Review of water quality models simulating in-stream nutrient dynamics

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Abstract

Many waterbodies around the world are adversely impacted by harmful algal blooms (HABs). One primary driver of these blooms is often high concentrations of anthropogenic phosphorus loading. The phosphorus mitigation plans require accurate information on nutrient sources and transport, to and through water bodies, including the stream network. Diffuse sources, are particularly difficult to quantify due to the cost of in situ monitoring, and is often supplemented using various water quality models. SWAT, a comprehensive watershed-scale model, is widely used to assess and improve downstream water quality using QUAL2E equations. EPA developed QUAL2E can model phytoplankton growth but has a limited capacity to model benthic algae. Although SWAT requires a lesser number of parameters while simulating water quality outputs, unlike, HSPF, INCA, SPARROW, WASP, and MIKE-SHE, the water quality algorithm within SWAT needs modifications for simulating phosphorus legacy within the waterbodies. This study reviews the existing water quality models to improve the water quality algorithm within SWAT. Most of the water quality models can simulate processes, including the proliferation of fixed and floating algal biomass and phosphorus cycling (QUAL2E/K, WASP, HSPF). Some water quality models are better in simulating the time-dependent factors, such as light attenuation, form and concentration of nutrients, and water temperature (HSPF, INCA). There are a few water quality algorithms that can simulate both horizontal stream flow and shallow flow (SHETRAN, INCA). Both horizontal and shallow flow takes into account the anisotropy and variable biogeochemistry impacts on the turbulence of water, thus, the water quality. Some water quality models simulate the non-linear relationship between nutrient concentration and discharge timing and magnitude (SPARROW). There are some commercialized models like MIKE-SHE that simulate reasonably good results, but the water quality algorithm/equation/process is not publically available. Our review of the existing water quality models will help in identifying, modifying, and implementing the SWAT source code revisions required to improve and mitigate water quality degradation from a finer spatial scale, including small ditches and streams, to the large-scaled watershed over time.

Title: Review of water quality models simulating in-stream nutrient dynamics (Abstract ID: 747129)

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Abstract

Many waterbodies around the world are adversely impacted by harmful algal blooms (HABs). One primary driver of these blooms is often high concentrations of anthropogenic phosphorus loading. The phosphorus mitigation plans require accurate information on nutrient sources and transport, to and through water bodies, including the stream network. Diffuse sources, are particularly difficult to quantify due to the cost of in situ monitoring, and is often supplemented using various water quality models. SWAT, a comprehensive watershed-scale model, is widely used to assess and improve downstream water quality using QUAL2E equations. EPA developed QUAL2E can model phytoplankton growth but has a limited capacity to model benthic algae. Although SWAT requires a lesser number of parameters while simulating water quality outputs, unlike, HSPF, INCA, SPARROW, WASP, and MIKE-SHE, the water quality algorithm within SWAT needs modifications for simulating phosphorus legacy within the waterbodies. This study reviews the existing water quality models to improve the water quality algorithm within SWAT. Most of the water quality models can simulate processes, including the proliferation of fixed and floating algal biomass and phosphorus cycling (QUAL2E/K, WASP, HSPF). Some water quality models are better in simulating the time dependent factors, such as light attenuation, form and concentration of nutrients, and water temperature (HSPF, INCA). There are a few water quality algorithms that can simulate both horizontal stream flow and shallow flow (SHETRAN, INCA). Both horizontal and shallow flow takes into account the anisotropy and variable biogeochemistry impacts on the turbulence of water, thus, the water quality. Some water quality models simulate the non-linear relationship between nutrient concentration and discharge timing and magnitude (SPARROW). There are some commercialized models like MIKE-SHE that simulate reasonably good results, but the water quality algorithm/equation/process is not publically available. Our review of the existing water quality models will help in identifying, modifying, and implementing the SWAT source code revisions required to improve and mitigate water quality degradation from a finer spatial scale, including small ditches and streams, to the large-scaled watershed over time.

