THE SIMULATION OF DISSOLVED OXYGEN AND ORTHOPHOSPHATE FOR LARGE SCALE WATERSHEDS USING WASP7.1 WITH NUTRIENT LUXURY UPTAKE

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ABSTRACT

Phosphorus is often listed as a parameter causing impairment of rivers and streams throughout the nation. Excess available phosphorus may increase primary productivity in the stream and cause eutrophication. When periphyton is the main type of organism responsible for primary productivity, the total phosphorus uptake can be significant for the analysis of the overall system. Orthophosphate is absorbed and stored by periphyton and macrophytes during times of excess concentrations in the stream, and it can be used to support productivity during times of low phosphorus concentrations. This phenomenon is called nutrient luxury uptake. Although the importance of nutrient luxury uptake has been known for many years, it hasn't been systematically adopted for large scale studies. One of the reasons for omitting this important component of the nutrient cycling in the stream is that watershed models do not incorporate nutrient luxury uptake algorithms due to its relative complexity. Recently, the Water Quality Analysis Program (WASP) version 7.1 was updated to include the nutrient luxury uptake for periphyton. The objective of this paper is to demonstrate the importance of using the nutrient luxury uptake algorithm for dynamic water quality models when periphyton is the main type of organism responsible for primary productivity. An application of the new WASP7.1 model with the nutrient luxury uptake algorithms was developed for a large scale and diverse watershed in New Jersey. The application consists of simulating dissolved oxygen and orthophosphate at selected water quality monitoring stations representing different flows and nutrient availability conditions. Water quality parameters affecting the transport and fate of phosphorus were calibrated in order to capture the uptake of phosphorus by periphyton. This is likely the first application of the nutrient luxury uptake within the WASP7.1 water quality modeling framework to a large scale and diverse watershed. The model results show the importance of using the nutrient luxury uptake when periphyton is the main type of organism responsible for primary productivity and dissolved orthophosphate is scarce. The observed and predicted data show a good representation of dissolved oxygen and orthophosphate for the selected stations. During times of phosphorus depletion in the water column, the periphyton productivity did not cease; this is consistent with data obtained from field sampling. These results would not be obtained without implementing the nutrient luxury uptake for periphyton.

KEYWORDS

WASP, luxury uptake, periphyton, dissolved oxygen, phosphorus, water quality modeling, eutrophication.

INTRODUCTION

The simulation of water quality has been widely used to understand processes that occur in the water bodies and to support actions leading to desired levels of water quality. The relationship between nutrient availability and primary productivity is probably one of the most common water quality processes addressed using mathematical models. Phosphorus and nitrogen are nutrients necessary to support algae and plant growth. The excess of nutrients in water can lead to excess primary productivity, which contributes to eutrophication and associated water quality problems.

Dissolved oxygen concentrations are normally adopted to assess water quality. Low levels of dissolved oxygen can be associated with excessive algae and plant productivity. Phosphorus is generally considered to be the primary nutrient limiting algal and plant growth in fresh waters. Due to its importance, phosphorus is often listed as an impairment parameter for rivers and streams throughout the nation. The role of nutrients in fresh waters and its effects on dissolved oxygen can be quantified using water quality models. These models provide a mechanistic representation of the biological processes and can help guide actions to improve water quality.

Water quality modeling dates back from the early years of the twentieth century (Chapra, 1997). The sophistication of the processes simulated and the range of problems that water quality models can represent has grown together with technological and computational development. Most water quality models developed after the 1970s adopted Monod method to represent the dynamics of nutrients in aquatic systems. The Monod method relates plant and algae growth rate with available nitrogen and phosphorus in the water column to simulate the biological uptake of nutrients by algae. Once the growth rate of algae or plants is determined by the Monod Method, the nutrient pool and dissolved oxygen concentrations in the water column are calculated according to the rates of algae consumption and release of nutrients and oxygen. This method provides a simple and effective approach to represent many aquatic systems. However, it may not provide realistic simulations when the organisms present in the water body, particularly attached algae, assimilate nutrients at rates more rapid than used for growth.

The rates of phosphorus uptake are correlated with the metabolism of dominant organisms in the water bodies (Wetzel, 2001). When periphyton is the main type of organism responsible for primary productivity, the phosphorus assimilation rates can be significant for the analysis of the overall system. Periphyton is the algae attached to any substrate, such as rocks and other organisms such as macrophytes found in the bottom of streams, rivers and lakes. Dissolved orthophosphate (DOPO) is absorbed and stored by periphyton during times of excess concentrations in the stream. The excess phosphorus stored can be used to support productivity during times of low phosphorus concentrations in the water column. This phenomenon is called nutrient luxury uptake.

