INTRICACIES OF MODELING THE EMERGING INTEGRATED FIXED-FILM ACTIVATED SLUDGE (IFAS) PROCESS

Article · January 2003

DOI: 10.2175/193864703784641973

INTRICACIES OF MODELING THE EMERGING INTEGRATED FIXED-FILM ACTIVATED SLUDGE (IFAS) PROCESS

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ABSTRACT

The Integrated Fixed-film Activated Sludge (IFAS) process is a technology that provides the means for effective nitrogen removal in a smaller footprint than those for conventional biological nitrification processes. It is particularly attractive for retrofitting carbonaceous-only activated sludge treatment plants as, in many cases, it can be added without the need for expanding reactor or clarifier volume. Improvements to the design of IFAS plants have been developed using process models based on the GPS-X Hybrid model, which was originally conceived for the Kaldnes Moving Bed Biofilm Reactor (MBBR), but contains all the features needed to model IFAS. The model was calibrated using pilot plant data. This paper presents the calibration steps along with typical operating data for the pilot plant. The paper also includes a discussion of the most pertinent calibration parameters, in particular the anoxic oxygen half-saturation coefficient and the hydrolysis rates used to calibrate nitrate concentrations. Nitrate concentrations measured in the pilot plant are much lower than would be predicted using a conventional activated sludge model, because of the high level of simultaneous nitrification and denitrification (SND) observed.

KEYWORDS

IFAS, modeling, nitrification, denitrification, calibration, hybrid, SND, MBBR

BACKGROUND

The Integrated Fixed-film Activated Sludge (IFAS) process is a modification of the activated sludge process whereby plastic media is suspended in the aeration basin to provide a surface on which biomass can grow. The attached-growth biomass on the media does not flow out of the aeration basin with the suspended-growth biomass, thereby reducing the solids loading on the clarifier in comparison with totally suspended-growth systems of equivalent capacity. By using the IFAS process, an activated sludge plant can approximately double its biomass inventory without increasing aeration tank volume or clarifier capacity. This feature of the IFAS process makes it an attractive proposition for carbonaceous-only plants in need of upgrading to nitrification. The IFAS process is an emerging technology that is increasing in popularity, particularly for plants facing new nitrogen-removal permits, but it must be noted that it is not a new process. It has roots in proprietary processes developed in the 1980's and 90's such as Captor, Tolley, Linpor, and Ringlace (Golla, 1992; Cooper, 1989; Hegemann, 1984; Lessel, 1991).

In recent years, Black & Veatch has conducted a number of pilot studies and implemented the process in the first municipal plant application using Kaldnes media in an IFAS process. Details of this work can be found elsewhere (Johnson, 2003). In the course of the pilot testing and design work for the projects, it was recognized that a good process model is required to facilitate good design and development of the IFAS process. This paper describes the approach taken in modeling the IFAS process and calibrating the model. Model parameter values are presented along with the results of sensitivity analysis of the most pertinent parameters for a recent process model calibration, based on data from pilot test work. This paper describes a logical approach to the modeling that can be used as a basis for further development and refinement of the models used in describing IFAS systems.

MODELING APPROACH

Different approaches can be taken for modeling the IFAS process. The simplest approach is to model it as a conventional activated sludge process with a high mixed liquor suspended solids (MLSS) concentration, and to make assumptions about the attached growth portion. Another approach would be to model the attached-growth biomass as one completely-mixed activated sludge (CMAS) tank and the suspended growth as a separate tank, with recycle streams to simulate the movement of biomass and substrate between the two. Neither approach is sufficiently sophisticated to model the complex mass-transfer and kinetic processes in the attached-growth biomass and the interactions between the attached-growth and suspended-growth microbial populations.

The dynamic modeling program, GPS-X, includes a model that was initially developed for the Moving Bed Biofilm Reactor (MBBR) process, but includes features salient to IFAS modeling. The model is termed the GPS-X "Hybrid" because it is a hybrid of a fixed-film model (GPS-X Technical Reference, Chapter 6, 2001) and a suspended-growth activated sludge model, based on the IWA activated sludge model, ASM1. The fixed-film model describes the biomass as a biofilm made up of a number of layers, each of which is modeled as a completely mixed tank. Modeling the diffusion of dissolved oxygen (DO) and other nutrients through succeeding layers and the utilization of substrate and nutrients within each layer enables the model to produce a nutrient profile through the depth of the biofilm. This is especially important in modeling the significant denitrification that is caused by anoxic conditions at the lower depths in the biofilm, and the notable DO sensitivity of fixed-film processes (Odegaard, 1994).

