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# Simulation of organics and nitrogen removal from wastewater in constructed wetland

M. Taheriyoun[1*] and M. Rad[2]
*Department of Civil Enigineering, Isfahan University of Technology, Isfahan, Iran*
[*] *e-mail: m.taheriyoun@gmail.com*

**Abstract:** Modelling wastewater treatment processes is an effective tool for prediction and analysis of treatment system performance. In this study, removal of organics and nitrogen compounds of municipal wastewater is simulated in a constructed wetland based on system dynamic approach using Stella software. In the developed model, organics are represented by BOD and nitrogen compounds including nitrate, ammonia and organic nitrogen. Removal mechanisms for BOD include microbial degradation, plant absorption, and sedimentation. The mechanisms for nitrogen removal are denitrification, sedimentation and plant absorption. The model was calibrated and validated for a horizontal subsurface flow wetland in Arundel mills, Maryland based on 24 data gathered biweekly during one year. An acceptable $R^2$ and Nash– Sutcliffe coefficient of efficiency between the simulated and observed concentration values were obtained which provides a reliable tool in operation and management of the specified wetland in this case study. Based on the results of the model, overall BOD removal consists of 43% for the share of microbial degradation, 27% plant absorption and 30% for sedimentation. Also from the overall nitrogen removal, the share of sedimentation for organic nitrogen is 22%, plant absorption 14% and denitrification is 45%. According to the results, the developed model can be efficiently used in prediction, design and operation of constructed wetland.

**Key words:** Constructed wetland, wastewater treatment, System dynamic model, organics, nitrogen

## 1. INTRODUCTION

Constructed wetlands (CWs) are artificial wastewater treatment systems designed to remove pollutants from contaminated water using natural processes. These systems have developed rapidly over the past decades, and CWs are now recognized as an alternative to conventional mechanical treatment systems in small communities. They offer low operation and maintenance costs since no mechanical components or external energy supply is required (Vymazal, 2011).

Modeling the treatment process is an effective tool in design and operation of these systems rather than spending a lot of time and cost to gather and analyze the experimental data. The models used for CWs are categorized in two groups: black box model and process models. Black box models are called as data driven model that can be trained and tested for a set of data, but process models consider the cause and effect analysis in the processes that occur in a treatment unit.

System dynamics (SD) is an object-oriented simulation method based on feedback. In addition to its ability to discuss the complex systems, it offers the user with the possibility of intervention in model development which provides the user confidence. The simplicity in model change and the ability of sensitivity analysis are the advantages of this method in comparison with the other methods.

CWs are complex systems that function according to a set of interrelated removal mechanisms such as absorption, biodegradation and sedimentation. One of the main functions of CWs is the removal of organics and nitrogen compounds from wastewater. SD has great abilities in prediction of dynamic behavior of a system and survey the share of each effective process in total removal of pollutants. Thus, in this study, this approach is used to simulate the removal process of organics and nitrogen in a horizontal subsurface CW. SD has been applied to model wetland systems by a number of researchers.

Pimpan and Jindal (2008) developed a mathematical model for the cadmium removal process in the free water surface (FWS) CWs using STELLA software as SD model tool. They concluded that the developed model could be used to explain the cadmium removal process in the FWS constructed wetland.

Wynn and Liehr (2001) modeled a subsurface-flow constructed wetland. The model consisted of six submodels, including the nitrogen and carbon cycles, both autotrophic and heterotrophic bacteria growth and metabolism, and water and oxygen balances. The main problem in this work was that too many processes and components were considered in the model with very little data.

Wang et al. (2012) applied a system dynamic simulation model for free-water surface constructed wetlands , the major parameters that affect the simulation output was obtained via sensitivity analysis by using generalized likelihood uncertainty estimation (GLUE). The model was able to simulate the variations of DO, BOD5, and TSS, TN and TP.

Galanopoulos and Lyberatos (2016) used Activated Sludge Model (ASM) methodology to model free water surface CW. The model predicted plant mass and water uptake rate, BOD5 and TN removal on a year round basis. They demonstrated that given inflow, climatic and effluent data, the required surface area to achieve adequate treatment could be determined.

Xuan et al. (2010) applied STELLA software to model nitrogen removal in a subsurface upflow wetland system. The model was calibrated for nitrate, ammonia and organic nitrogen using parameters such as ammonification constant, plant growth rate, plant N content, nitrosomonas growth rate and yield coefficient and denitrification rate.

In this study, SD approach was used to model BOD and nitrogen removal in a horizontal subsurface CW. The modeling approach used in this study is based on the available data and the most possible simple model structure.