Although the importance of nutrient luxury uptake has been known for many years, it has not been systematically adopted for large scale studies. Droop (1974) developed a method that relates algae and plant growth with the internal nutrient levels that can be used to simulate nutrient luxury uptake. In order to take into account the effects of nutrient luxury uptake, the mass balance of the internal nutrient pool of the organisms needs to be simulated. The simulation of the internal nutrient pools is complex and may involve intensive computational effort. The degree of complexity can increase considerably for dynamic models that include multiple simulation elements. The complexity for representing the dynamics of nutrient luxury uptake is probably one of the reasons why this important component of the nutrient cycling in fresh waters is omitted in the most popular water quality models. Recently, the Water Quality Analysis Program (WASP) (Wool et al., 2003) was updated to include the nutrient luxury uptake for periphyton.

The objective of this paper is to demonstrate the importance of adopting the nutrient luxury uptake algorithm for dynamic water quality models when periphyton is mainly responsible for primary productivity and the supply of DOPO is limited. In order to demonstrate the importance of luxury uptake for some aquatic systems, the new WASP7.1 was tested at selected locations within a large and diverse watershed in New Jersey. The application of WASP 7.1 with the nutrient luxury uptake consisted of simulating total phosphorus, orthophosphate ammonia, nitrate, organic nitrogen, phytoplankton and periphyton at selected locations. Water quality parameters affecting the transport and fate of phosphorus were calibrated in order to capture the uptake of phosphorus by periphyton for the entire watershed.

MODELING OF NUTRIENT AVAILABILITY AND GROWTH

Monod and Droop Methods

Nutrient luxury uptake is critical to sustain the growth of algae when the available nutrients in the water column are scarce (Wetzel 2001, Effler 1996 and Sigee 2005).` The most common approaches to quantify the interplay of nutrient availability and the growth of algae and aquatic plants are the Monod model and the Droop model (Droop, 1974). The Monod method, which is also called the Michaelis-Menten model (Chapra, 1997), is the simpler approach of the two. It consists of calculating the maximum specific growth rate *G(N)* that can be achieved, according to the water column concentration of phosphorus [P] or nitrogen [N] and their respective half saturation constant K_p or K_n (Equation 1).

$$G(N) = \frac{[P]}{K_p + [P]} \qquad (1)$$

The Monod approach is simpler because it directly relates growth with available nitrogen and phosphorus in the water column. However, it ignores the phenomenon of luxury uptake, where nutrients are acquired and stored at levels well beyond the immediate demand for growth. By drawing on internal nutrient reserves, algae can grow at nearly maximum rates during periods of water column nutrient depletion (Effler, 1996).

The Droop method relates algae and plant growth with the internal nutrient levels, cell quota (Q), and the minimum cell quota (Q_0), which is the internal nutrient concentration where growth ceases (Equation 2). This method allows nutrient luxury uptake to be taken into account, but it is more complex from a computational standpoint. The Droop method requires the mass balance of the internal nutrient pool to be calculated, considering the contributions from nutrient uptake from the water column, and the losses through demand and growth (Effler, 1996).

$$G(N) = 1 - (Q_0 / Q) \quad (2)$$

Although the effect of nutrient luxury uptake for algae growth has been known for many years, it is not until recently that it has been more commonly applied for modeling efforts. The relative computational complexity required by the Droop method delayed its implementation in compartmented and dynamic water quality models such as WASP.

Water Quality Analysis Program (WASP)

WASP7.1 is the latest version of the Water Quality Analysis Program and is supported by the U.S. Environmental Protection Agency. WASP7.1 is a compartmental model that uses finite difference methods to simulate the transport and fate of pollutants within a stream network. WASP7.1 simulates conventional pollutant dynamics and toxic pollution (Ambrose, R.B. et al. 1993).

Previous versions of WASP were divided into two main simulation sub-models: EUTRO and TOXI. EUTRO was used for conventional pollution problems involving dissolved oxygen, biological oxygen demand, nutrients and eutrophication. TOXI was applied for toxic pollution involving organic chemicals, metal and sediment (Ambrose, R.B. et al. 1993). The WASP7.1 version presents new additions to the existing basic sub-models. Besides EUTRO and TOXI, more sub-models were added to address specific modeling needs. PERIPHYTON is one of the new sub-models added to WASP7.1. It allows the simulation of attached algae with the luxury uptake of nutrients.

