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# A simple model of wastewater treatment plants for managing the quality of the Seine River

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**Abstract:** The aim of this paper is to introduce a simple model for wastewater treatment plants that can be used for evaluating control strategies on the basin of the Seine River under different scenarios. The model represents a bioreactor without oxygen limitation. The construction of the model was based on the ASM1 with only one microbial population. The performance of the model was tested on daily data for a four year period over the three main wastewater treatment plants of the Seine River in Paris (Seine Aval, Seine Centre, and Seine Grésillons). Results demonstrated that the model was effective for predicting the concentrations of ammonia, nitrites, nitrates, biological oxygen demand, and total suspended solids. The developed model was found to be parsimonious and it can thus provide a useful tool in optimizing river quality once coupled to control strategies.

*Keywords:* Modeling, wastewater treatment, parameter identification, bio-filtration.

## 1. INTRODUCTION

The Seine River estuary (France) is the receptacle of a drainage basin characterized by high population density, heavy industrial activity, and intensive agriculture. In the recent years, European policy in water quality has been implemented to have an integrated pollution prevention and control of surface freshwater in order to ensure its ecological status (Water Framework Directive)(European Commission (2000); Romero et al. (2016)).

The management of an integrated river basin is a complicated task that depends on the urban wastewater system (sewers and treatment plants) and the river dynamics. Mathematical models have been used to understand these three main parts with a special focus on the biological wastewater treatment plants (WWTP). The Activated Sludge Model no.1 (ASM1) (Henze et al., 1987) is generally presented as the state-of-the-art for modeling WWTP. The ASM1 has been applied to the simulation of full-scale industrial and municipal WWTP with the extension to nitrogen and phosphorous removal (Henze et al., 1999), and the inclusion of storage bio-polymers under transient conditions (Gujer et al., 1999).

The ASM1 models are based on eight dynamic reactions including two types of microorganisms' species (*i.e.* heterotrophs and autotrophs). The 8 reactions include:(i) aerobic growth of heterotrophs; (ii) anoxic growth of heterotrophs;(iii) aerobic growth of autotrophs; (iv) decay of heterotrophs;(v) decay of autotrophs; (vi) ammonification of soluble organic nitrogen; (vii) hydrolysis of entrapped organics; and (viii) hydrolysis of entrapped organic nitrogen. This model has been successfully implemented in a variety of wastewater treatment processes (WWTP) design and simulation projects (Nelson and Sidhu (2009); Van Loosdrecht et al. (2015)).

As research and technology evolve, other types of systems have become more popular such as Membrane Bioreactors (MBRs) which offer several advantages over conventional activated sludge treatments. The applicability of ASMs into MBRs is limited at representing the properties of activated sludge which affect membrane fouling (Meng et al. (2009); Ng and Kim (2007)). However, some works have shown good results at extending ASM1 for aerobic MBR (Baek et al. (2009); Fenu et al. (2010)) where sludge removal was included to consider high sludge retention times (SRT).

Although ASM1 is a starting point for modeling, the complexity of the model plays an important role when control strategies are considered. The model presents some disadvantages regarding the non-linearity of the kinetics such as the difficulty to identify the kinetic parameters, and the uncertainty in simulations due to the unpredicted influent characteristics. Some alternatives to use the model in control strategies have suggested its linearization (Smets et al., 2003) and its reduction (Vanrolleghem et al., 2005). In this context, this paper deals with the introduction of a simple model for aerobic MBR based on ASM1 which could be easily used for implementing control strategies at the river basin system. The model is identified and applied to three WWTPs in the Seine River.

