Experiences with computer simulation at two large wastewater treatment plants in northern Poland

J. Makinia*, M. Swinarski and E. Dobiegala*****

* Technical University of Gdansk, Department of Hydro- and Environmental Engineering, ul. Narutowicza 11/12, 80-952 Gdansk, Poland

** SAUR Neptun Gdansk S.A., ul. Walowa 46, 80-858 Gdansk, Poland

*** Przedsiebiorstwo Wodociagow i Kanalizacji Sp. z o.o., ul. Witominska 21, 81-311 Gdynia, Poland

Water Science and Technology **Vol 45 No 6 pp 209–218** © IWA Publishing 2002

Abstract Mathematical modelling and computer simulation have became a useful tool in evaluating the operation of wastewater treatment plants (WWTPs) in terms of nutrient removal capability. In this study, steady-state simulation results for two large biological nutrient removal WWTPs are presented. The plants are located in two neighbouring cities Gdansk and Gdynia in northern Poland. Simulations were performed using a pre-compiled model and layouts (MUCT and Johannesburg processes) implemented in the GPS-X simulation package. The monthly average values of conventional parameters, such as COD, Total Suspended Solids, total N, N-NH_4^+, P-PO_4^- were used as input data. The measured effluent concentrations of COD, N-NH_4^+, N-NO_3^- and P-PO_4^- as well as reactor MLSS were compared with model predictions. During calibration, performed from the process engineering perspective, default values of only five model parameters were changed. The opportunities for further applications of such models in municipal WWTPs are discussed.

Keywords Activated sludge; computer simulation; full scale wastewater treatment plants; mathematical modelling; model calibration; nutrient removal; plant operation

Introduction

In recent years, several different mechanistic activated sludge models have been developed (Henze *et al.*, 1995 and 1999; Barker and Dold, 1997; Murnleitner *et al.*, 1996; Rieger *et al.*, 2001). All these models are capable of simulating COD removal, nitrification, denitrification and biological phosphorus removal. Due to a large number of processes involved, the model structures are complex with many kinetic and stoichiometric coefficients. The results of several studies (Mino *et al.*, 1997; Cinar *et al.*, 1998; Van Veldhuizen *et al.*, 1999; Brdjanovic *et al.*, 2000; Satoh *et al.*, 2000; Wichern *et al.*, 2000) have indicated that values of only a few coefficients need to be adjusted during model calibration. Most of these coefficients can be estimated using specialized studies such as batch tests or concentration profiles along the bioreactor. However, under the traditional plant operation even such data are not usually available and routinely performed analyses of conventional parameters (e.g. BOD_5, TSS) are not directly applicable to the mentioned models (Grady *et al.*, 1999).

In the literature, there are very few examples of modelling using "steady state" (averaged over a certain period) operating data as model inputs. Cinar *et al.* (1998) tested such an opportunity with Activated Sludge Model No. 2 (Henze *et al.*, 1995) at four full-scale WWTPs, obtaining successful results in two cases. A similar approach was used in this study. The operating data originated from two large biological nutrient removal (BNR) plants located in northern Poland. The main efforts were focused on demonstrating the methodology of converting such data to modelling purposes and the role of plant operation in process modelling rather than evaluating predictive capabilities of the model itself.

Methods

Process description of the WWTPs

"Wschod" WWTP. The "Wschod" WWTP is the largest facility in northern Poland serving a population of the city of Gdansk and adjusting communities (approximately 500,000 inhabitants). Including the industrial wastewater discharges the total pollutant load to the plant corresponds to approximately 700,000 PE. The designed hydraulic capacity is equal 180,000 m^3d^{-1}, but the actual average daily flowrate is currently only approx. 85,000 m^3d^{-1}. Although a separate sewerage system exists in the entire catchment, a significant increase in the wastewater flowrates (by 20–60%) has been observed during and after storm events.

The "Wschod" WWTP went into operation in the early 1970s, but only mechanical treatment was provided until 1998. Then the plant was gradually upgraded with a biological step. Six parallel biological reactors running in the MUCT process and twelve circular secondary clarifiers were constructed. A schematic flow diagram of a single reactor is shown in Figure 1. The air is supplied to the aeration zone by means of a diffused aeration system. The set point for dissolved oxygen (DO) concentration (2 gO_2 m^{-3}) is controlled based on the "on-line" measurements in each compartment of the aeration zone. In order to improve biological phosphorus removal efficiency a primary sludge fermenter was added to the treatment line.