There are several physical-chemical processes that affect the transport and interaction among nutrients, phytoplankton, periphyton, carbonaceous material, and dissolved oxygen in the aquatic environment (Wool et al. 2003). Figure 1 presents the main kinetic interactions for the nutrient cycling and dissolved oxygen as modeled within the WASP7.1 PERIPHYTON sub-model. The blue dark boxes represent systems simulated in WASP7.1, and the arrows represent the relationships among them.

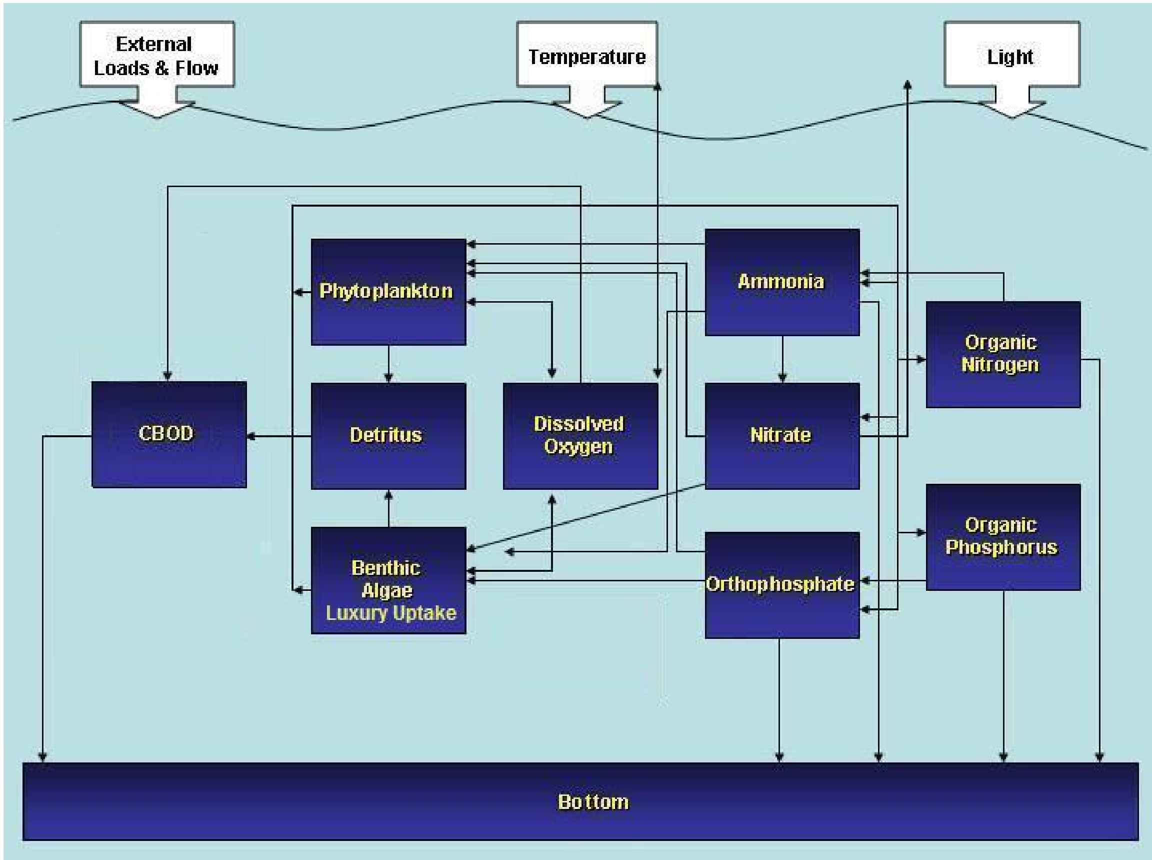

Figure 1: Kinetic interactions for the nutrient cycle and dissolved oxygen as modeled within WASP7.1 PERIPHYTON sub-model (Modified from Wool et al. 2003)

The PERIPHYTON algorithm and the simulation of the nutrient luxury uptake in WASP 7.1 were adapted from a formulation previously developed for the River and Stream Water Quality Model (QUAL2K). QUAL2K is a one dimension steady-state water quality model that can simulate multiple branches and segments in a stream network (Chapra et al., 2006).

SIMULATION OF PHOSPHORUS AND DISSOLVED OXYGEN WITH LUXURY UPTAKE (WASP7.1)

Nutrient luxury uptake becomes a critical component of water quality modeling when strong primary productivity is observed despite of the limitation of nutrient availability. The importance of adopting modeling frameworks that consider the nutrient luxury uptake can be demonstrated at sites presenting high strong diurnal dissolved oxygen variations when dissolved orthophosphate concentrations are below detection limits. Three existing monitoring stations (Sites 1, 2 and 3), located in a large and diverse watershed in New Jersey, were selected to test the WASP 7.1 model and the importance of simulating nutrient luxury uptake in these areas.