## 2. CASE STUDY

The case study is a horizontal subsurface flow wetland constructed in Arundel mills, Maryland. The data for nitrogen and organics was available from June 1991 to June 1992 including 24 data gathered biweekly during one year. The outflow from a septic tank enters the wetland system for further treatment. The specification of wetland and influent wastewater are indicated in Tables 1 and 2 (Thompson and Liehr, 2001).

*Table 1. The case study CW characteristics*

| Length | Width | Depth | Water depth | Porosity | Mean detention time |
|---|---|---|---|---|---|
| 70.1m | 45.7m | 0.8m | 0.75m | 40% | 2days |

*Table 2. Influent wastewater characteristics*

| Parameter | Unit | Mean | Standard deviation | Maximum | Minimum |
|---|---|---|---|---|---|
| Flow | $m^3/d$ | 510 | 169.5 | 1000 | 380 |
| BOD | mg/L$\frac{gr}{m^3}$ | 17.1 | 12.6 | 38.0 | 2.2 |
| Nitrate | mg/L$\frac{gr}{m^3}$ | 5.84 | 1.05 | 7.94 | 4.52 |
| Ammonium | mg/L$\frac{gr}{m^3}$ | 3.76 | 2.708 | 9.75 | 0.00 |
| Organic Nitrogen | mg/L$\frac{gr}{m^3}$ | 4.44 | 2.281 | 8.98 | 2.27 |

## 3. METHODOLOGY

### *3.1 Simulation of BOD removal process*

A conceptual model for BOD removal in the wetland is illustrated in Figure 1. This model consists of two stocks for dissolved and particulate organic carbon, which are related with hydrolysis process. Other processes consist of carbon removal, microbial degradation, plant absorption and sedimentation.

The assumptions considered in the model are as, the wetland system reacts as a complete mixed reactor, all processes of BOD removal are first order and the processes mostly effective in BOD removal include bacterial degradation, plant absorption and sedimentation (DeBusk, 1999).

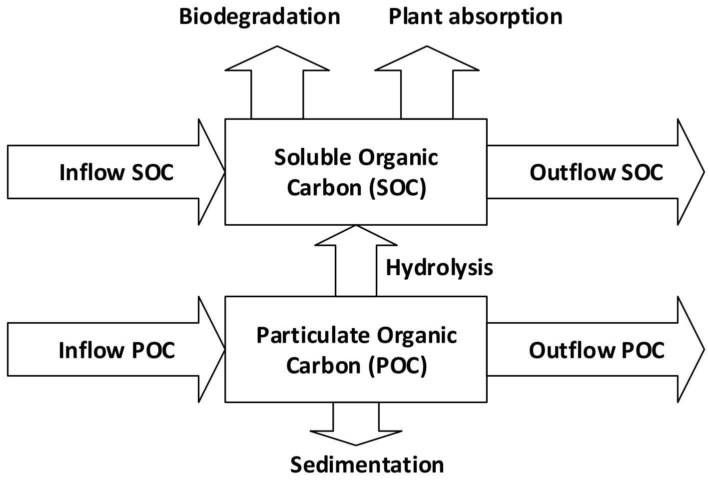


*Figure 1. Conceptual model of organic carbon removal*

### *3.2 Simulation of Nitrogen removal process*

To develop the model for nitrogen removal, firstly the conceptual model is illustrated in Figure 2. The assumptions used in this model are, wetland reacting as a complete mixed reactor, the only processes that are effective in nitrogen removal include plant absorption and bacterial degradation. The process of sedimentation is ignored due to little effect on N removal (Mayo and Bigambo, 2005). All processes follow first order reaction kinetics. As seen in Figure 2 three stocks of organic nitrogen, nitrate and ammonia nitrogen are considered and interrelation between the stock are presented. The models are developed in STELLA software and 12-month data of the case study are input in the model.