"Debogorze" WWTP. The "Debogorze" WWTP treats wastewater originating from the city of Gdynia and four surrounding smaller towns. Currently, a population of approximately 330,000 inhabitants is connected to the plant by a separate sewerage system in the entire catchment. The average pollutant load corresponds to over 500,000 PE. It means that a significant contribution originates from the industrial wastewater discharges although in terms of volume they account only for 18% of the total amount. The average daily wastewater flowrate was equal to 66,000 m^3d^{-1} in 2000, however, during heavy storm events the wastewater flowrates were reaching the hydraulic capacity of the plant (135,000 m^3d^{-1}).

The "Debogorze" WWTP provided only mechanical treatment until the beginning of the 1990's. The first biological step (a conventional activated sludge process) was completed in 1994, but even then the plant effluent did not meet the new Polish standards of 1991. Therefore, a further expansion towards BNR was necessary. The project was completed in the middle of 1997. Currently, the biological step of the plant consists of four parallel bioreactors (Johannesburg process) and six secondary clarifiers. A schematic flow diagram of a single reactor is shown in Figure 2. The air flowrate to the aerobic zone is provided with a diffused aeration system and is controlled at the set point of 4 gO_2 m^{-3} in the third compartment (the only point where DO concentrations are measured "on-line"). At the "Debogorze" WWTP, a primary sludge fermenter was also constructed to improve biological phosphorus removal efficiency.

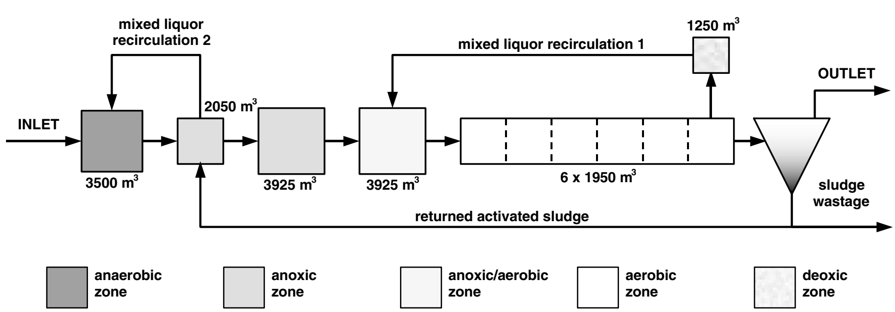

Figure 1 A schematic flow diagram for a single biological reactor at the "Wschod" WWTP

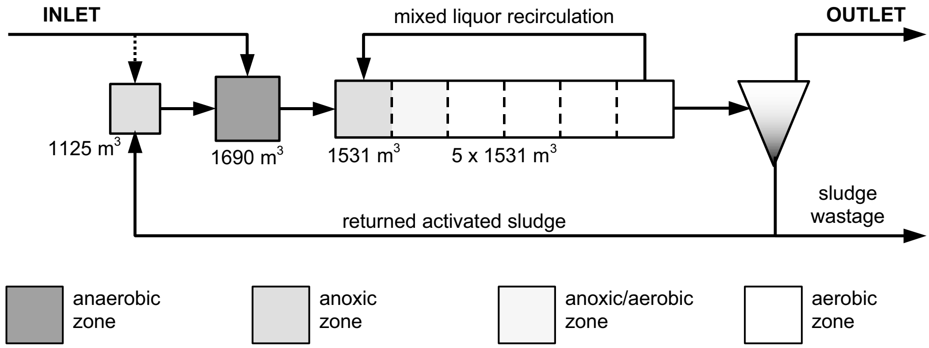

Figure 2 A schematic flow diagram for a single biological reactor at the "Debogorze" WWTP

Databases for "steady state" simulations

For simulation purposes, routine operational data from the "Wschod" and "Debogorze" WWTPs were used. Conventional parameters measured in the primary effluent (including the recycle from the fermenters) are listed in Table 1. The corresponding values represent the range of monthly average values calculated based on the daily composite samples. Lab analyses were performed 5 times per month at the "Debogorze" WWTP (except for volatile fatty acids which were measured every day in grab samples) and approximately 10 times per month at the "Wschod" WWTP. On the same days, composite samples of wastewater in the secondary effluent were analysed for the same range of parameters (plus nitrates). Some of these parameters were further used to evaluate model predictions.