The selected areas are monitoring stations containing measurements of nutrient and diurnal dissolved oxygen (DO) concentrations. The sites differ in terms of average flows, concentration of dissolved orthophosphorus (DOPO), and diurnal DO variation. The analysis was performed during times of low flow and high primary productivity during the summer months of 2004. A one-dimension and continuous WASP 7.1 application was developed specifically for these selected areas. The model includes a hydrodynamic file with continuous flows, non-point source inputs from contributing sub-watersheds, known point source dischargers, time series of temperature, solar radiation, settling rates, and kinetics parameters. The PERIPHYTON algorithm was selected for the simulations. The model was calibrated using monitoring data collected by Omni Environmental LLC (TRC Omni Environmental, 2005). Calibration consisted of adjusting kinetic parameters such as periphyton growth rates, phosphorus cell quotas and maximum phosphorus uptake by periphyton. Figures 2, 3 and 4 show the observed and predicted diurnal DO and DOPO for sites 1, 2 and 3, respectively.

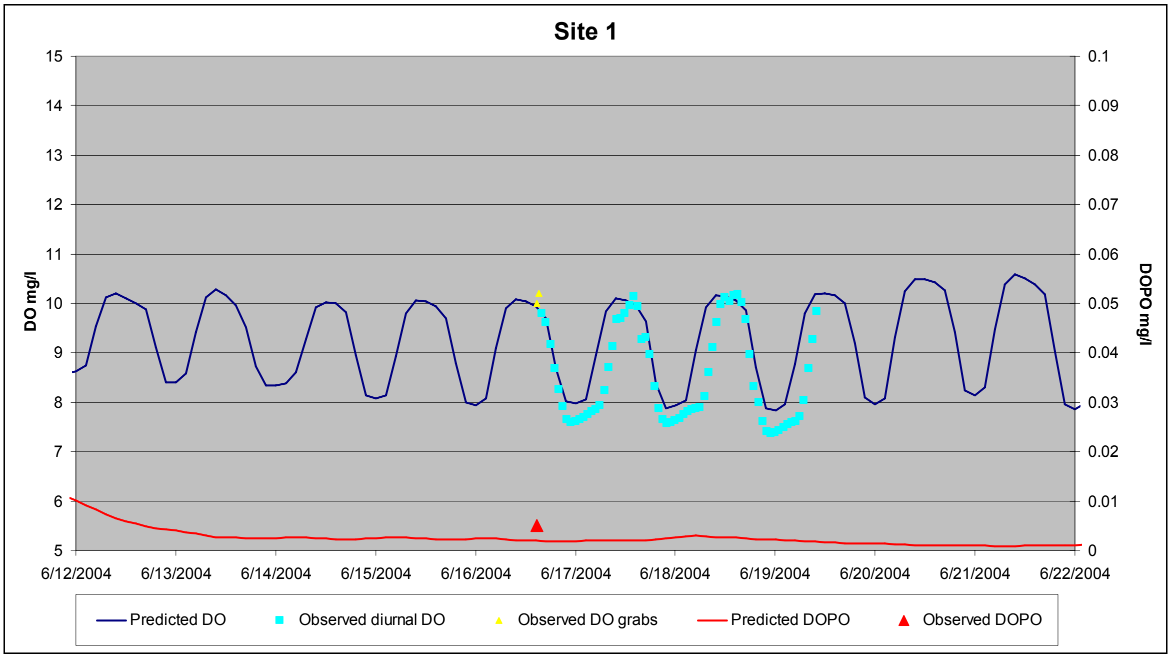

Figure 2: Predicted and observed concentrations of diurnal dissolved oxygen and dissolved orthophosphate at site 1

Site 1 is characterized by steady flow conditions (22 cfs), moderate productivity, and very low DOPO concentration. Diurnal variation of dissolved oxygen and DOPO concentrations are fairly constant. The detection limit of orthophosphorus is 0.01 mg/l. When diurnal DO measurements were performed, DOPO concentrations were consistently below detection. The DOPO sample, shown as half of the detection limit in Figure 2, confirms the low phosphorus levels simulated by the model. Even though simulated phosphorus was below detection limits, WASP 7.1 was able to capture the diurnal variation of dissolved oxygen very well during this event.