Keywords: *Water-Quality Models; Soil and Water Assessment Tool; In-Stream Processes; Nutrient Dynamics; Harmful Algal Blooms (HABs)*

BACKGROUND

1. Eutrophication, which is commonly caused by elevated levels of reactive forms of phosphorus (P), increases the prevalence of harmful algal blooms and hypoxia while decreasing water quality (Conley, 2000; Mainstone et al., 2000; Bennett et al., 2001).

2. Sources of reactive P include point sources (e.g., discharges from industrial and municipal wastewater) and non-point sources (e.g., agricultural runoff, septic tank leaks, and riverbank erosion). Often, non-point sources are difficult or prohibitively expensive to quantify (Jarvie et al., (2002, 2005)). Process-based models offer a low cost and flexible approach for estimating the magnitude and impact of difficult to quantify non-point sources.

3. To model nutrient cycling within a process-based water quality model, modelers often make several assumptions. Some models often ignore high-resolution spatial variability (small streams, ditches). Simultaneously, others simplify the different processes controlling P cycling within the rivers/streams (Withers and Jarvie, 2008). Here, we focus on the implications of ignoring or naively modeling instream P cycling.

4. In-stream P cycling processes (e.g., uptake/release, adsorption/desorption, coprecipitation/dissolution, and advection/diffusion) can have substantial impacts on the magnitude, timing, and form of P exports to recipient ecosystems (Vannote et al., 1980; Bryce et al.,1999; Allan, 2004). For example, Jarvie et al. (2011) showed that the Sandusky and Thames Rivers retained up to 48% and 14% of P flux on an annual scale. Thus, accounting for instream processes in the water quality model is essential for characterizing the impact of non-point P sources on P exports to recipient ecosystems.

5. Some commercialized models can simulate reasonably the different in-stream processes, but the water quality algorithm/equation/process is not publicly available. On the other hand, an open-source, distributed, and processed-based hydrologic and water quality model, namely, the Soil and Water Assessment Tool (SWAT), has been explicitly used in the science community last 30 years (Arnold et al., 1998).

6. This study aims to identify the limitations within the SWAT model in simulating various in-stream processes.

IN-STREAM PHOSPHORUS CYCLING

In-stream phosphorus cycling includes redistribution pathways where the transformation of P from inorganic to organic and back to dissolved form takes place (Figure 1).

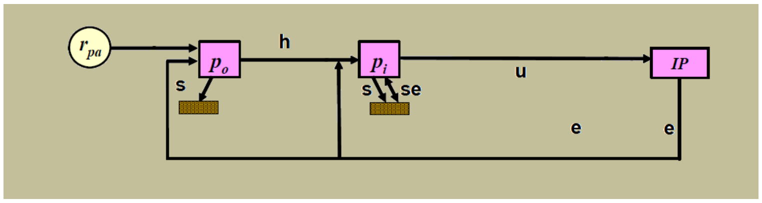

Figure 1. Phosphorus cycling with mass transfer and model kinetics

where, R_{pa} is the amount of Phosphorus within per unit biomass of phytoplankton (1mg P / 1.25 mg Phytoplankton Biomass algae) (Filstrup and John, 2017); p_o is organic phosphorus; p_i is inorganic phosphorus; IP is the sum of phytoplankton phosphorus and benthic algae phosphorus; h hydrolysis; u is uptake by aquatic biota; e is the excretion from sediments and aquatic biota detritus; s is settling, and se is the sediment exchange.

Redistribution pathways include different processes. Erosion of stream channels during high flow conditions, remobilization of P due to physical disturbance of bed sediments or macrophyte communities, the release of P from bed sediments, or death of aquatic biota (Figure 2).