Table 1 highlights the importance of choosing a more sophisticated model to describe the IFAS process by comparing the effluent nitrate, ammonia, and alkalinity for a pilot IFAS plant with the results obtained from a model based on a conventional activated sludge plant (Conventional AS Model) and two sets of results from the GPS-X Hybrid model for the same pilot plant. The first set of GPS-X results is based on calibration information from a previous pilot test (Initial Calibration); the second set is based on a more complete calibration using the actual pilot data (Fully Calibrated). The percentage value shown in the table beneath effluent nitrate and alkalinity value is the error between the model value and actual pilot data expressed as a percentage of the pilot data. This data shows that the conventional activated sludge plant model gives a reasonable prediction of the effluent ammonia concentration (it predicts that the pilot will fully-nitrify, and it does!), but it significantly over-estimates the effluent nitrate concentration. The GPS-X Hybrid model gives a better prediction of the effluent nitrate concentration, even with the initial calibration based on data from a previous pilot study, and it can be finely calibrated to match both effluent ammonia and nitrate concentrations. In this example, the conventional activated sludge under-predicts effluent alkalinity – most likely because it under-predicts the denitrification processes which recover alkalinity. The GPS-X model, on the other hand, predicts an effluent alkalinity higher than measured values, though the error is of a lesser magnitude than the overestimate by the conventional model.

Table 1: Model Calibration - Conventional Activated Sludge and GPS-X Hybrid

	Pilot Data	Conventional AS Model	Hybrid Model	
			Initial Calibration	Fully Calibrated
Effluent Nitrate, mg/L	7.1	10.5	8.6	7.0
% Error		*48%*	*21%*	*-2%*
Effluent Ammonia, mg/L	0.05	0.09	0.6	0.05
Effluent Alkalinity, mg/L	150	117		174
% Error		*-22%*		*16%*

Development of the Hybrid model has involved a great deal of calibration work, particularly by Kaldnes and Anglian Water Services (AWS) using MBBR processes (Wicks, 2002), which has established reasonable default values for the model and provided valuable experience in determining which parameters should be adjusted when calibrating the model for MBBR. However, the model has not been widely used for IFAS processes, leaving its calibration for IFAS an uncharted territory.

MODEL CALIBRATION

In designing IFAS systems, a number of GPS-X Hybrid models have been constructed and calibrated using pilot plant data. The pilot plant used in each of these studies consists of three tanks in series. The first tank operates in an anoxic mode with no IFAS media present, as a suspended growth system. The remaining two tanks are filled with media to a prescribed fill percentage and aerated. Figure 1 is a process layout for the pilot plant calibration. As indicated on the figure, in the pilot plant, and consequently in the model, no mixed liquor is returned from the aerobic reactors to the anoxic zone to achieve a higher degree of denitrification. The effect of recycling mixed liquor was instead simulated by increasing the return activated sludge (RAS) flow rate.

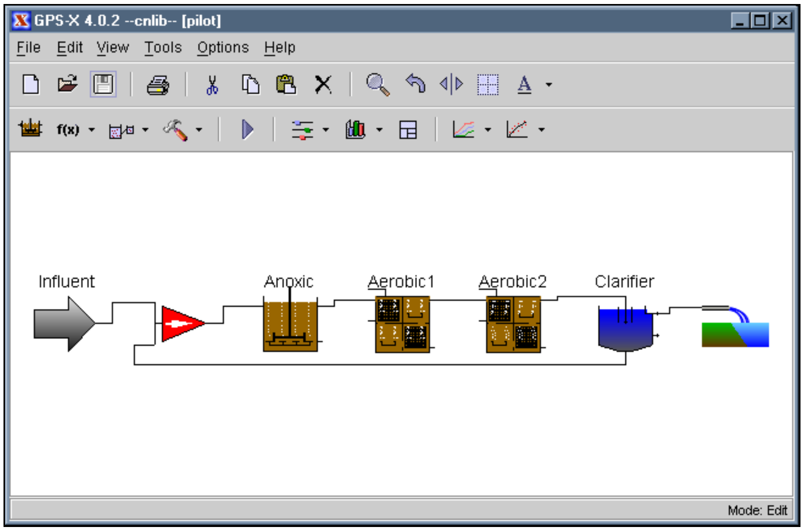

Figure 1 : Layout of Pilot Plant Model

Each pilot model was calibrated using the following three-step approach:

1. The biofilm thickness is fixed to match the mass of solids attached to the media per unit area.
2. The rate of wasting is fixed to match the suspended-growth MLSS.
3. Kinetic parameters are adjusted to match ammonia and nitrate concentrations in the effluent and through the plant.