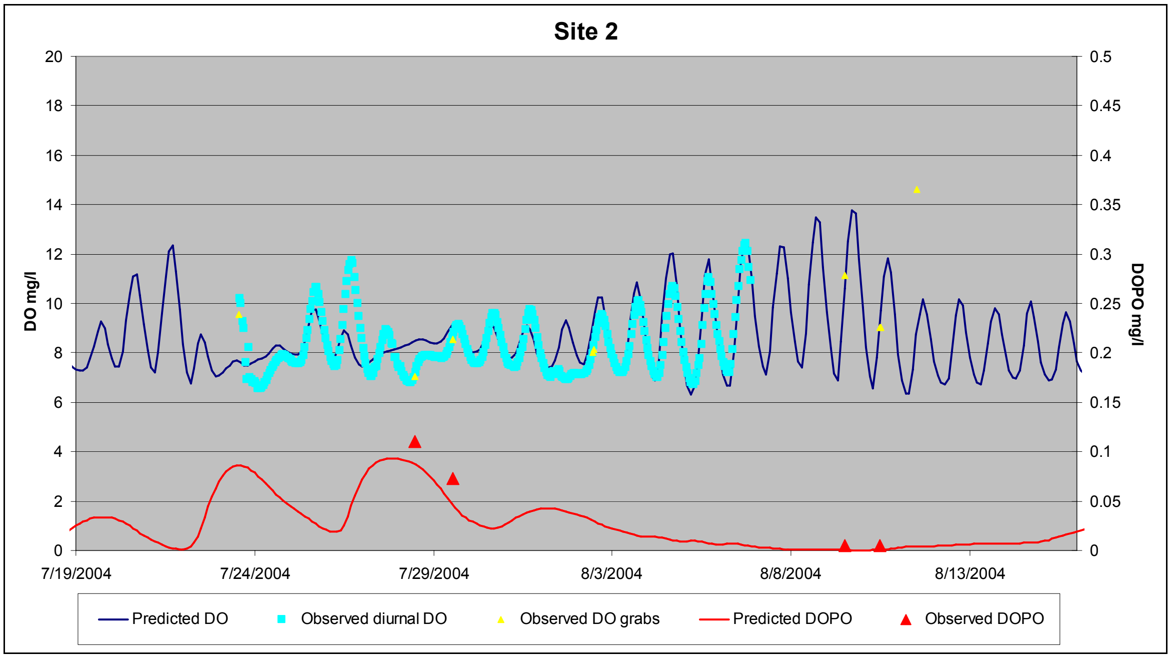

Figure 3: Predicted and observed concentrations of diurnal dissolved oxygen and dissolved orthophosphate at site 2

Results at Site 2 reflect more nutrient variability due to storm events that occurred during the sampling event. The DOPO sampled during the storm events show the non-point source inputs to the model. Strong diurnal DO variation is observed at times of poor DOPO availability. The simulated peak flow at Site 2 is 1655cfs. The lowest flow at the time of high productivity was 170 cfs. Diurnal DO variation is well represented during times of high and low DOPO availability.

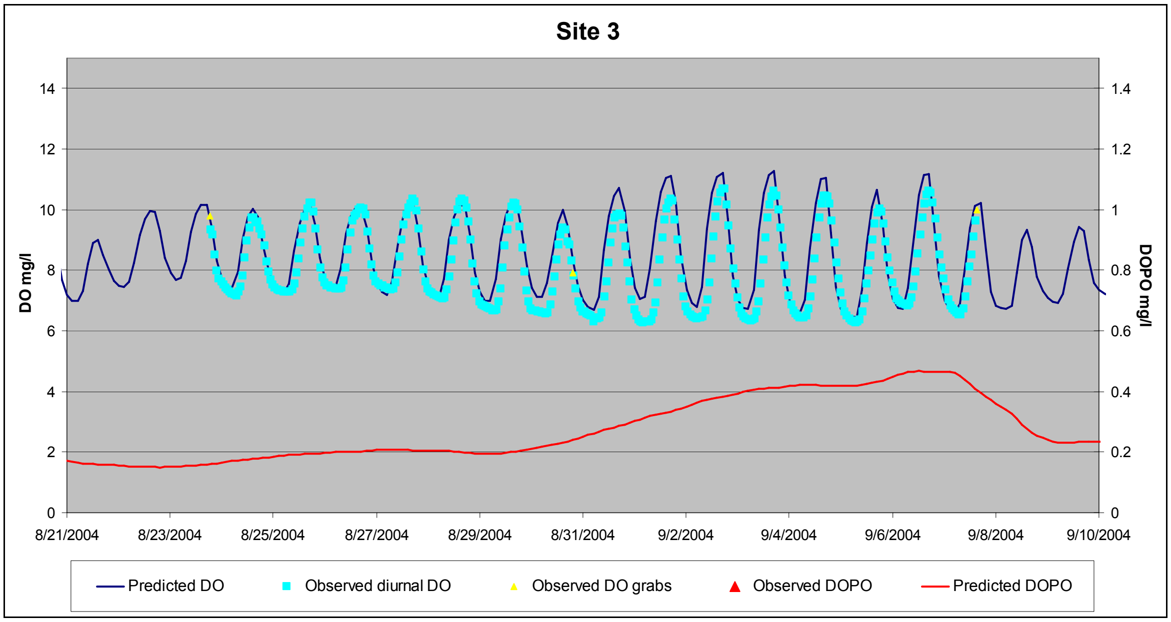

Figure 4: Predicted and observed concentrations of diurnal dissolved oxygen and dissolved orthophosphate at site 3