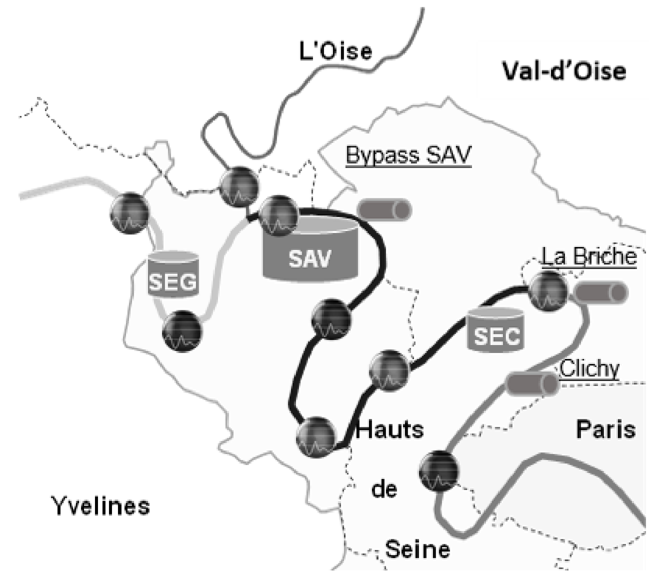


Fig. 1. Water treatment in the Seine River

This paper is organized as follows. Section 2 describes the system under study in the Seine River. Section 3 derives the simple model. Section 4 details the data of the WWTP plants and the model application. Finally, section 5 summarizes the results and highlights the importance of the model for managing river quality.

## 2. WASTEWATER TREATMENT PLANTS

The Seine River is one of the largest rivers in France with its basin covering 15% of its territory. The Seine is a highly adjusted river, navigable along two thirds of its course. It is also the major receiver of the wastewaters of 16 million of inhabitants of Ilê de France (Even et al., 2007). The Seine River has a flow rate varying from 100 to 1000 $m^3/s$ over dry and rain periods, respectively. Urban wastewater from Paris area is distributed along six wastewater treatment plants, from which three WWTPs treat the water and discharge into the Seine River downstream from Paris, whilst the other three do it upstream from Paris.

In this paper, the area of study is located downstream from Paris and its suburbs (Fig.1) where the three main WWTPs are: Seine Centre (SEC), Seine Aval (SAV), and Seine Grésillons (SEG).

These three plants treat around 2.25 millions of cubic meters per day. The allowable nominal flows of these plants are 240,000 $m^3/d$, 1,700,000 $m^3/d$, and 100,000 $m^3/d$, for SEC, SAV, and SEG, respectively.

The plants Seine Centre and Seine Grésillons use bio-filtration for the treatment of wastewater, whilst SAV combines the classical AS biological treatment with bio-filtration (Rocher et al., 2012).

## 3. MATHEMATICAL MODEL

### 3.1 Model Assumptions

In order to propose a model capable to describe the different types of treatment among the three WWTPs of these study, we suggest the reduction of the WWTPs into one MBR. The system is displayed in Fig.2 where $Q_{in}$ represents the influent rate, $Q_{out}$ is the flow rate of the effluent going into the river and $Q_w$ is the waste flow rate. Following the description of Baek et al. (2009) that is based on the ASM1, we assume that the air supply is sufficient for microbial growth. Alkalinity was also discarded because pH in the plant is well maintained at neutral pH.

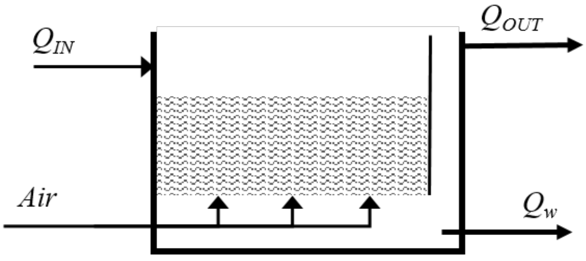


Fig. 2. System representation of the reduced WWTP

The model considers the conversion of carbon (heterotrophic bacteria) and the autotrophic conversion of ammonia nitrogen ($NH_4$) into nitrites ($NO_2^-$) and then into nitrates ($NO_3^-$). The nitrates are further reduced to nitrous oxide ($N_2O$), and in turn to nitrogen gas ($N_2$). This process is called denitrification which occurs under oxygen depletion and the primary oxygen source for the microorganisms become the nitrates. A carbon source (*e.g.* methanol, $CH_3OH$) is required for denitrification to occur.