Modelling process

Several different approaches to modelling are possible (Andrews, 1992), but the most crucial step in the entire process is model calibration. It can be viewed from different perspectives (system engineering vs. process engineering) as presented by Van Veldhuizen *et al.* (1999). In the first case, parameters for calibration are selected based on sensitivity analysis, whereas the second approach involves the process knowledge and professional experience of the modeler. Cinar *et al.* (1998) used the term "human expert" for this

Table 1 Characteristics of the settled wastewater and operational parameters at the "Wschod" WWTP and "Debogorze" WWTP

Parameter	Unit	"Wschod" WWTP	"Debogorze" WWTP
Wastewater:			
COD	gCOD m^{-3}	458–799	477–629
BOD_5	$gBOD_5\ m^{-3}$	206–324	270–374
TSS	g m^{-3}	179–435	190–252
TKN	gN m^{-3}	62–76	66–81
$N\text{-}NH_4^+$	gN m^{-3}	40–52	34–43
$P_{tot.}$	gP m^{-3}	11.1–22.5	11.8–22.0
$P\text{-}PO_4^-$	gP m^{-3}	6.5–13.2	9.4–14.6
Volatile fatty acids (grab samples)	$g(CH_3COOH)\ m^{-3}$	not regular	86–128
Operation:			
Influent flowrate to a single reactor (Q)	$m^3\ d^{-1}$	20,600–25,600	14,500–18,600
Returned activated sludge, (Q_{RAS})	% of Q	110	125
Mixed liquor recirculation 1 (Q_{MLR1})	% of Q	320	300–400
Mixed liquor recirculation 2 (Q_{MLR2})	% of Q	100	–
MLSS concentration	kg m^{-3}	3.43–4.11	4.69–6.59
Sludge retention time (SRT)	d	15–22	15–23
Temperature in the bioreactors	°C	12.4–20.8	13.5–20.7

method. Its example with respect to a model of the activated sludge process was discussed by Henze *et al*. (1995). Coen *et al*. (1997) proposed a procedure for calibrating a general model of WWTP from the process engineering perspective. The most important elements involved the determination of reactor hydraulics, characterization of wastewater and biomass as well as calibration of model parameters. For the purpose of this study, a similar approach was adapted and a general modelling environment was organized into three layers: theoretical models, modelling process and plant operation (Figure 3). Since this research was focused on evaluating the applicability of plant operating data to comprehensive models, special attention was paid to relationships between the last two mentioned layers (i.e. modelling process and plant operation). In the plant operation layer, existing measurements at a WWTP are specified. These data should be analysed using statistical methods (e.g. standard deviation) since highly variable data are not suitable for steady state models. In some cases, the scope and methods of measurement would need a revision based on the requirements of the modelling process.

It should be emphasized that not all elements of this general approach could be implemented at the "Wschod" and "Debogorze" WWTPs. For example, during the operation of both plants no attempts have been made so far to study the actual reactor hydraulics, although the aeration zones were designed as "plug flow". Some recent studies (Coen *et al*., 1998; Van Veldhuizen *et al*., 1999; Koch *et al*., 2000; Makinia and Wells, 2000) have suggested that a hydraulic model should be an integral part of the overall reactor model. Unfortunately, the existing empirical formulae do not provide reliable information in this area (Makinia, 1998). Currently, tracer studies appear to be the only acceptable method for evaluating the actual flow conditions. Since the pre-compiled GPS-X layouts of MUCT and Johannesburg processes have a limited number of cells (10), it was assumed that each compartment in the reactor flow schemes (Figures 1–2) was represented by a separate cell.

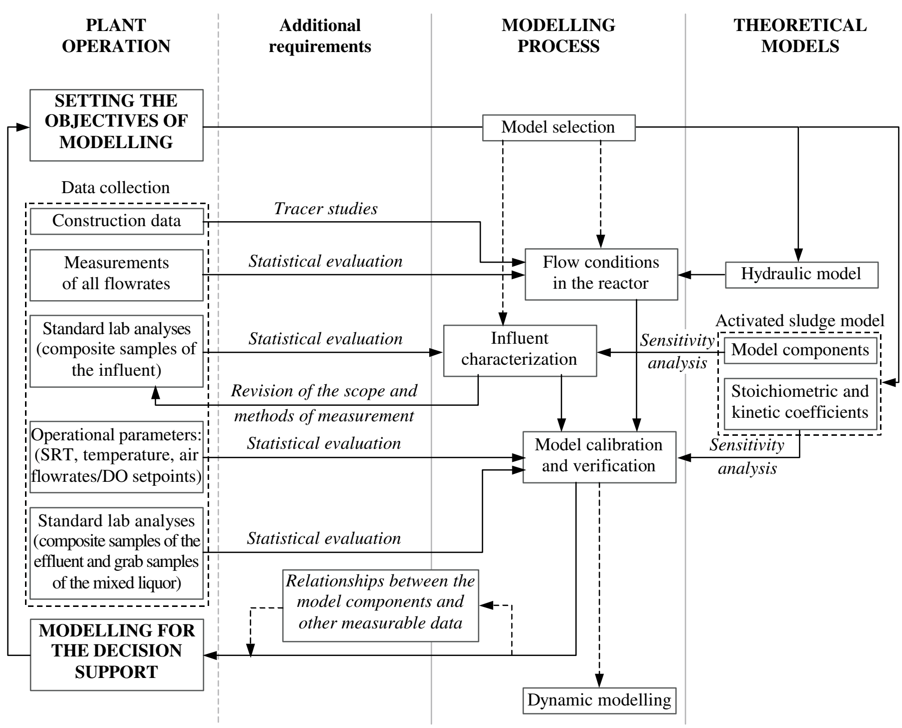

Figure 3 Organization of the modelling environment for a "steady state" WWTP model from the process engineering perspective

Consequently, the “plug flow” was approximated by 5 tanks-in-series at the “Debogorze” WWTP and 6 tanks-in-series at the “Wschod” WWTP.