Site 3 presents strong diurnal DO variation and high DOPO concentrations. Dissolved orthophosphate was not sampled during the time of the diurnal sampling event. However, sampling performed at this site for different time periods reveal an average concentration of 0.21 mg/l and minimum concentration of 0.07 mg/l of DOPO. Average low flow during the time period shown in Figure 4 is 350 cfs. Therefore, the results obtained with WASP 7.1 with nutrient luxury uptake algorithm are able to capture observed levels of primary productivity under conditions of high and low phosphorus availability.

COMPARISON OF WASP SIMULATIONS WITH AND WITHOUT LUXURY UPTAKE

In the previous section, the effectiveness of WASP 7.1 was demonstrated for sites with significant diurnal dissolved oxygen variation under different conditions of flow and DOPO availability. The importance of using a modeling approach with the Droop method for nutrient limitation can be demonstrated by modeling the same areas discussed previously using a modeling framework that adopts the Monod method. An application of WASP 7.0, which adopts the Monod method for nutrient limitation, was developed for the same selected sites within the New Jersey watershed. The results obtained with WASP 7.0 and WASP 7.1 can be compared to demonstrate the importance of the nutrient luxury uptake for the simulation of sites presenting high productivity under scarce nutrient supply.

The same input data and kinetic parameters were used for both WASP applications. No additional calibration was performed for the WASP 7.0 application. Therefore, periphyton growth rates and half-saturation uptake rates for nutrients from the water column, which are calibration parameters for both approaches, were assumed to be the same. The comparison of diurnal DO variation obtained with the Droop method and the Monod method is shown in Figures 5, 6 and 7.

Figure 5 shows the comparison for Site 1, where DOPO concentrations are below the detection limit for a ten day period. The Monod method captures only half of the diurnal dissolved oxygen variation. In addition, the diurnal dissolved oxygen simulated with WASP 7.0 does not present the typical sinoidal shape. This indicates that phosphate concentration in the water column is not enough to support growth during times of nutrient depletion.

Figure 6 shows the comparison for Site 2, where DOPO concentrations vary during a 25 day period. This site allows a comparison during times of different phosphorus availability. The Monod method provides a realistic response of nutrient limitation when phosphorus is less scarce. When phosphorus concentrations are above 0.05 mg/l, the diurnal DO simulation is similar for both WASP versions. However, when DOPO drops under 0.025 mg/l, the Monod method is not able to sustain the same growth levels as the Droop method.

Figure 7 shows the comparison for Site 3, where DOPO is above 0.15 mg/l. The degree of diurnal DO variation simulated for this site is the same according to both methods. The Monod method seems to provide concentrations approximately 1 mg/l lower than the Droop method. This lower DO average could be addressed by changing calibration parameters in the WASP 7.0.