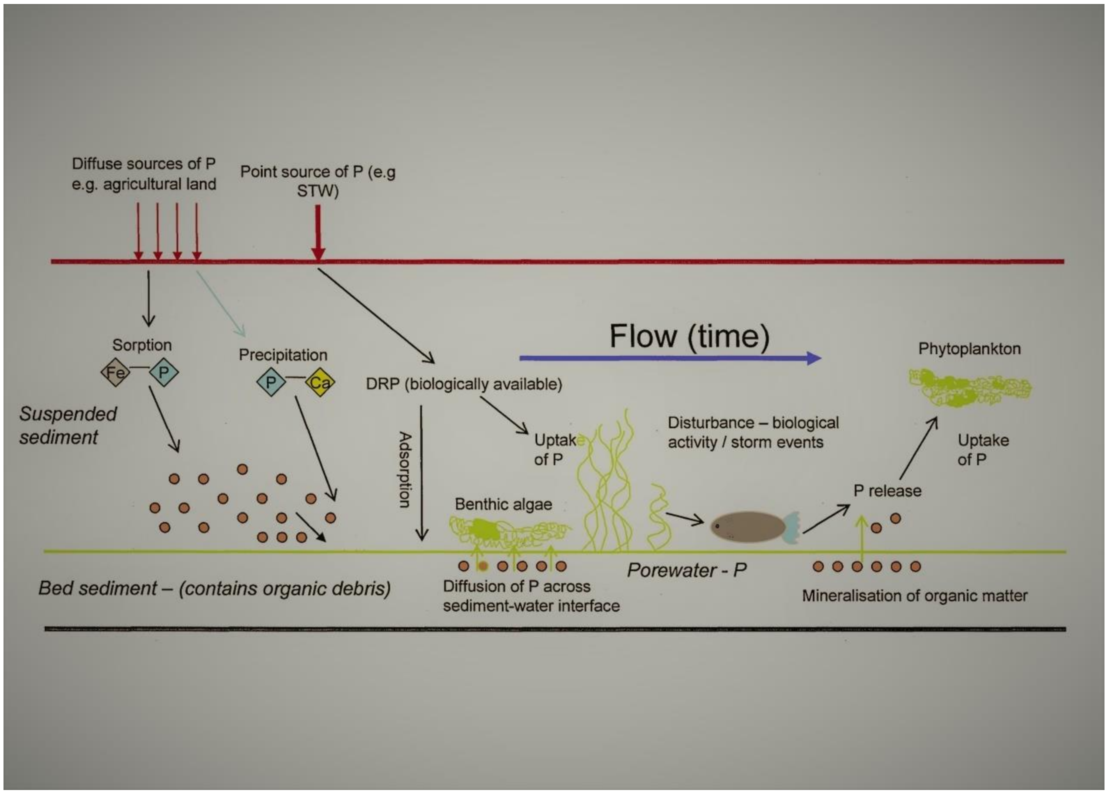

Figure 2. Conceptual diagram of in-stream processes influencing P concentration in flowing waters. (Adapted from Withers and Jarvie, 2008)

SWAT In-Stream Processes (Developments and Limitations)

In SWAT, the concentration of algae in the stream drives P nutrient cycling

The growth of algae is decided by the rate at which “chlorophyll a” grows or decays, the respiration rate of phytoplanktons, settling rate, and amount of algae present in the stream

$$\Delta algae = \left((\mu_a . algae) - (\rho_a . algae) - \left(\frac{\sigma_1}{depth} . algae \right) \right) . TT$$

$\Delta algae = change\ in\ algal\ biomass\ concentration, mg\ alg/L$

$\mu_a = local\ specific\ growth\ rate\ of\ algae, day^{-1}\ or\ h^{-1}$

$\rho_a = local\ respiration\ or\ death\ rate\ of\ algae, day^{-1}\ or\ h^{-1}$

$\sigma_1 = local\ settling\ rate\ for\ algae, \frac{m}{day}\ or\ \frac{m}{hr}$

$depth = depth\ of\ water\ in\ the\ channel, m$

$algae = algal\ biomass\ concentration\ at\ the\ beginning\ of\ the\ day, mg - alg/L$

$TT = Flow\ travel\ time\ in\ the\ reach\ segment\ (day\ or\ h)$

However, SWAT ignores organic forms of phosphorus are generated by algae's death

Also, it was observed that SWAT in-stream kinetics formulation does not apply to any species other than phytoplankton