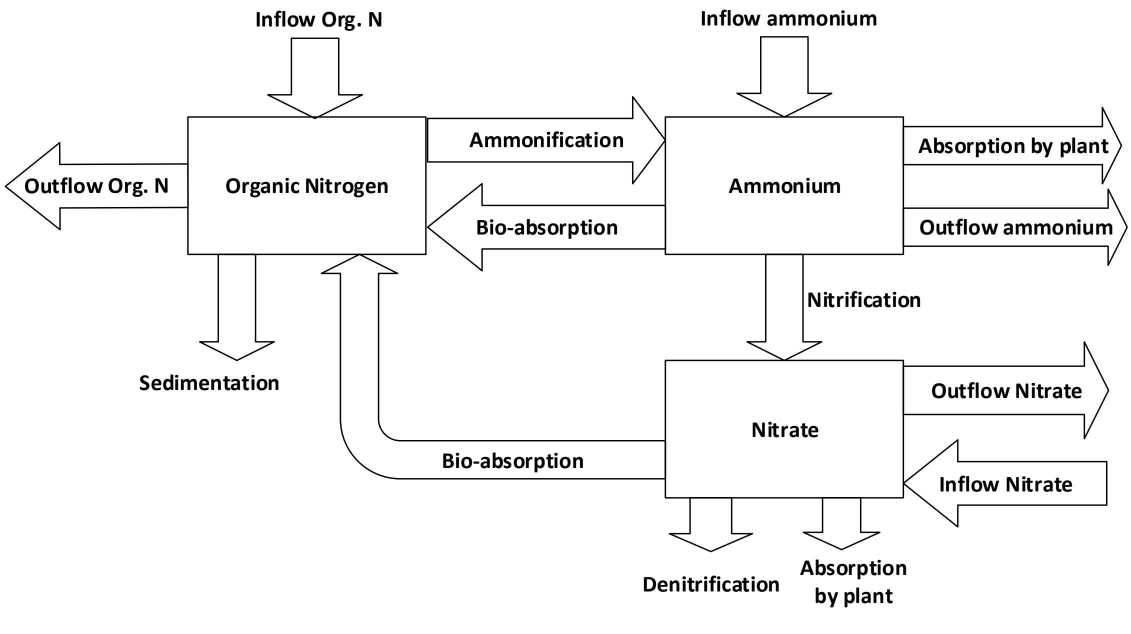


*Figure 2. Conceptual model of nitrogen*

The performance of each simulation is evaluated by the Nash–Sutcliffe coefficient of efficiency, (Nash and Sutcliffe, 1970), computed as follows:

$$E = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2} \quad (1)$$

where $O_{avg}$ represents the mean of the observed values, $Si$ and $Oi$ are the simulated and observed values respectively, and n is the number of values considered. In addition, correlation coefficient $R^2$ is between simulated and observed data are calculated for further assessment.

To calculate the share of each effective process in BOD and Nitrogen removal in the wetland, the average removal efficiency due to each process is divided by the total average removal of BOD and Nitrogen according to the Eq. (1).

$$S_i = \frac{R_i}{R_T} \times 100 \quad (2)$$

where $S_i$ is the share of process i, $R_i$ average removal efficiency of the process i and $R_T$ is total average annual biweekly removal.

One of the main objectives of modeling is the scenario analysis, which is the process of analyzing possible future events in the system by considering alternative possible outcomes. Scenario building is designed to improve system operation by analyzing the future results from the specified scenarios. In this study, scenarios of different input organic and nitrogen loading into the wetland is considered and the results of their simulation is analyzed.

## 4. RESULTS

Calibration and validation of models were done for all 24 biweekly data during one-year period. Data are divided into two sets including the first 16 data for calibration and the second 8 data for validation.

Figure 3 illustrates the observed and simulated BOD and nitrogen data for calibration and validation periods. Nash–Sutcliffe (Eq. 1) and correlation coefficients ($R^2$) are shown in the figures. They demonstrates acceptable agreement between observed and simulated data in both calibration and validation periods.

The share of each effective process in BOD and Nitrogen removal is shown in Figures 4 and 5 according to Eq. 2. Figure 4 indicates that the most effective process in organic removal in the wetland is the microbial degradation. In the removal of total nitrogen, denitrification is the dominant process, which is about 45%, and the absorption by plant has the minimum effect on total N removal in the wetland.

For the scenario analysis, four scenarios are defined based on fluctuation of input load of the wetland. These scenarios include the change of input load in the base scenario (existing condition) multiplied by the factors 0.5, 0.75 as lower level and 1.5 and 2 as upper level. Figure 6 shows the results of scenarios for BOD and TN removal by the wetland system. The graphs show time series of effluent concentration due to base scenario and other four scenarios indicated by the load factors (alpha).

Generally, it can be concluded that the sensitivity of the wetland performance to the change of input load is increased in higher loads, i.e. the sensitivity is maximum in peak concentration and it is minimum after a decline in concentration.