Steps 1 and 2 effectively fix the quantities and proportions of biomass inventory in the attached growth and suspended growth phases. These steps are relatively straightforward as they are based on parameters that can be measured directly and are easily calibrated in the model. The third, and final, step is more difficult as it requires manipulation of many more parameters, many of which are impossible to measure and must either be estimated or inferred from other parameters. Table 2 contains the information extracted from the model for its initial calibration using Steps 1 and 2, described above. The "Total Equivalent Solids" concentration is equivalent to the mixed liquor suspended solids (MLSS) concentration that would be required to maintain the same biomass inventory in each reactor as that contained in the attached growth on the media plus the suspended growth. The "Attached Solids" is calculated by simply subtracting the suspended solids from total equivalent solids value. This value is then used along with media fill and specific surface area to calculate the "Attached solids per m^2" which is then compared to measured data. The "Max Biofilm Thickness" parameter in the model is adjusted until the attached solids per m^2 values match. Finally, the waste activated sludge (WAS) flow is adjusted in the model until the MLSS values also match.

Table 2 : Initial Calibration Data

Average Influent Concentrations and flows	
Influent Flow	9.8 m^3/day
BOD	102 mg/L
COD	186 mg/L
TSS	84 mg/L
VSS	74 mg/L
Ammonia	18.7 mg/L
TKN	34.7 mg/L
Nitrate	0.2 mg/L
RAS flow	19.6 m^3/day
First IFAS Reactor	
Mixed Liquor Suspended Solids	1750 mg/L
Total Equivalent Solids (Attached + Suspended)	4390 mg/L
Attached Solids	2650 mg/L
Attached Solids per m^2	13.2 g/m^2
Dissolved Oxygen	3.0 mg/L
Reactor Volume	0.67 m^3
Media Fill	40%
Media Specific Surface	500 m^2/m^3
Max Biofilm Thickness	0.14 mm
Second IFAS Reactor	
Mixed Liquor Suspended Solids	1740 mg/L
Volatile Solids, % of MLSS	86%
Total Equivalent Solids (Attached + Suspended)	3250 mg/L
Attached Solids	1510 mg/L
Attached Solids per m^2	7.6 g/m^2
Dissolved Oxygen	4.0 mg/L
Reactor Volume	0.67 m^3
Media Fill	40%
Media Specific Surface	500 m^2/m^3
Max Biofilm Thickness	0.08 mm

As mentioned previously, calibration of the kinetic parameters is more difficult. It is done out by comparing data from the model with data from the pilot plant for each of the reactors and then repeatedly adjusting kinetic parameters until the values match. This iterative procedure can be simplified somewhat by using the dynamic data exchange (DDE) capabilities of GPS-X that enable the user to dynamically link a model to an Excel spreadsheet, where the model outputs are compared against pilot data. Table 3 shows the results of carrying out the third step using this approach. Information for each parameter is shown in three lines – the first line is the value from the model, the second is the pilot plant data and the final line, labeled "Calibration Fit", is simply the model data compared with the pilot data expressed as a percentage of the pilot data. The results are shown for the mixed liquor entering the pilot reactors (influent plus RAS), for each of the three reactors, and for the effluent. Calibration fit values which indicate that the model value is within ±10 percent of the pilot value are highlighted in **BOLD** type. Values in excess of 20% outside the pilot values are shown in *Italics*.

It can be seen that it is possible to an obtain extremely good fit between the model and pilot plant data for most of the parameters presented in Table 3, with the notable exception of the nitrate concentrations in the reactors (although the effluent nitrate concentration does match well).