The method for influent characterization is presented in more detail in the next section. Calibration and validation of the activated sludge model was performed based on the monthly average measurements. It was assumed for the calibration phase that the least possible number of parameters would be adjusted to obtain reasonable fits. Moreover, it was also hypothesized that the same set of parameters would be used at the “Wschod” and “Debogorze” WWTPs. Both plants were subject to earlier studies (Makinia *et al*., 2000), which involved the period of start-up and stabilization of the biological processes (the years 1998–1999). The resulting set of parameters was used as the first approximation for the purpose of this research. Then, some refinements (reducing the number of parameters adjusted) were introduced based on the results for September, 1999 through December, 1999. Finally, the model was validated using independent data for the entire year 2000.

Influent characterization

The settled wastewater including the recycle from the primary sludge fermenters needed to be characterized at both plants studied. The calculation procedure is presented in Figure 4. Due to a limited number of measured parameters the organic matter fractionation was performed with only two input parameters (COD and TSS) and several stoichiometric coefficients listed in Table 2. A minor modification compared to the original GPS-X influent model was introduced by estimating initially the X_I concentration (instead of X_S as it is in GPS-X) as a fraction of XCOD through a stoichiometric coefficient, f_{Xi}. This change was made based on the approach of Grady *et al*. (1999) who assumed that according to the experimental evidence 35–40% of the particulate organic matter in domestic wastewater was non-biodegradable. However, calibration of the influent model indicated that the X_I fraction was actually a little lower at the “Wschod” and “Debogorze” WWTPs. Another approach of Grady *et al*. (1999) was adapted to convert biodegradable COD (COD_{biod}) to ultimate BOD (BOD_U).

A special conversion was also needed for the i_{CV} (“true”) coefficient. A new coefficient, called i_{CV}’ (“actual”), was introduced to take colloidal matter in the filtrate into account (Figure 5). The relationship between i_{CV}’ and i_{CV} (Eq. (4)) was derived by solving the set of Eqs (1–3). The values of i_{CV}’ varied within the range of 1.85–2.46 at the “Wschod” WWTP and 2.07–2.51 at the “Debogorze” WWTP, respectively.

$$COD_{filt.} = COD - i_{cv} \cdot VSS \qquad (1)$$

$$COD_{col.} = i_{col.} \cdot COD_{filt.} \qquad (2)$$

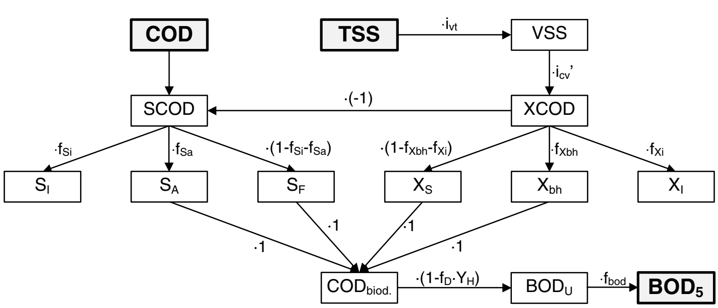

Figure 4 A procedure for fractionation of the organic matter in wastewater based on COD and TSS measurements

Table 2 Stoichiometric coefficients used for fractionation of the organic matter in the settled wastewater

Coefficient	Symbol	Unit	Value at Wschod	Value at Debogorze	Estimation method
VSS:TSS ratio	i_{vt}	–	0.65	0.72	actual measurements
"true" XCOD:VSS ratio	i_{cv}	gCOD g^{-1}	1.48	1.48	literature data (Hydromantis, 1999)
fraction of colloidal matter in the filtrate	i_{col}	–	0.4	0.4	literature data (Henze *et al*., 1994)
"actual" XCOD:VSS ratio	i_{cv}'	gCOD g^{-1}	1.85–2.46	2.07–2.51	actual measurements
fraction of non-biodegradable soluble organic matter (S_I) in SCOD	f_{Si}	–	0.07–0.15	0.07–0.16	actual measurements
fraction of volatile fatty acids (S_A) in SCOD	f_{Sa}	–	0.45	0.44–0.75	actual measurements
fraction of heterotrophic biomass (X_{bh}) in XCOD	f_{xbh}	–	0.1	0.1	literature data (Henze, 1992)
fraction of non-biodegradable particulate organic matter (X_I) in XCOD	f_{Xi}	–	0.3	0.3	model calibration
fraction of active biomass contributing to biomass debris	f_D	–	0.2	0.2	literature data (Grady *et al*., 1999)
yield growth for heterotrophic biomass	Y_H	gCOD $gCOD^{-1}$	0.6	0.6	literature data (Grady *et al*., 1999)
BOD_5:BOD_U ratio	f_{BOD}	–	0.66	0.66	literature data (Grady *et al*., 1999)