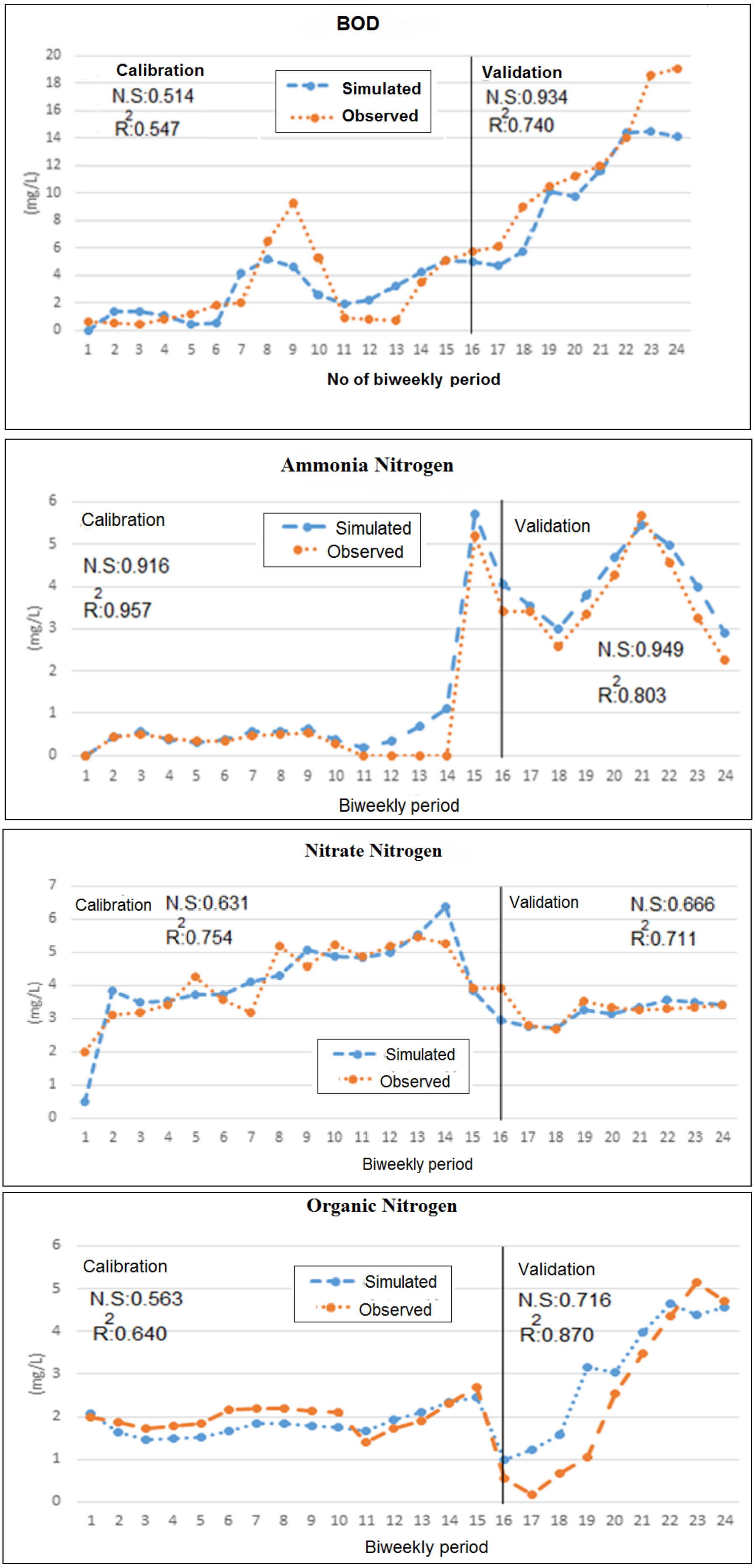


*Figure 3. Results of calibration and validation of BOD, Ammonia, Nitrate, Organic Nitrogen*