Table 3: IFAS model calibration outputs

Through-Plant Calibration (all concentrations in mg/L, Biofilm mass in g/m²)					
	ML In (Inf+RAS)	**Anoxic**	**R2 Aerobic IFAS**	**R3 Aerobic IFAS**	**Effluent**
Model Ammonia	6.41	6.17	2.17	0.20	0.05
Pilot Ammonia	*5.8*	*6.8*	*2.1*	*0.20*	*0.05*
Calibration Fit	110%	**91%**	**103%**	**101%**	**93%**
Model Nitrate/Nitrite	4.57	0.57	4.39	6.80	6.98
Pilot Nitrate/Nitrite	*3*	*0.1*	*2.6*	*6.0*	*7.1*
Calibration Fit	*152%*	*575%*	*169%*	113%	**98%**
Model Alkalinity	205	219	191	175	174
Pilot Alkalinity	*186*	*200*	*187*	*188*	*150*
Calibration Fit	110%	**109%**	**102%**	**93%**	116%
Model TSS	1787	1796	1789	1784	11
Pilot TSS	*1523*	*1820*	*1977*	*1810*	*12*
Calibration Fit	117%	**99%**	**91%**	**99%**	**93%**
Model VSS	1506	1516	1509	1504	9.44
Pilot VSS	*1291*	*1553*	*1623*	*1529*	
Calibration Fit	117%	**98%**	**93%**	**98%**	
Model DO	0.78	0.00	3.00	4.00	1.94
Pilot DO		*0.24*	*2.9*	*4*	
Calibration Fit		*2%*	**103%**	**100%**	
Model Biofilm Mass			13.48	7.85	
Pilot Biofilm Mass			*13.45*	*7.76*	
Calibration Fit			**100%**	**101%**	
Notes: Values from the model (normal type) are compared with values measured in the pilot plant (*in italics*). Comparison is formatted to highlight the areas where calibration is good or bad. Model values within +/- 10% of the pilot values are in **BOLD** type – values outside of +/- 20% are in *italics*.					

The results presented in this table are from the same model as used to generate the values presented in Table 2.

Table 4 lists the pertinent calibration parameters for the Hybrid model for the first IFAS zone (R2, in Table 3) and presents the values used for three different plant designs. These values are shown alongside the default values in the model. Pilot 2 values were used to develop the model results shown in the preceding tables in this paper.

Table 4: Calibration Values for First Reactor for Three Designs Compared to Defaults

	Site Name				
First IFAS Reactor	*Default*	**Pilot 2**	**Pilot 1**	**Site 3 Design**	*Units*
Biofilm Related Parameters					
Maximum biofilm thickness	*0.5*	0.14	0.15	0.15	*mm*
High concentration inhibition					
Autotrophic high concentration inhibition	*5,000*	3,250	2,500	2,500	*gCOD/m³*
Active Heterotrophic Biomass					
Heterotrophic maximum specific growth rate	*3.2*	6	*3.2*	*3.2*	*1/d*
Aerobic oxygen half saturation coefficient	*0.2*	*0.2*	*0.2*	*0.2*	*gO2/m³*
Anoxic oxygen half saturation coefficient	*0.2*	**3**	3	3	*gO2/m³*
Anoxic growth factor	*0.8*	*0.8*	1	1	-
Nitrate half saturation coefficient	*1*	0.1	0.1	*1*	*gN/m³*
Ammonia (as nutrient) half saturation coefficient	*0.05*	0.005	0.005	0.005	*gN/m³*
Active Autotrophic Biomass					
Autotrophic maximum specific growth rate	*0.75*	0.9	0.9	0.9	*1/d*
Oxygen half saturation coefficient	*0.2*	0.5	*0.2*	*0.2*	*g/m³*
Autotrophic decay rate	*0.04*	0.17	0.17	0.17	*1/d*
Hydrolysis					
Maximum specific hydrolysis rate	*2.81*	**6**	6	6	*1/d*
Anoxic hydrolysis factor	*0.37*	0.5	*0.37*	*0.37*	-
Ammonification					
Ammonification rate	*0.016*	0.04	0.04	0.04	*m³/gCOD/d*
Temperature					
Temperature coefficient for muh *(maximum growth)*	*1.12*	1.03	1.03	1.03	-
Temperature coefficient for mua *(maximum growth)*	*1.12*	1.07	1.07	1.07	-
Temperature coefficient for kh *(half-saturation)*	*1.07*	1.00	1.00	1.00	-
Temperature coefficient for ka *(half-saturation)*	*1.03*	1.00	1.00	1.00	-

Notes: Numbers in *italics* not changed from the default parameters. Kinetic parameters not shown are as default.

There are 17 kinetic parameters that have been adjusted in calibrating just one of the three reactors in the model. An attempt was made to be consistent in applying the same kinetic parameters in each reactor, but in some instances slight variations were necessary to obtain a better calibration. Some parameters, such as the growth and decay rate coefficients for the autotrophic biomass, were adjusted to match the values currently used by Black & Veatch for activated sludge process in general, and were not specifically calibrated to the pilot plant data.