$$XCOD = i_{cv} \cdot VSS + COD_{col.} \tag{3}$$

$$i_{CV}' = i_{CV} \cdot (1 - i_{col.}) + \frac{i_{col.} \cdot COD}{VSS} \tag{4}$$

In order to perform fractionation of the nitrogenous matter, concentrations of TKN had to be known. The N-NH_4^+/TKN and soluble inert N/TKN ratios were estimated based on the actual measurements in the primary effluent and secondary effluent, respectively. The N-NH_4^+/TKN ratio used for simulation varied within the range 0.60–0.76 at the "Wschod" WWTP and 0.42–0.65 at the "Debogorze" WWTP. A soluble inert N/TKN ratio equal to 0.02 was assumed for all simulations at both plants. The model default values remained unchanged for other stoichiometric coefficients relating to fractionation of the nitrogenous matter.

Concerning characterization of the phosphorus fractions, limited data exist in the literature. Barker and Dold (1997) suggested that concentrations of P-PO_4^- (considered as soluble reactive phosphorus) can be calculated as 0.85–0.90 of total P concentrations. Henze *et al*. (1999) assumed a constant composition of all organic fractions (i.e. constant P to COD ratio). Brdjanovic *et al*. (2000) calculated concentrations of P-PO_4^- by subtracting the content of P in all these fractions from the measured concentrations of total P. This approach was compared with actual measurements from the "Wschod" and "Debogorze"

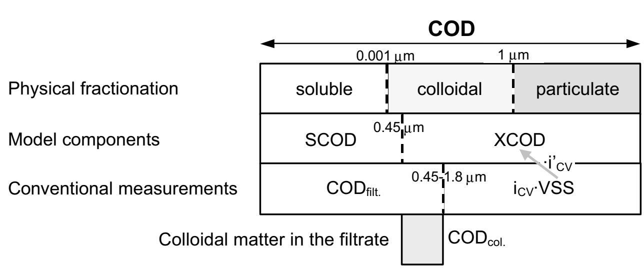

Figure 5 The impact of colloidal matter on fractionation of the model components

WWTPs. The $P\text{-}PO_4^-/P_{tot.}$ ratio in the primary effluent varied within the range 0.55–0.77 (actual) vs. 0.56–0.71 (calculated) at the “Wschod” WWTP and 0.63–0.84 (actual) vs. 0.67–0.80 (calculated) at the “Debogorze” WWTP, respectively. For the purpose of this study, the actual concentrations of $P\text{-}PO_4^-$ were used as input data, but there is no doubt that there is uncertainty in such an approach. The impact of the influent phosphorus characterization on model predictions should be studied in the future, e.g. by means of sensitivity analysis.

Modelling tool

Simulations were performed using the Entry Level of GPS-X 3.0 simulation package (Hydromantis, 1999). This version of the package enables to use only pre-compiled plant configurations with associated models. A general model of Dold (1990) was implemented for MUCT and Johannesburg processes.

Results and discussion

In order to obtain reasonable fits between the model predictions and actual measurements, only a few parameters needed to be adjusted (Table 3). This issue is discussed below:

- the maximum specific growth rate for autotrophic bacteria, $\mu_{A,max}$, was decreased to 0.38 d^{-1} (20°C) at both plants studied, whereas the ammonia half saturation constant, K_{NH}, was increased to 1.5 gN m^{-3} at the “Wschod” WWTP and 1.8 gN m^{-3} at the “Debogorze” WWTP. Such a situation is most probably caused by the relatively high content of the industrial wastewater treated at these plants. Nevertheless, the values of both parameters remained within the range reported in the literature. For example, in the review of Copp and Murphy (1995) $\mu_{A,max}$, and K_{NH} varied within the range 0.25–1.23 d^{-1} and 0.06–5.6 gN m^{-3}, respectively.
- low effluent concentrations of $N\text{-}NH_4^+$ were observed at the “Wschod” WWTP in the winters 1998/1999 and 1999/2000, which resulted in introducing an extremely low value (1.02) for the Arrhenius temperature correction factor, θ_A. For comparison, simulations with the θ_A default value were performed and then a nitrification failure was predicted at low temperatures. Higher concentrations of $N\text{-}NH_4^+$ observed during last winter (2000/2001) may indicate, however, that the factor would have to be changed closer to default values (1.11–1.12). Indeed, better predictions were obtained for October, 2000 through December, 2000 when the θ_A default value was used (a dotted line in Figure 7).
- the anoxic hydrolysis reduction factor, η_h, was increased from 0.37 to 0.8 at both plants due to the higher denitrification rates observed. The corrected value corresponds well to some literature data reported by Orhon *et al.* (1996).
- no adjustments were made with respect to the kinetics and stoichiometry of the process of biological phosphorus removal.
- the yield coefficient of non-poly heterotrophic bacteria, Y_H, was decreased from 0.67 g cell COD g^{-1} to 0.5 g cell COD g^{-1} at the “Wschod” WWTP in order to improve the predictions of reactor MLSS concentration and sludge production. The new value also remained within the range (0.43–0.72 g cell COD g^{-1}) reported in the literature (Grady *et al.*, 1999).

Based on the analysis presented above, it turned out that only in three cases (Y_H, , K_{NH}, θ_A) were the calibrated values different for the “Wschod” and “Debogorze” WWTPs.

A comparison between measured and calculated concentrations of $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ and $P\text{-}PO_4^-$ in the secondary effluent as well as reactor MLSS is presented in Figure 6 for the “Wschod” WWTP and in Figure 7 for the “Debogorze” WWTP, respectively. The overall prediction results may be considered as satisfactory, however, some discrepancies

Table 3 Kinetic parameter values adjusted during model calibration

Coefficient	Symbol	Unit	Default value*	Actual values	
				Debogorze	Wschod
Yield coefficient for non-polyP heterotrophic bacteria	Y_H	gCOD $gCOD^{-1}$	0.666	0.666	0.5
Anoxic hydrolysis reduction factor	η	–	0.37	0.8	0.8
Maximum specific growth rate for autotrophic bacteria	$\mu_{A,max}$	d^{-1}	0.45	0.38	0.38
Ammonia half-saturation constant	K_{NH}	gN m^{-3}	1.0	1.8	1.5
Arrhenius correction factor for autotrophic bacteria	q_A	–	1.123	1.11	1.02

* – default values occurring in the model implemented in the GPS-X 3.0 pre-compiled layouts

require further justification. At the "Debogorze" WWTP, a failure with respect to predicting nitrate concentrations occurred in the months from February to March, 2000. It is worth mentioning that a similar problem was experienced for the same period of the previous year (Makinia *et al.*, 2000). A possible explanation for this phenomenon is the change in aerobic conditions in the anoxic/aerobic zone of the reactor. Due to difficulties with maintaining the effluent limits for N-NH_4^+ that zone was aerated temporarily and it occurred exactly at the same time as the prediction failure.

Discrepancies between measured values and model predictions for N-NH_4^+ occurred in September, 1999 at the "Wschod" WWTP and September, 2000 at the "Debogorze" WWTP. The only explanation for the higher measured concentrations would be the inhibition of nitrifiers. This effect was not taken into account during the modelling process.

The mean absolute prediction errors for five parameters are listed in Table 4. The highest errors (reaching 50% of the measured values) refer to the concentrations of ammonia nitrogen and soluble phosphorus at both WWTPs. However, it should be emphasized that these errors become much lower in terms of the overall removal efficiency.

Conclusions

Based on the results of the study conducted at the "Wschod" and "Debogorze" WWTPs, the following conclusions can be derived:

- It was demonstrated that routine operating data are applicable to comprehensive, mechanistic models. The main efforts were focused on adjusting these data for modelling purposes.
- During calibration the model default values were changed for four parameters at the "Debogorze" WWTP and five parameters at the "Wschod" WWTP. Only in three cases (Y_H, K_{NH}, θ_A) were the calibrated values different for both plants.

Table 4 Average prediction errors for the selected parameters at the "Wschod" and "Debogorze" WWTPs

Parameter	Unit	"Wschod" WWTP		"Debogorze" WWTP	
		Measured value	Prediction error	Measured value	Prediction error
Concentrations:					
COD	gCOD m^{-3}	37.6	2.6	36.3	3.6
N-NH_4^+	gN m^{-3}	0.63	0.31	3.51	1.76(0.97*)
N-NO_3^-	gN m^{-3}	9.0	1.20	10.2	2.39(1.35*)
P-PO_4^-	gP m^{-3}	0.19	0.10	0.73	0.38
MLSS	kg m^{-3}	3.72	0.36	5.46	0.42
Removal efficiency:					
COD	%	93.5	0.46	93.6	0.65
N-NH_4^+	%	98.6	0.65	90.9	4.55
P-PO_4^-	%	97.9	1.15	94.8	3.13