$$NH_4 + 3O_2 \rightarrow 2NO_2^- + 4H_2O + 4H^+$$
$$4NO_2^- + O_2 \rightarrow 2NO_3^-$$
$$6NO_3^- + 5CH_3OH \rightarrow 2N_2 + 5CO_2 + 7H_2O + 6OH^-$$

Nevertheless, the model takes into account only one microbial population ($X$) that gathers the action of heterotrophic and autotrophic microorganisms. In this regard, the 8 reactions described above are reduced to 4 including: (i) Growth of microorganisms; (ii) Decay of microorganisms; (iii) Hydrolysis of entrapped organics; and (iv) Hydrolysis of entrapped organic nitrogen.

As the model is based on a MBR, membrane fouling should be considered (Lee et al. (2002); Meng et al. (2009); Ng and Kim (2007)). However, as the most important aspect to take into account is related to the high Sludge Retention Times (SRT), the simple model only consider this feature by a constant ($s_d$) to simulate the long SRT for the degradation of Total Suspended Solids ($TSS$).

Additionally, the model assumes that a fraction of $TSS$ is active biomass present in the influent, in consistent accordance with the fraction of heterotrophic biomass described in the ASMs (Henze et al., 1999). Moreover, no biomass was accounted for in the effluent due to the utilization of membrane.

### 3.2 Model Description

The reduced system represents the dynamics of the biological oxygen demand ($BOD_5$), the ammonia nitrogen ($NH_4$), nitrite ($NO_2$), nitrate ($NO_3$), and total suspended solids ($TSS$). The model is described by the mass balances as follows,

$$\frac{dBOD_5}{dt} = BOD_{5,in}\frac{Q_{in}}{V} - BOD_5\frac{Q_{out}}{V} - BOD_5\frac{Q_w}{V} - r_1X \quad (1)$$

$$\frac{dNH_4}{dt} = NH_{4,in}\frac{Q_{in}}{V} - NH_4\frac{Q_{out}}{V} - NH_4\frac{Q_w}{V} - r_2X \quad (2)$$

$$\frac{dNO_2}{dt} = NO_{2,in}\frac{Q_{in}}{V} - NO_2\frac{Q_{out}}{V} - NO_2\frac{Q_w}{V} - r_3X + \frac{1}{Y_{NH_4/NO_2}}r_2X \quad (3)$$

$$\frac{dNO_3}{dt} = NO_{3,in}\frac{Q_{in}}{V} - NO_3\frac{Q_{out}}{V} - NO_3\frac{Q_w}{V} - r_4X + \frac{1}{Y_{NO_2/NO_3}}r_3X \quad (4)$$

$$\frac{dX}{dt} = f_XTSS_{in}\frac{Q_{in}}{V} - X\frac{Q_w}{V} + Y_{X/BOD}r_1X + Y_{X/NH}r_2X - bX \quad (5)$$

$$\frac{dTSS}{dt} = (1 - f_X)\,TSS_{in}\frac{Q_{in}}{V} - TSS\frac{Q_{out}}{V}s_d - TSS\frac{Q_w}{V} \quad (6)$$

where $X$ is the biomass (mg$X$/L), and the reactor volume is represented by $V$ (m$^3$). $Q_{in}$ holds for the influent flow rate, whilst the output of the WWTP is divided into effluent flow rate $Q_{out}$, and waste flow rate $Q_w$. For the sake of simplicity $Q_w$ was taken as 0.1 $Q_{in}$. Yield coefficients for biomass production with respect to the different $i$ compounds are represented as $Y_{X/i}$, whilst $Y_{NH_4/NO_2}$ and $Y_{NO_2/NO_3}$ are the yield conversion coefficients of ammonium into nitrites, and nitrites into nitrate, respectively.