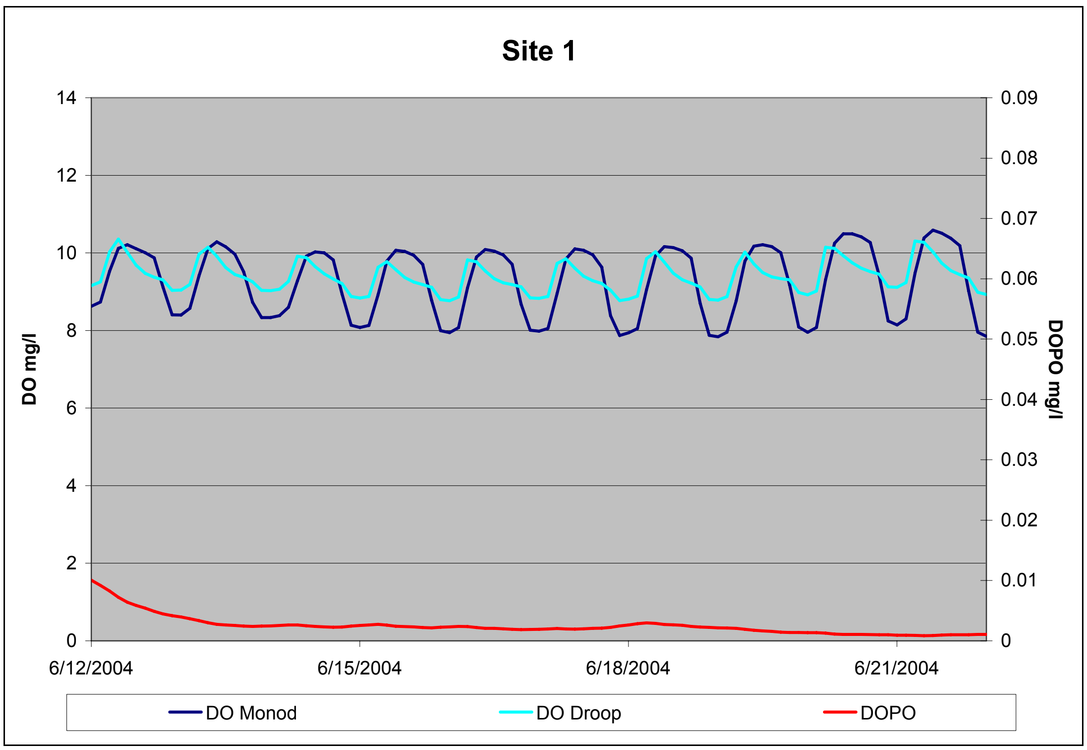

Figure 5: Comparison of dissolved oxygen variation obtained with the Droop method and the Monod method for site 1

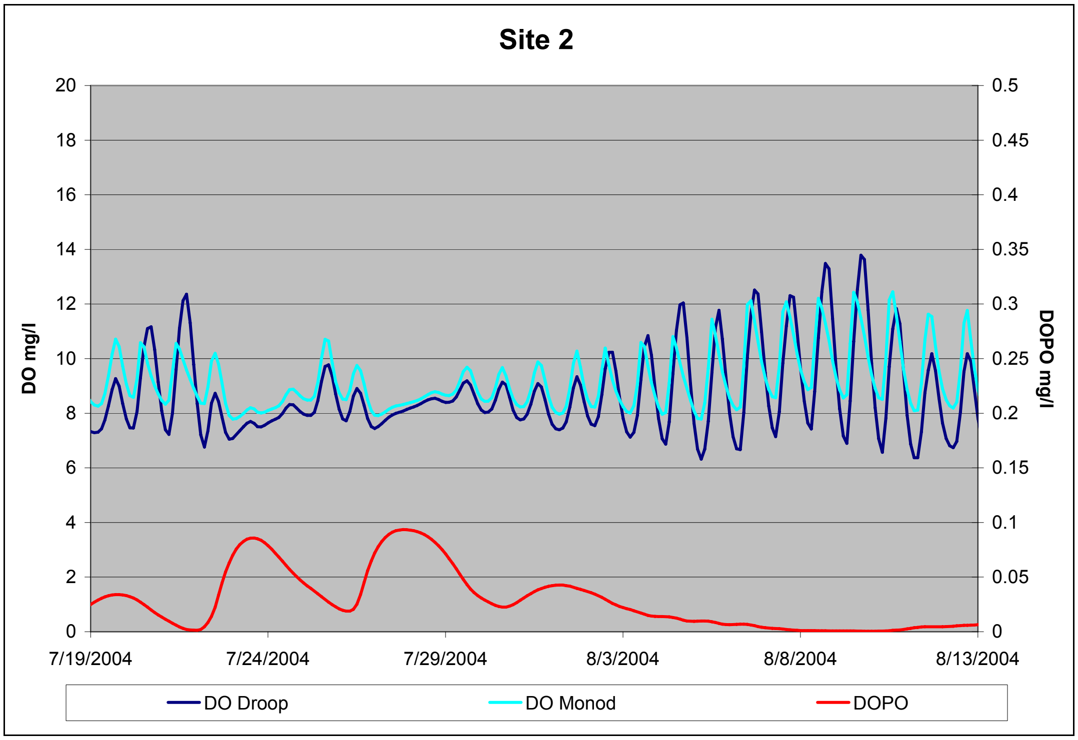

Figure 6: Comparison of dissolved oxygen variation obtained with the Droop method and the Monod method for site 2