Two parameters are highlighted in bold in Table 4 – the anoxic oxygen half-saturation coefficient for the heterotrophic biomass and the maximum specific hydrolysis rate. Both were adjusted to values significantly different from the default values as well as from those normally used in activated sludge process modeling. The anoxic oxygen half-saturation coefficient is a switching function used in the model to determine how low the dissolved oxygen concentration must be for anoxic processes to occur. Increasing this value significantly increases the amount of denitrification that occurs under aerobic conditions. In other words, it increases the amount of simultaneous nitrification and denitrification (SND) in the model. The hydrolysis rate determines how rapidly the slowly biodegradable substrate breaks down to soluble substrate that can be utilized by the heterotrophic biomass, either aerobically or anoxically. Both of these parameters had a great impact on the effluent nitrate concentration and it was necessary to adjust them in order to match the model values to the effluent nitrate concentrations observed in the pilot plant. As noted previously, even with these extreme adjustments, it was not possible to match the nitrate concentrations in each reactor as closely as were the other parameters.

SENSITIVITY ANALYSIS

Both the anoxic oxygen half-saturation coefficient and the hydrolysis rate had a significant impact on the effluent nitrate concentration in the model. In order to give a good indication of the magnitude of the influence of these parameters on the effluent nitrate concentration, a number of sensitivity analyses were conducted. In a sensitivity analysis, the model is repeatedly run maintaining all parameters at the same values except for the parameter of interest, which is incrementally increased for each model run over a designated range. The results are usually presented graphically as a plot of the model output value versus the parameter of interest. In this analysis, the model output value that is plotted against each parameter is the effluent nitrate concentration. Phillips (2002) gives a more detailed description of sensitivity analysis in process models and provides several examples.

Initially, three sets of sensitivity analyses were carried out. The first was for the anoxic oxygen half-saturation coefficient and the second and third to show the effect of varying hydrolysis rates. In addition, separate analyses were run to determine the effect of adjusting oxygen diffusivity. This parameter was not adjusted in the calibration runs but was analyzed to determine its potential use for calibration as an alternative to adjusting the anoxic oxygen half-saturation coefficient.

Figure 2 shows the results of the sensitivity analysis for the anoxic oxygen half-saturation coefficient for reactor 2. The dotted vertical line shows the normal default value and the large point on the curve shows the calibrated model value. It can be seen that increasing this parameter has a significant impact on the effluent nitrate concentration, reducing it from just over 10 mg/L at the default setting to 6.98 mg/L for the calibrated model.

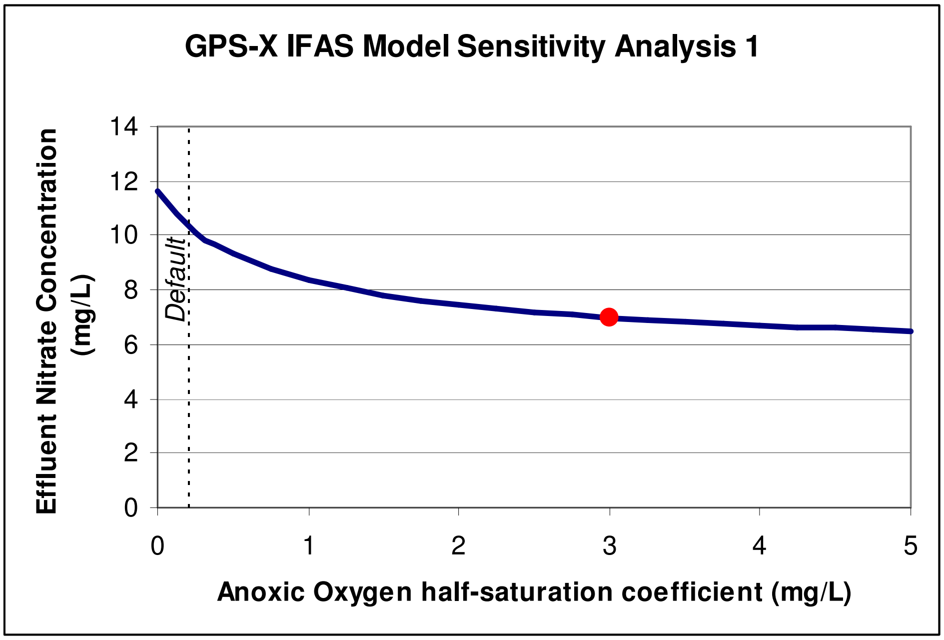

Figure 2: Anoxic Oxygen Half-Saturation Coefficient Sensitivity Analysis

The next two sets of sensitivity analyses show that increasing the hydrolysis rate in reactor 2 actually increase the effluent nitrate slightly, but increasing the hydrolysis rate in reactor 1 decreased the effluent nitrate more significantly. Using the higher hydrolysis rate for both reactors in the calibrated model (again indicated by the large point), has an overall effect of decreasing the effluent nitrate concentration