Kinetics are described by Monod equations for the consumption of carbon ($r_1$), the nitrification of ammonia into nitrites ($r_2$), the nitrification of nitrites to nitrates ($r_3$), and the de-nitrification of nitrates into $N_2$ gas ($r_4$).

$$r_1 = \rho_{1,\max}\frac{BOD_5}{K_{BOD} + BOD_5} \quad (7)$$

$$r_2 = \rho_{2,\max}\frac{NH_4}{K_{NH} + NH_4} \quad (8)$$

$$r_3 = \rho_{3,\max}\frac{NO_2}{K_{NO2} + NO_2} \quad (9)$$

$$r_4 = \rho_{4,\max}\frac{NO_3}{K_{NO3} + NO_3} \quad (10)$$

$\rho_{j,\max}$ $j = 1 - 4$ represent the maximum specific rates of the 4 reactions. The parameters $K_{BOD}$, $K_{NH}$, $K_{NO2}$, and $K_{NO3}$ are the half saturation coefficients for $BOD_5$, $NH_4$, $NO_2$, and $NO_3$, respectively. In summary, the simple model involves 6 state variables and 15 parameters. The application of the model to the three WWTP is presented into the next section.

## 4. RESULTS

Four years of data with a daily frequency were available to calibrate and to validate the model. The data for the three WWTPs cover the period from January the 1$^{st}$, 2009 to December the 31$^{st}$, 2012. The flow rates, and influent and effluent concentrations of the model state variables are displayed in Fig.4,5, and 6 for SEC, SAV, and SEG, respectively. Four periods of missing data were identified for Seine Centre (SEC) corresponding to 70 days on 2009, 20 days in 2011, and 25 days in 2012. All these periods are marked up by dashed lines. For SAV and SEG, only one period of missing data was observed both in 2011. The corresponding volumes for SEC, SAV, and SEG were 20,600, 163,300, and 29,680 m$^3$, respectively.

Three data sets of 150 days were taken for model calibration: Beginning of 2009, middle of 2010, and late 2012. The rest of the data was used for validation. No filtering was used in order to capture the transient characteristics of the data. Parameter estimation was performed via the pattern search algorithm implemented in MATLAB. For the sake of simplicity, the fraction of active biomass $f_X$, the biomass decay $b$, and the yields for biomass over $BOD_5$ ($Y_H$) and $NH_4$ ($Y_H$) were taken from the literature (Henze et al., 1987), which led to 11 parameters to be estimated. The calibrated values are reported in Table 1.

Table 1. Calibrated parameters for the model

| Parameter | Unit | SEC | SAV | SEG |
|---|---|---|---|---|
| $\rho_{1,\max}$ | mg$O_2$/(mg$X - d$) | 3.99 | 2.56 | 1.93 |
| $\rho_{2,\max}$ | mg$NH_4$/(mg$X - d$) | 0.84 | 0.83 | 0.89 |
| $\rho_{3,\max}$ | mg$NO_2$/(mg$X - d$) | 1.68 | 1.27 | 0.92 |
| $\rho_{4,\max}$ | mg$NO_3$/(mg$X - d$) | 1.21 | 1.38 | 0.85 |
| $K_{BOD}$ | mgO$_2/L$ | 13.67 | 11.65 | 14.26 |
| $K_{NH}$ | mg$NH_4/L$ | 6.59 | 14.98 | 8.53 |
| $K_{NO2}$ | mg$NO_2/L$ | 2.46 | 1.15 | 2.55 |
| $K_{NO3}$ | mg$NO_3/L$ | 1.40 | 2.69 | 4.20 |
| $Y_{X/BOD}$ | mg$X$/mgO$_2$ | 0.67* | 0.67* | 0.67* |
| $Y_{X/NH}$ | mg$X$/mg$NH_4$ | 0.24* | 0.24* | 0.24* |
| $Y_{NH4/NO2}$ | mg$NH_4$/mg$NO_2$ | 0.28 | 0.25 | 0.27 |
| $Y_{NO2/NO3}$ | mg$NO_2$/mg$NO_3$ | 0.68 | 0.64 | 0.70 |
| $s_d$ | - | 35.8 | 14.8 | 38.2 |
| $b$ | 1/d | 0.01* | 0.10* | 0.10* |
| $f_X$ | - | 0.08* | 0.08* | 0.08* |