* – without the period January–April, 2000

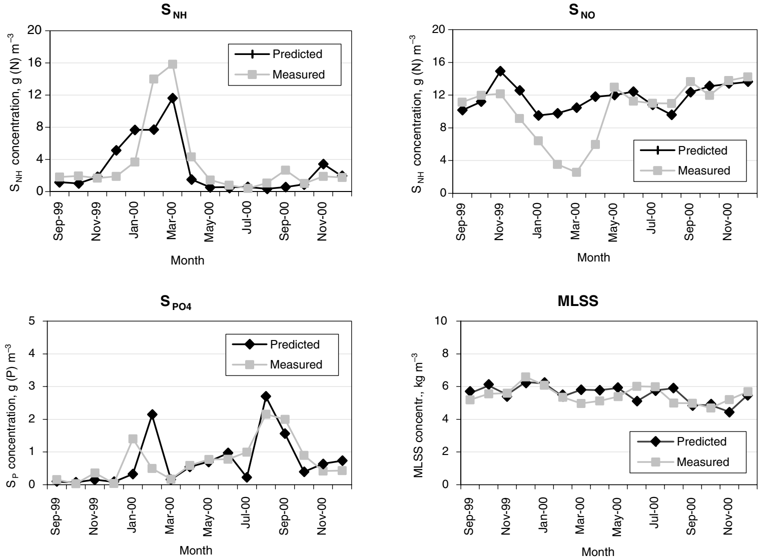

Figure 6 Measured and predicted values of the selected parameters at the "Debogorze" WWTP

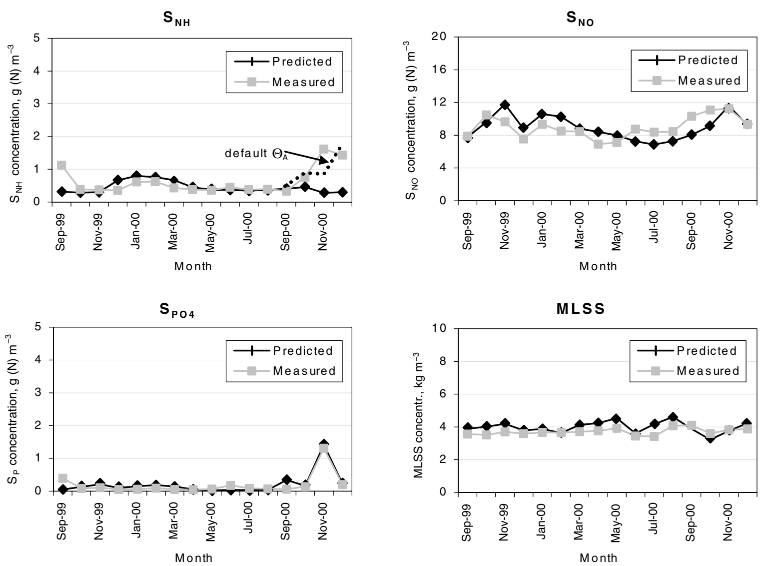

Figure 7 Measured and predicted values of the selected parameters at the "Wschod" WWTP

- In the present form, the model can be used to evaluate seasonal changes in nitrification/denitrification efficiency, amount of sludge produced and the impact of VFA generation on efficiency of biological phosphorus removal.
- The set of model coefficients obtained from steady state simulation should be validated with the results of specialized studies (e.g. batch tests and continuous monitoring) and dynamic simulation.

Acknowledgements

This research has been financially supported by the Polish Committee for Scientific Research (Grant No. 7 T09C 074 20).

References

Andrews, J.F. (1992). Mathematical modeling and computer simulation. In: *Dynamics and Control of the Activated Sludge Process*, J.F. Andrews (ed.). Technomic Pub. Co., Lancaster, PA, pp. 23–66.

Barker, P.S. and Dold, P.L. (1997). General model for biological nutrient removal activated-sludge systems: model presentation. *Wat. Env. Res.*, **69**, 969–984.

Brdjanovic, D., Van Loosdrecht, M.C.M., Versteeg, P., Hooijmans, C.M., Alaerts, G.J and Heijnen, J.J. (2000). Modeling COD, N and P removal in a full scale WWTP Haarlem Waarderpolder. *Wat. Res.* **34**, 846–858.

Cinar, O., Daigger, G.T. and Graef, S.P. (1998). Evaluation of IAWQ Activated Sludge Model No.2 using steady-state data from four full-scale wastewater treatment plants. *Wat. Env. Res.*, **70**, 1216–1224.