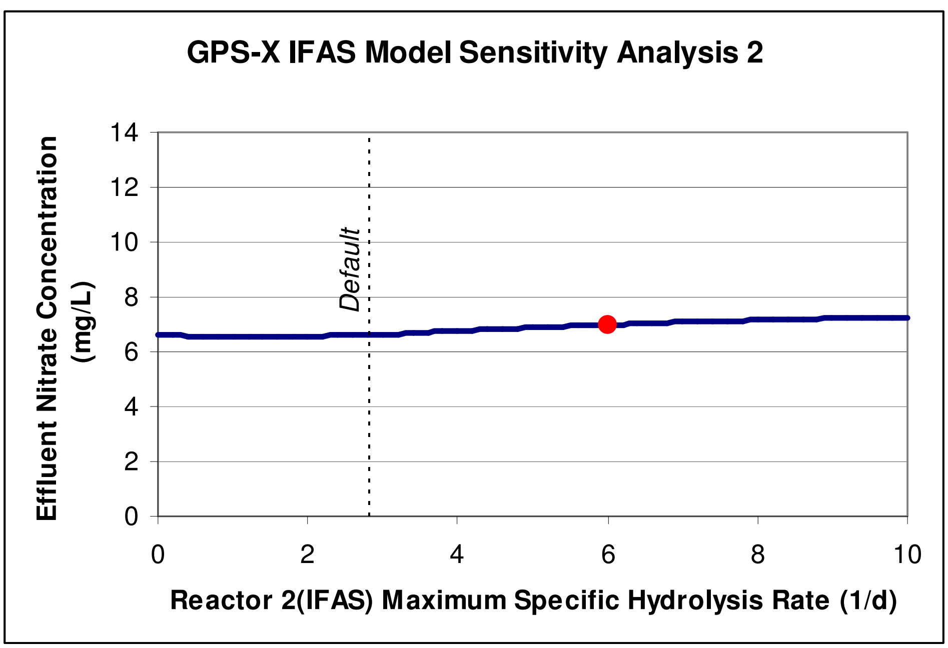

Figure 3: Hydrolysis Rate Sensitivity Analysis – Reactor 2

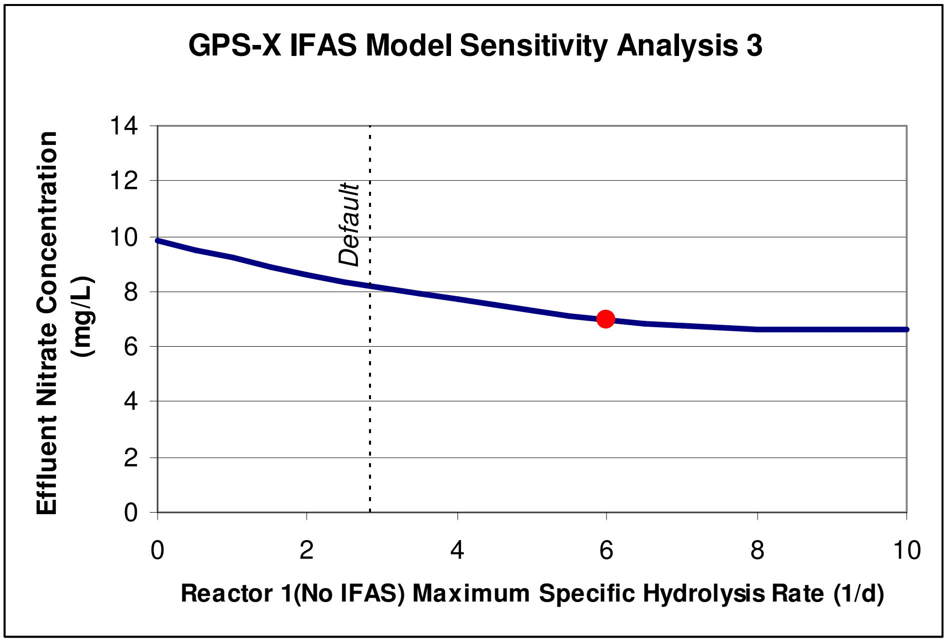

Figure 4: Hydrolysis Rate Sensitivity Analysis - Reactor 1

The final set of sensitivity analyses was conducted to investigate the impact of adjusting the dissolved oxygen diffusivity. In theory, decreasing this parameter should restrict the movement of dissolved oxygen into the biofilm, which should decrease dissolved oxygen concentrations in the biofilm and consequently increase the amount of anoxic activity. The net effect should be reduction of the effluent nitrate concentrations as the diffusivity is decreased. Two sets of sensitivity analyses were carried out for this parameter. The first analysis used the existing calibrated model and in the second analysis the anoxic oxygen half-saturation coefficients are reset back to their default concentrations. In both sets of analyses, the parameter was adjusted in reactor 2 only.