*Parameters taken from Henze et al. (1987)

It is worth noting that the majority of parameters for SEC and SEG are similar. This was expected since both use only bio-filtration systems for wastewater treatment. The most remarkable difference in the parameters was on the maximum specific rate for carbon assimilation, and the nitrification of ammonia into nitrites and nitrates. The higher values for SEC in these parameters were related to the difference of the working volume and the flow rate of the WWTPs. A lower volume and a higher flow rate for SEC had to be compensated with higher values of its coefficients. Regarding SAV parameters, most of the parameters differed from SEC and SEG, especially on the kinetics. This is due to the difference in plant configuration, since SAV also accounts with an active sludge treatment part.

Sensitivity analysis can be used to assess the influence of each parameter on the measured outputs, as well as the possible interaction between these effects. In this study, local sensitivity analysis was carried out based on the dynamic sensitivity equations calculated as,

$$\dot{S}_j = \frac{\partial f}{\partial x} S_j + \frac{\partial f}{\partial \theta} \tag{11}$$

where $S$ represent the sensitivity functions evaluated at the identified parameter values $\theta$. Results of the sensitivity analysis are presented in Fig.3 where it is observed that the parameter $\rho_{2,\max}$ affects all the state variables. It is worth noting that the effect of parameters on biomass ($X$) is less important on SEG where the biomass concentration is also lower. Nitrate concentration ($NO_3$) was the most affected by the parameters since it results from the sequential nitrification of ammonia as depicted in the reactions above.

The comparison of the model simulations and the experimental data is displayed on Fig.4, 5, and 6 where in general there exists a good agreement of the model with the experimental data.

Table 2. Statistical performance on SEC

| Variables | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|
| $TSS$ | 0.085 | 0.033 | 0.032 | 0.039 |
| $BOD_5$ | 0.098 | 0.049 | 0.044 | 0.064 |
| $NH_4$ | 0.186 | 0.098 | 0.098 | 0.118 |
| $NO_2$ | 0.101 | 0.161 | 0.164 | 0.148 |
| $NO_3$ | 0.251 | 0.332 | 0.251 | 0.269 |

In order to evaluate the performance of the model, we used the normalize Root Mean Square Errors ($RMSE$) with respect to the total number days per years. The $RMSE$ values for the three WWTPs are reported annually on Tables 2, 3, and 4.

Table 3. Statistical performance on SAV

| Variables | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|
| $TSS$ | 0.085 | 0.132 | 0.071 | 0.065 |
| $BOD_5$ | 0.077 | 0.111 | 0.056 | 0.073 |
| $NH_4$ | 0.126 | 0.196 | 0.123 | 0.109 |
| $NO_2$ | 0.090 | 0.079 | 0.080 | 0.222 |
| $NO_3$ | 0.129 | 0.170 | 0.123 | 0.151 |

Concerning SEC results (Fig.4), it is observed that the flow rate is almost constant, and the plant works in a stationary way with intermittent variations representing rain periods.

Table 4. Statistical performance on SEG

| Variables | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|
| $TSS$ | 0.137 | 0.124 | 0.101 | 0.135 |
| $BOD_5$ | 0.185 | 0.117 | 0.133 | 0.130 |
| $NH_4$ | 0.057 | 0.056 | 0.076 | 0.039 |
| $NO_2$ | 0.128 | 0.081 | 0.185 | 0.145 |
| $NO_3$ | 0.269 | 0.207 | 0.267 | 0.175 |

The model shows good agreement with the results for nitrates, $TSS$, and $BOD_5$ concentrations. However, it is not precise for $NH_4$, where the conversion is well taken into account, but the intermittent behavior of the flow rate seems to have a stronger impact on its dynamics. This should also be reflected into nitrates concentrations since $NH_4$ is consumed to form $NO_2$, but the model results for nitrite follow correctly the dynamics with the exception of an increase at the end of 2010. Nevertheless, the reported $RMSE$ values (Table 2) for $NH_4$ are low which represent a good performance of the model.