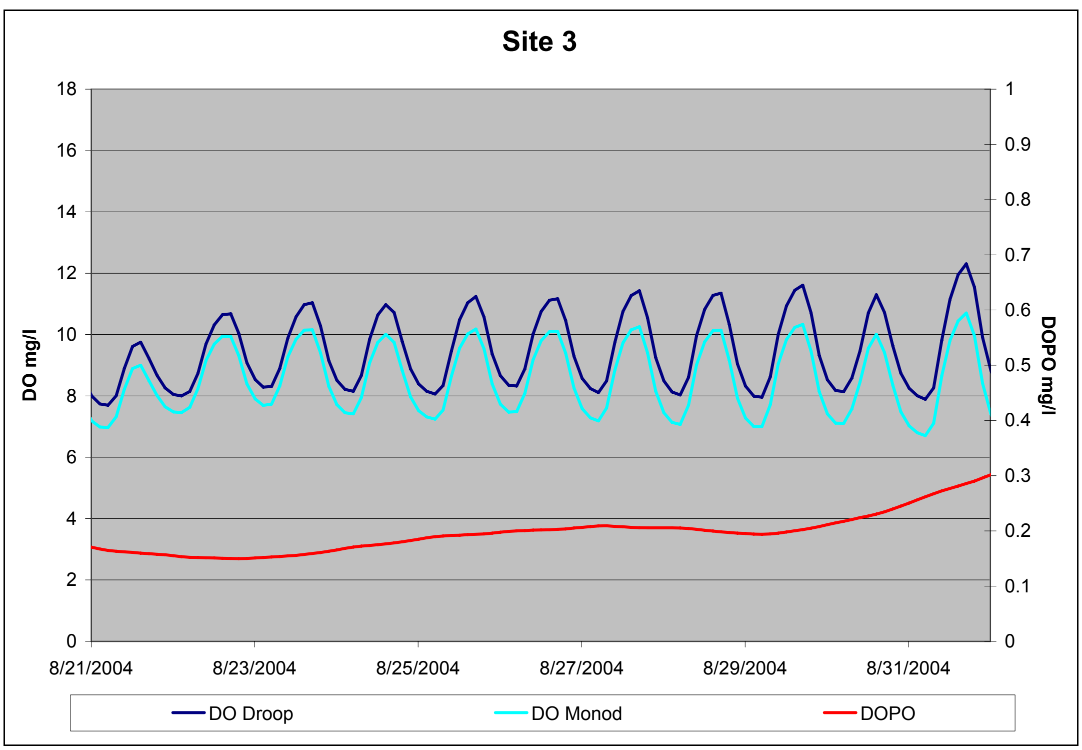

Figure 7: Comparison of dissolved oxygen variation obtained with the Droop method and the Monod method for site 3

In locations with abundant orthophosphate supply, the simulation with WASP 7.0 could be recalibrated to fit the observed data. However, further calibration will not improve the diurnal DO productivity at locations with low DOPO supply, such as Sites 1 and 2. In the case of Site 1, the lack of orthophosphate is clearly reflected in the shape of the diurnal DO variation timeseries. Increasing the maximum periphyton growth rates would not improve the model performance at this location. In the case of site two, higher growth rates could improve the model performance under low flow conditions. However, the diurnal DO pattern observed in Site 1, which is also present in Site 2 to a smaller extent, could become more pronounced, and times of less productivity could be over predicted.

CONCLUSIONS

The importance of considering the phenomenon of nutrient luxury uptake when there is limited phosphorus supply and periphyton is the main type of organism responsible for primary productivity is demonstrated in this paper. The Monod method for nutrient limitation has been successfully adopted for many years, and it is used in most water quality models. Although this method is widely used, it cannot provide an adequate representation of diurnal DO under low concentrations of available nutrients when the phenomenon of luxury uptake of nutrients is important. The Droop method can successfully address the problem of luxury nutrient limitation.

As environmental concerns and water quality restrictions grow, the need for methods and equipment that are able to represent a broader range of conditions and sophisticated water processes become necessary. WASP 7.1 incorporates the Droop method, and is thus able to simulate the luxury uptake of nutrients by periphyton. WASP 7.1 was applied for selected areas representing different conditions of flow and DOPO availability within a large and diverse watershed in New Jersey. The model was able to capture the variation of diurnal DO under the different conditions. The importance of the nutrient luxury uptake for periphyton was demonstrated by comparing the simulations obtained with WASP 7.1 and WASP 7.0. The simulations with WASP 7.0, which adopt the Monod method, cannot capture the diurnal dissolved oxygen when the nutrient supply is short.

The inclusion of the Droop method for simulating nutrient limitation and periphyton growth in WASP is a significant advancement. The processes occurring in large and diverse watersheds, which are characterized by areas with distinct nutrient availability, can be better represented within a single model. This modeling framework provides a way to better understand water quality process and a better approach to support actions leading to desired levels of water quality.

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