Coen, F., Vanderhaegen, B., Boonen, I., Vanrolleghem, P.A. and Van Meenen, P. (1997). Improved design and control of industrial and municipal nutrient removal plants using dynamic models. *Wat. Sci. Tech.*, **35**(10), 53–61.

Coen, F., Petersen, B., Vanrolleghem, P.A., Vanderhaegen, B. and Henze, M. (1998). Model-based characterisation of hydraulic, kinetic and influent properties of an industrial WWTP. *Wat. Sci. Tech.*, **37**(12), 317–326.

Copp, J.B. and Murphy, K.L. (1995). Estimation of the active nitrifying biomass in activated sludge. *Wat. Res.*, **29**, 1855–1862.

Dold, P.L. (1990). Incorporation of biological excess phosphorus removal in a general activated sludge model. In: *Proceedings of the 13th International Symposium on Wastewater Treatment*. November, Montreal, pp. 83–113.

Grady, C.P.L., Jr, Daigger, G.T. and Lim, H.C. (1999). *Biological Wastewater Treatment. Second Edition, Revised and Expanded*. Marcel Dekker, New York.

Henze, M. (1992). Characterisation of wastewater for modelling of activated sludge processes. *Wat. Sci. Tech.*, **25**(6), 1–15.

Henze, M., Kristensen, G.H. and Strube, R. (1994). Rate-capacity characterization of wastewater for nutrient removal processes. *Wat. Sci. Tech.*, **29**(7), 101–107.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C. and Marais, G.v.R. (1995). Activated Sludge Model No. 2. *Scientific and Technical Report No.3*, IAWQ, London.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C., Marais, G.V.R. and Van Loosdrecht, M.C.M. (1999). Activated Sludge Model No. 2d. *Wat. Sci. Tech.*, **39**(1), 165–182.

Hydromantis, Inc. (1999). GPS-X 3.0 – the Entry Level. *Hydromantis, Inc*., Hamilton, Ontario.

Koch, G., Kuhni, M., Gujer, W. and Siegrist, H. (2000). Calibration and validation of Activated Sludge Model No. 3 for Swiss municipal wastewater. *Wat. Res.*, **34**, 3580–3590.

Makinia, J. (1998). *Mathematical modeling of the activated sludge reactor with dispersive flow*. PhD dissertation. Department of Civil Engineering, Portland State University, Portland, OR.

Makinia, J. and Wells, S.A. (2000). A general model of the activated sludge reactor with dispersive flow (part I): model development and parameter estimation. *Wat. Res.*, **34**, 3987–3996.

Makinia, J., Dobiegala, E., Gielert, M., Swinarski, M. and Lewandowski, M. (2000). Evaluation of the opportunity for using computer simulation in municipal wastewater treatment plants: the Gdansk-Gdynia case study. In: *Proceedings of the Conference "The WSCHOD WWTP – the Largest Investment for the Baltic Sea Protection at the Beginning of the 21st Century"*, Gdansk, May 2000, pp. 127–138. (*in Polish*).

Mino, T., San Pedro, D.C., Yamamoto, S. and Matsuo, T. (1997). Application of the IAWQ Activated Sludge Model to nutrient removal process. *Wat. Sci. Tech.*, **35**(8), 111–118.

Murnleitner, E., Kuba, T., Van Loosdrecht, M.C.M. and Heijnen, J.J. (1996). A metabolic model for the biological phosphorus removal by denitrifying organisms.. *Biotechnol. Bioeng.*, **52**, 685–695.

Orhon, D., Sozen, S. and Artan, N. (1996). The effect of heterotrophic yield on the assessment of the correction factor for anoxic growth. *Wat. Sci. Tech.*, **34**(5–6), 67–74.

Rieger, L., Koch, G., Kühni, M., Gujer, W. and Siegrist, H. (2001). The EAWAG bioP-module for Activated Sludge Model No. 3, *Wat. Res*., **35**, 3887–3903.

Satoh, H., Okuda, E., Mino, T. and Matsuo, T. (2000). Calibration of kinetic parameters in the IAWQ Activated Sludge Model: a pilot scale experience. *Wat. Sci. Tech.*, **42**(3–4), 29–34.

Van Veldhuizen, H.M., Van Loosdrecht, M.C.M. and Heijnen, J.J. (1999). Modelling biological phosphorus and nitrogen removal in a full scale activated sludge process. *Wat. Res.*, **33**, 3459–3468.

Wichern, M., Wulf, P., Obenaus, F., Rieger, L. and Rosenwinkel, K.-H. (2000). Modelling of full-scale WWTP's with different treatment processes using the Activated Sludge Model No. 3, In: *Proceedings of the Conference on Wastewater and EU-Nutrient Guidelines*, Amsterdam, September 2000.