SAV results are presented on Fig.5 and Table 3. Flow rate data display seasonality where smaller values are observed in summer which corresponded to the dry season. Otherwise, the peaks show the rain periods. From the dynamics of nitrites and nitrates, a major change on dynamics is detected where the oxidation of nitrites to nitrates is large. A change on the configuration of the WWTP occurred in 2012 where more bio-filters were added; therefore, the model was recalibrated for that year. The values of the normalized $RMSE$ (Table 3) were similar among the four year period for all the variables.

Results for model implementation on SEG are displayed in Fig.6 where we see a high variance on flow rates along the four years data. The lower flow rates corresponded to summer months for 2009 and 2012, and the middle of 2011. It is worth noting that the decreases on the flow rate reflect an increase on the influent concentrations of $NH_4$ and $BOD_5$.

Regarding the model performance, underestimation of $NO_3$ is observed at the beginning of 2009 and the end of 2011, which is not linked to nitrite consumption. This is also reflected on the higher values of $RMSE$ for $NO_3$ for these years in Table 4. The rest of the variables showed homogeneous $RMSE$ values along the evaluation period.

Additional tests need to be performed to reduce the model. For instance, it would be possible to consider that nitrates and nitrites are taken by $r_2$ with their respective conversions from $NH_4$, or they could be modelled as one entity as reported in the literature (Henze et al. (1999); Petersen et al. (2002); Nelson and Sidhu (2009)). However, we decided to model them separately to evaluate all the measured variables.

The next step of the presented work will consist on the use of the model into control strategies that will be implemented on the Seine River around the area of study presented in Fig.1. The integrated model-based control strategy will take into account the three WWTPs in order to maintain good water quality of the Seine River.

Following the ideas of Vanrolleghem et al. (2005); Butler and Schütze (2005); and Sweetapple et al. (2014), a further step will be the inclusion of a sewer model to complete an integrated control strategy that remains simple for the urban wastewater system.

## 5. CONCLUSION

This work presented a simple model for wastewater treatment plants. The model considered six state variables to represent the quality of water. Model implementation in the three major WWTPs of the Seine River was performed with ease where results showed good performances over a four year evaluation period. The model demonstrated to capture correctly the dynamics of the considered variables with a simple structure providing a good trade-off between