Figure 5 shows the results of the two analyses: the solid line curve shows the results for the calibrated model and the broken line curve is for the model with default anoxic oxygen half-saturation coefficients. It is apparent that the effluent nitrate concentration does decrease as the diffusivity decreases, as expected. However, the curve for the values with the anoxic oxygen half-saturation coefficients reset to default values is much higher than for the calibrated model, even when the diffusivity approaches zero. This indicates that the oxygen diffusivity could not be used to calibrate the model as effectively as the anoxic oxygen half-saturation coefficients.

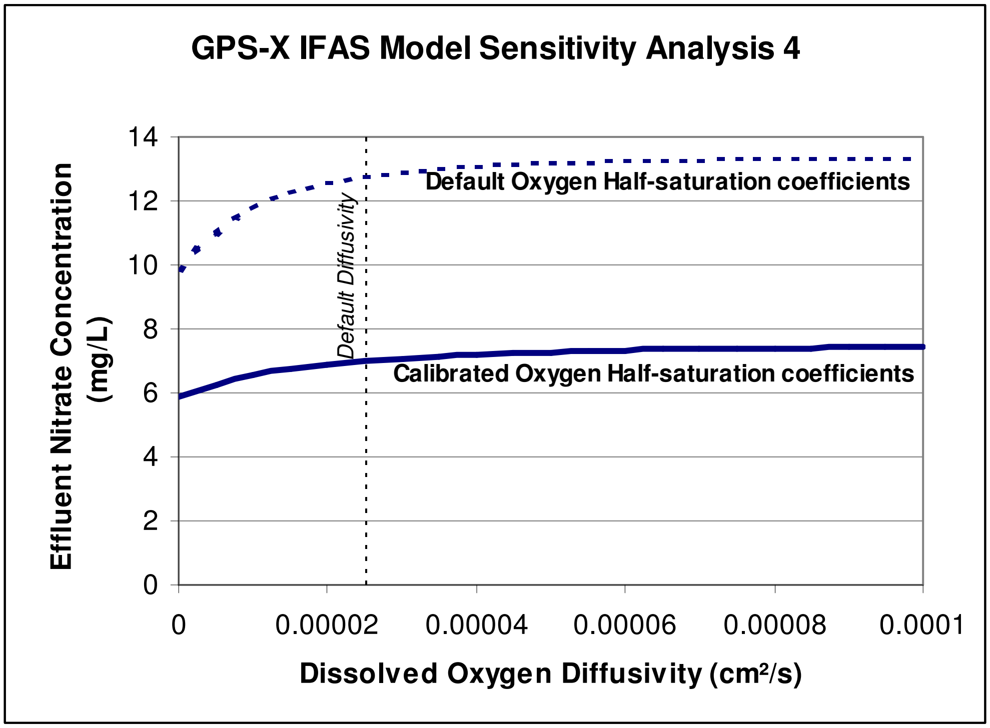

Figure 5: Dissolved Oxygen Diffusivity Sensitivity Analysis

DISCUSSION

The GPS-X Hybrid model provides a good framework for developing IFAS process models. It is possible to calibrate the model to achieve a good match between the biomass concentration in both the attached growth and suspended growth phases of the process in each reactor. The model is readily calibrated to match ammonia concentrations and nitrification rates throughout the process.

In addition to the work presented in this paper, which has focused on the steps required to calibrate the Hybrid model to given data, the model can also be used to determine the effect of adjusting design parameters such as recycle flows, tank sizes, and percentage fills and the effect of environmental factors such as temperature and operating dissolved oxygen concentration.

The most difficult parameters to calibrate in the model are the denitrification rates that dictate the nitrate concentrations through the plant. The pilot data indicates that effluent nitrate concentrations are much lower than expected from modeling the process, either as an activated sludge process or using the Hybrid model with default kinetic parameters. It is evident that the IFAS process includes a significant degree of SND. Simulating this in the model necessitates adjusting key kinetic parameters to values beyond the normally accepted range. The hydrolysis rate in these calibrations has been increased to a value much greater than the default value; however, it is recognized that this parameter is difficult to measure, and the default value may not suitable for all applications – particularly for attached growth processes. Morgenroth, et al. (2002) discuss this further in their paper.