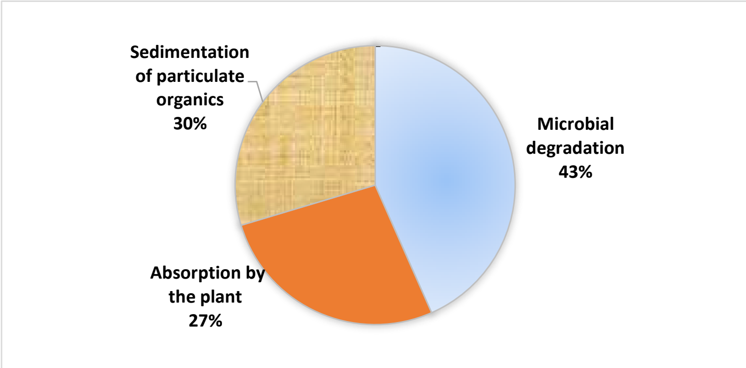


*Figure 4. The share of effective processes in BOD reduction*

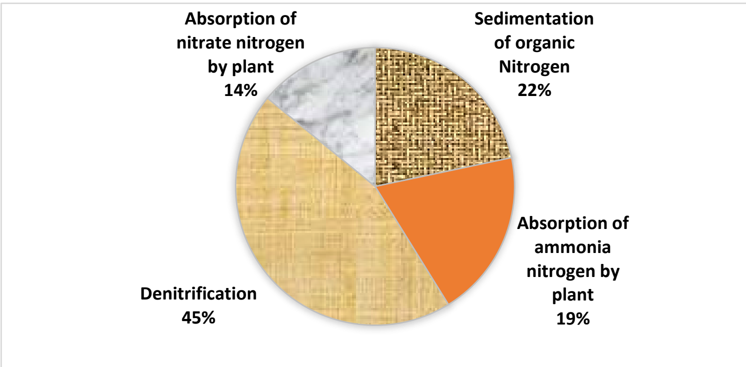


*Figure 5. The share of effective processes in total Nitrogen reduction*

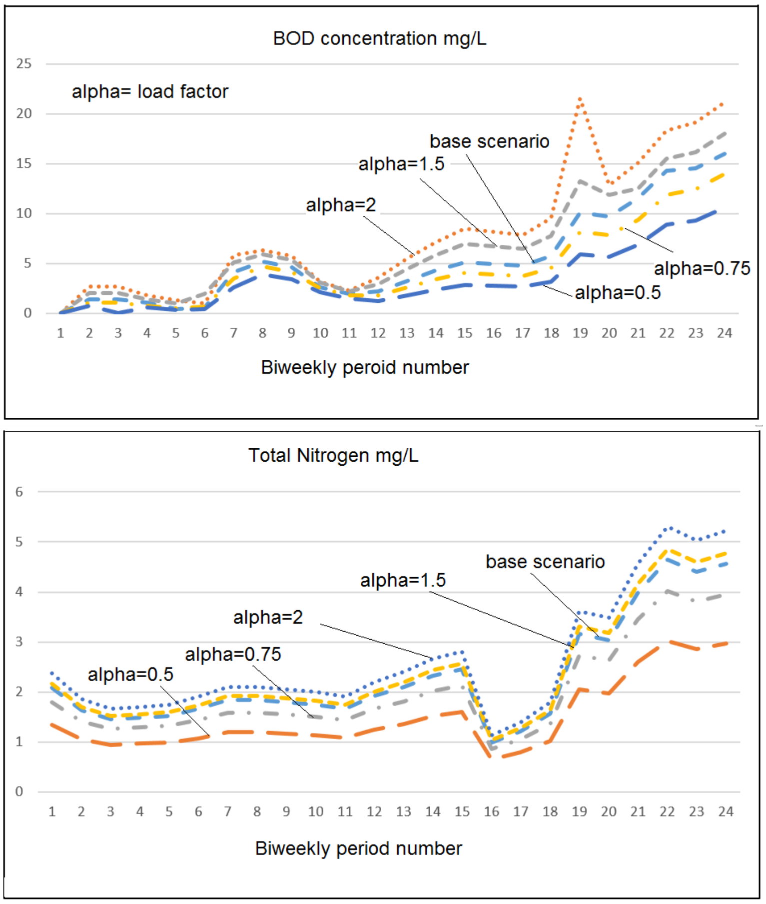


*Figure 6. Scenario analysis of different BOD and Nitrogen load input to the wetland*

## 5. CONCLUSION

A system dynamic approach was used to simulate the BOD and nitrogen removal processes in a constructed wetland. Bacterial degradation, plant absorption and physical process of sedimentation were considered as the most effective mechanism in BOD removal. For Nitrogen removal, plant absorption and bacterial degradation were the substantial processes. The model was calibrated and validated for one year biweekly data of a constructed wetland in Maryland, US. To demonstrate the application of the model in the wetland operational analysis, the apportionment of each effective process in organic and nitrogen removal is calculated. The results showed that the most effective process in organic removal is the microbial degradation and in nitrogen removal is denitrification. Scenario analysis showed that the sensitivity of effluent concentration due to the change of input load is maximum in peak concentration and it is minimum after a decline in concentration. Totally, results showed that the developed model is an effective tool in process analysis, prediction, design and operation of constructed wetlands.

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