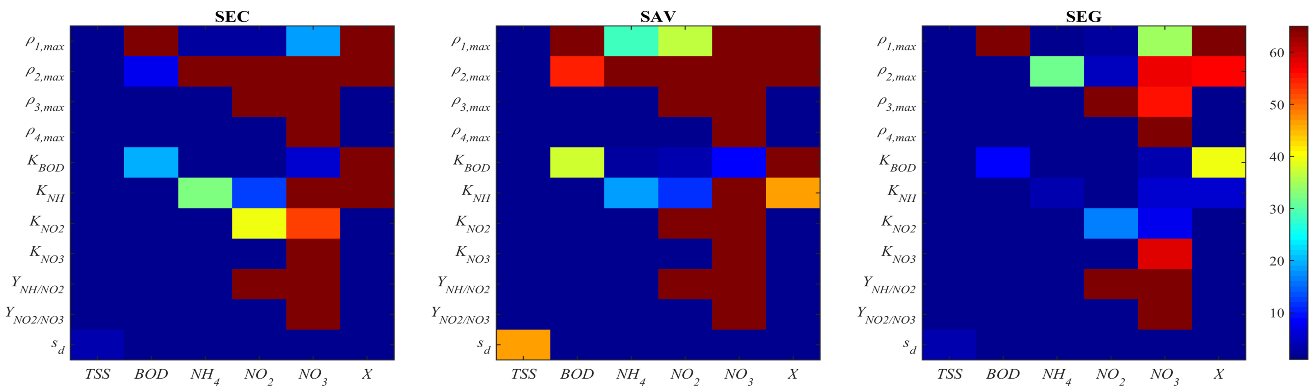


Fig. 3. L2 Norm of Parameter Sensitivity

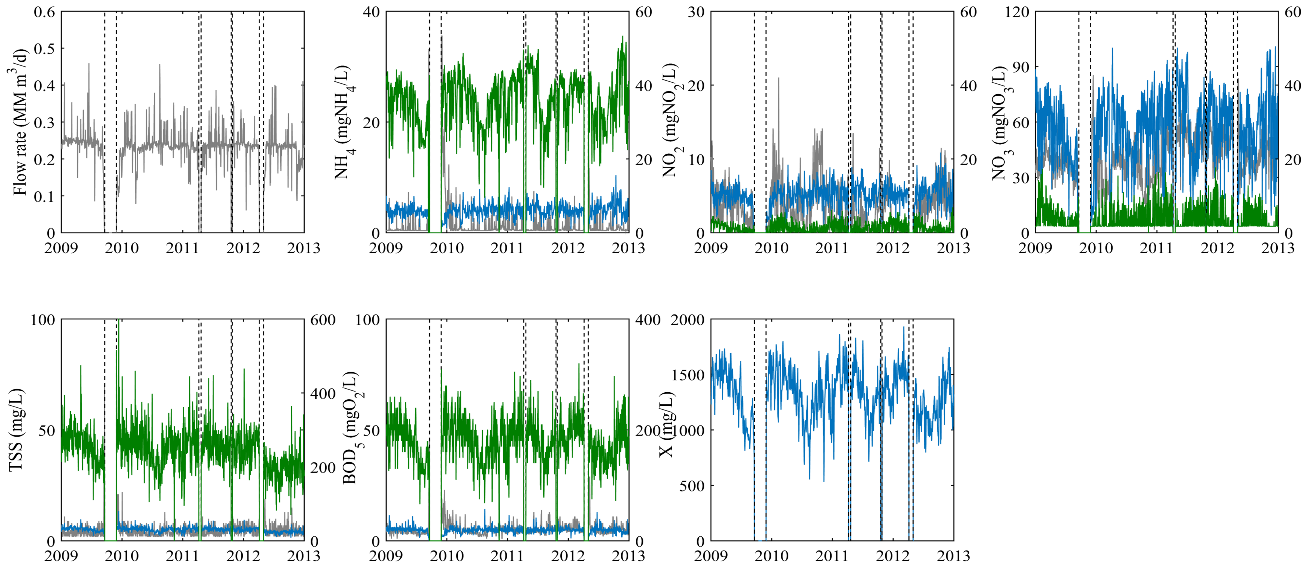

Fig. 4. Predicted concentrations for SEC. (—) Effluent concentrations, (···) Influent concentrations, (—) Model output

knowledge and complexity. This model is a first step towards an integrated model based control of river quality.

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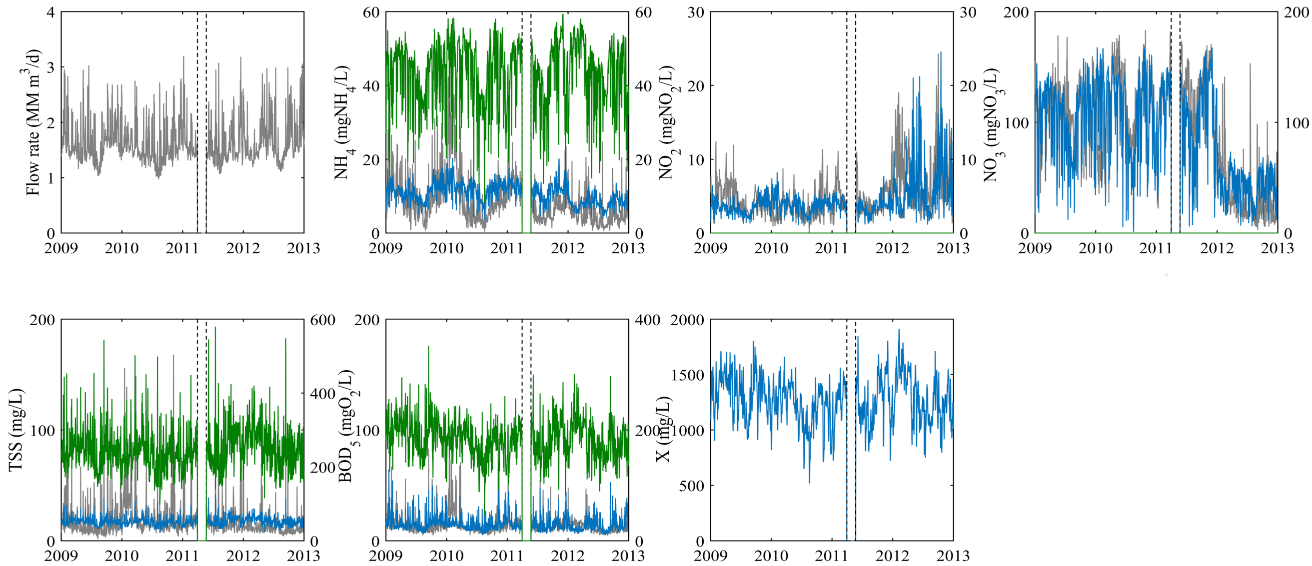