The need to significantly increase the anoxic oxygen half-saturation coefficients to such high values is of greater concern. It is unlikely that anoxic processes are really occurring at dissolved oxygen concentrations as high as those modeled in the calibrated models, but adjusting this parameter does enable the modeler to mimic the SND observed in the actual process. The actual mechanism for the increased degree of SND may not be fully understood, but this approach does allow the data to be fitted. It is a compromise in the modeling that enables us to move forward with the calibration until we have more information and gain a more thorough understanding of the process.

It is suggested that one cause for the high degree of SND and the difficulty in forcing the model to match observed data may be related to the role played by nitrite in nitrification and denitrification processes. It may be that in the IFAS process a significant portion of the nitrite formed in the first step of nitrification is not oxidized to nitrate but is instead dentrified. Further testing is required to substantiate this theory, including adjusting the Hybrid model to model both nitrification and denitrification in two steps, and more detailed measurements of nitrite concentrations in IFAS processes.

It is worth mentioning here that the Hybrid model is just one approach to modeling the IFAS process. The formulation of an IFAS model requires a synergy of fixed-film and attached growth models, which could be achieved by several methods. One commonly used approach is to model the suspended growth process using a conventional model or design equation, and then to account for the additional nitrification using a design equation for the nitrification rate per surface area. Another, similar, approach would be to model the biofilm processes using an empirical fixed-film model such as that proposed by Velz (1948). It should be noted that both of these approaches are significantly less sophisticated than the Hybrid model and do not take into account the interactions between the attached growth and suspended growth biomass phases.

The modeling work described in this paper was based on pilot studies using Kaldnes media. The approach is equally applicable to all IFAS processes, but care must be taken in choosing an appropriate specific surface area that represents the <u>effective, or protected,</u> surface area available for biomass growth. With some types of media, this can be a difficult and contentious subject. It is recommended that pilot studies be conducted to calibrate the model for various types of media. A model calibrated for one type of media should generally not be used to predict the performance of a different type.

CONCLUSIONS

The GPS-X Hybrid model is a useful tool for modeling IFAS processes. It is possible to calibrate the model to achieve a good match with pilot plant data. A three-step approach to modeling the IFAS process has been developed. The first two steps consist of setting the biomass inventory for the attached growth and suspended growth phases. In the final, and more difficult, step the kinetic parameters are adjusted to calibrate the nitrification and denitrification processes in the model.

Further work is required to develop our understanding of denitrification in the IFAS process, in particular the mechanisms for SND. Focusing our attention to the role played by nitrite in the two step processes of nitrification and denitrification may increase this understanding and provide insight that may further improve the model.

REFERENCES

Cooper, P. (1989) Demonstration and evaluation of the Captor process for sewage treatment. *US EPA Project Summary,* EPA/600/S2-88/060

Golla, P.S., Reddy, M. P., Laken, T. and Lin, A. (1992) Captor process application in Moundsville/Glendale WWTP, WV. *Proceedings 16th Biennial IAWPRC International Conference,* Washington DC.

Hegemann, W. (1984) A combination of activated sludge process with fixed film biomass to increase the capacity of waste water treatment plants. *Water Science & Technology*, Vol 16, pp 119-130.

Hydromantis Inc. (2001) GPS-X Version 4.01, Technical Reference Manual.

Johnson, T. L., McQuarrie, J. P. and Shaw, A. R. (2003) The Advantages of Age. Integrated fixed-film activated sludge process enhances treatment, not footprint, *Water Environment and Technology*, April 2003, pp 34-39

Lessel, T. H. (1991) First practical experience with submerged rope-type (Ringlace) biofilm reactors for upgrading and nitrification. *Water Science & Technology* Vol. 23, pp 825-834

Morgenroth, E., Kommedal, R. and Harremoes, P. (2002) Processes and modeling of hydrolysis of particulate organic matter in aerobic wastewater treatment – a review. *Water Science & Technology*, Vol. 45, No. 6 pp 25-40

Odegaard, H., Rusten, B. and Westrum, T. (1994) A new moving bed biofilm reactor – applications and results. *Water Science & Technology* Vol. 29, No.10-11 pp.157-165

Phillips, H. and Shaw, A. R. (2002) A New Approach to Optimizing the Operation and Control of Enhanced Nitrogen Removal Plants Using Computer Modeling Sensitivity Analysis. *Water Environment Federation, 4th Annual Plant Operations and Maintenance Specialty Conference,* Kansas City, Missouri, August 2002.

Velz, C. J. (1948) A basic law for the performance of biological beds. *Sewage Works Journal*, Vol. 20, No.4.

Wicks, J (2002) GPS-X Training: Kaldnes Modeling. *AWG Training Course,* Kansas City, Missouri, March 2002.