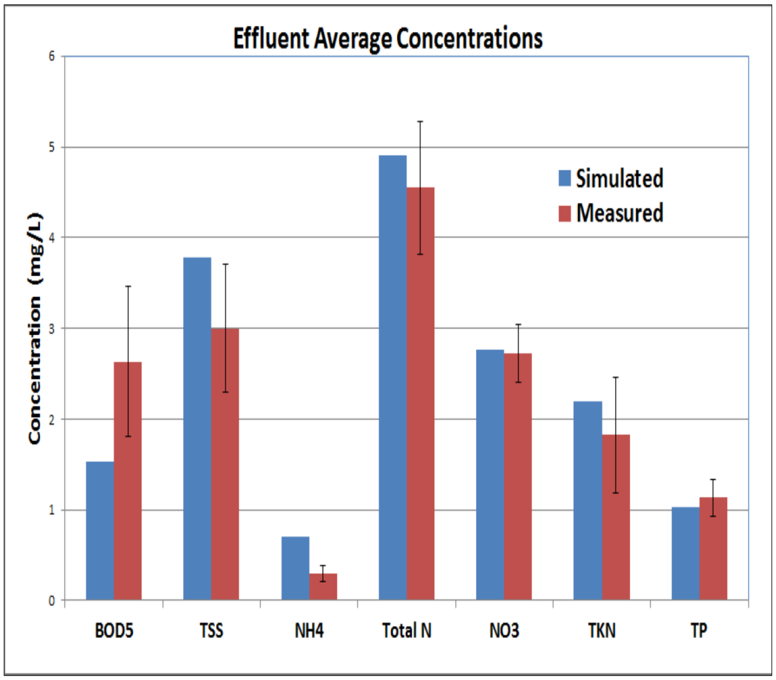
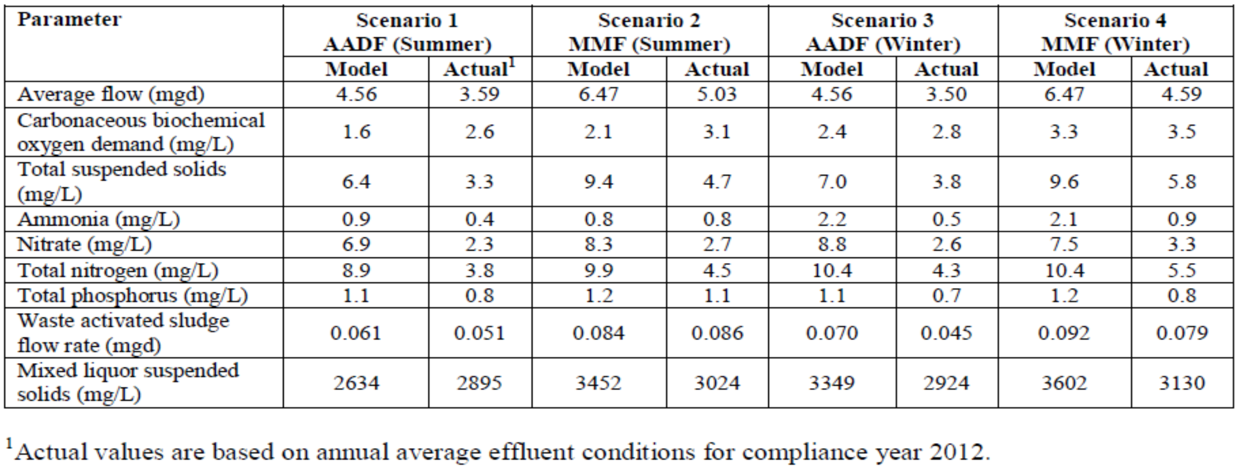


Figure 7. Steady State Model Predictions vs. Average Measured Performance

Model simulations were carried out while adjusting typical calibration parameters (influent fractions, settling parameters, etc.) to match the model to the plant performance. The steady-state model predictions vs. average measured performance (average +/- 1 standard deviation) for BOD, TSS, NH4, NO3, TN, TKN, and TP (*Figure 7)* as well as mixed liquor suspended solids (MLSS) agreed well with the average measured parameters, except with effluent TSS and BOD. The predicted effluent TSS was 1 mg/L higher than average measured TSS while the predicted effluent BOD was 1 mg/L lower than average measured BOD in the final clarifier effluent.

Model predictions (*Figure 8*) for annual average daily flows (AADF) and maximum monthly flow (MMF) at summer and winter conditions were compared to the actual plant performance for compliance year 2012. Overall, the model predictions agreed with respect to the annual average parameters measured in the final clarifier effluent and to the annual average MLSS and waste activated sludge (WAS) flow rate. The actual AADF and MMF for Roth Lane in 2012 were lower than those used for modeling to take into account additional flows and loadings from a nearby facility. In addition, the slight discrepancy between model predictions and actual effluent data could be attributed to the fact that the two CSRs were being operated in series during low flows and loadings conditions. The flexibility of operating the CSRs in series provided Hampden Township the opportunity to reduce sludge production and the operational costs associated with polymer addition. The actual annual average WAS flow rates were generally lower than those predicted by the model.



Parameter	Scenario 1 AADF (Summer)		Scenario 2 MMF (Summer)		Scenario 3 AADF (Winter)		Scenario 4 MMF (Winter)	
	Model	Actual[1]	Model	Actual	Model	Actual	Model	Actual
Average flow (mgd)	4.56	3.59	6.47	5.03	4.56	3.50	6.47	4.59
Carbonaceous biochemical oxygen demand (mg/L)	1.6	2.6	2.1	3.1	2.4	2.8	3.3	3.5
Total suspended solids (mg/L)	6.4	3.3	9.4	4.7	7.0	3.8	9.6	5.8
Ammonia (mg/L)	0.9	0.4	0.8	0.8	2.2	0.5	2.1	0.9
Nitrate (mg/L)	6.9	2.3	8.3	2.7	8.8	2.6	7.5	3.3
Total nitrogen (mg/L)	8.9	3.8	9.9	4.5	10.4	4.3	10.4	5.5
Total phosphorus (mg/L)	1.1	0.8	1.2	1.1	1.1	0.7	1.2	0.8
Waste activated sludge flow rate (mgd)	0.061	0.051	0.084	0.086	0.070	0.045	0.092	0.079
Mixed liquor suspended solids (mg/L)	2634	2895	3452	3024	3349	2924	3602	3130

[1] Actual values are based on annual average effluent conditions for compliance year 2012.

Figure 8 – Model Predictions vs. Actual Plant Performance

In addition, the model prediction for effluent nitrate was somewhat greater than the actual annual average values making the predicted effluent TN concentrations greater. It should be noted that the ASM3 model uses the oxygen half-saturation coefficient for heterotrophic bacteria, a kinetic coefficient that governs denitrification in the bioreactor as a function of dissolved oxygen. The ASM3 model default value used for the oxygen half- saturation coefficient is 0.2 mg oxygen per liter. However, there have been several studies arguing that the oxygen half-saturation coefficient should be 0.3 mg oxygen per liter, which would reduce the effluent nitrate concentration and reduce the predicted effluent TN values.

The calibrated plant model developed for Roth Lane is a powerful performance-predicting tool, which has been used to evaluate the capability of the CSR process in meeting strict effluent TN and TP limits under a variety of loadings and operating conditions. Model predictions and actual plant performance data highlighted the operational flexibility of the CSR process.

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