Fig. 5. Predicted concentrations for SAV. (—) Effluent concentrations, (···) Influent concentrations, (—) Model output

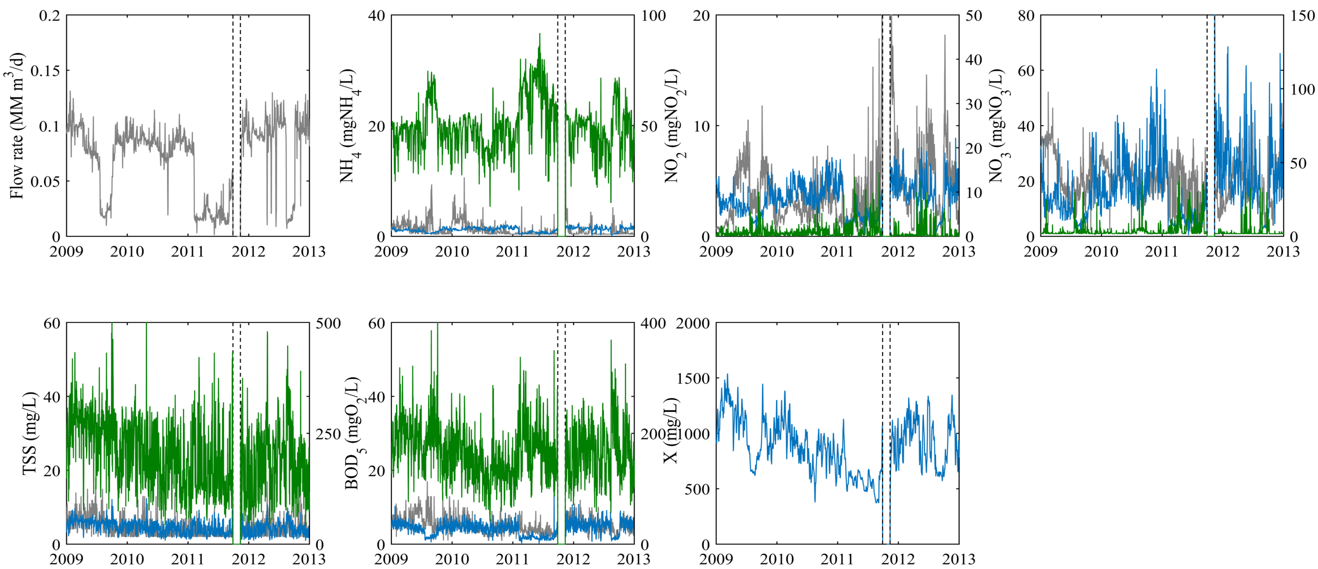


Fig. 6. Predicted concentrations for SEG. (—) Effluent concentrations, (···) Influent concentrations, (—) Model output


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