To overcome the limitation Santhi et al., 2001, introduced a first-order decay kinetic function that included periphyton. The function was developed to characterize the microbial transformation of in-stream soluble P to organic P with respect to flow conditions.

$$PC_o = PC_i \times e^{-a\left(\frac{chl}{q}\right)}$$

$$\Delta SP = SP_i - SP_o$$

$$OP_o = OP_i + \Delta SP$$

PC_o *and* PC_i *are reach soluble P inflow and outflow concentrations in* $\frac{g}{m^3}$

“a” is the degradation coefficient

“chl” is channel length in km

“q” is flow rate in mm/day;

SP_i *and* SP_o *are the inflow and outflow soluble P loads in kg*

OP_i *and* OP_o *are the inflow and outflow organic P loads in kg*

On the contrary, White et al. 2014 observed that the existing in-stream P submodel within SWAT does not adequately represent the in-stream processes associated with suspended algae systems, specific to the site, Illinois River Watershed in Oklahoma.

The SWAT water quality sub-routine (QUAL2E) was replaced with the routine that represents streambed storage and SRP interactions within the water column.

Although, the modified SWAT in-stream routine has performed well in many regions but may not be equally applicable to all areas.

(A) Soluble Phosphorus In-stream Submodel

$$EPC = \frac{\sum_{t=1}^{-DI} SP_t \left(1 + \frac{t}{DI}\right)}{\sum_{t=1}^{-DI} \left(1 + \frac{t}{DI}\right)}$$

$$EPC > SP_{in}$$

$$SP_{out} = EPC + \left(SP_{in} - EPC\right)e^{-Kout\,TT})$$

$$EPC < SP_{in}$$

$$SP_{out} = EPC + \left(SP_{in} - EPC\right)e^{-Kin\,TT})$$

$$SP_{trans} = SP_{in} + \left(1 - e^{-SPTT} EPC)\right)$$

$EPC = Equilibrium\ Phosphorus\ Concentration$

$SP_t = soluble\ phosphorus\ concentration\ on\ day\ "t"\ in\ mgL^{-1}$

$DI = period\ of\ influence\ in\ days\ (user\ specified)$

$SP_{in} and\ SP_{out}$
$= Concentrations\ of\ Soluble\ P\ entering\ and\ leaving\ the\ reach\ in\ \ mgL^{-1}$

$K_{in}\ and\ K_{out}\ =$
$soluble\ P\ transformation\ coefficients\ into\ and\ out\ of\ the\ benthic\ sediments$

$TT = Travel\ time\ in\ reach\ in\ hours$

(B) Particulate Phosphorus In-stream Submodel

$$f_{bf} = \frac{Q}{Q_{bf}}$$

$$PP_{out} = PP - PP\,\frac{(F_{bf} - F_{dep})}{(F_{eqv} - F_{dep})}$$

$$PP_{out} = PP - BP_{conc}\frac{(F_{bf} - F_{eqv})}{(F_{eqv} - F_{eq})}$$

$f_{dep} = bank\ flow\ condition\ where\ 100\ \%\ deposition\ takes\ place$

f_{scr}
$= bank\ flow\ condition\ where\ 100\ \%\ scoring\ from\ streambed$

f_{eqv}
$= bankflow\ condition\ where\ deposition\ is\ equivalent\ to\ scouring$

$PP = Particulate\ P\ concentration\ in\ the\ reach\ water\ column$

$PP_{out} = Particulate\ P\ concentration\ leaving\ the\ reach$

$BP_{conc} = Concentration\ of\ benthic\ P\ in\ the\ water\ column\ if\ 100\%\ of$
$benthic\ P\ were\ released$

Proposed SWAT In-stream Water Quality Processes Modifications

The review of different in-stream algorithms within SWAT to date proves that there is a scope of improvement in the water quality algorithm to include both suspended and benthic P forms.

A simplified in-stream P cycle is shown in Figure 3.

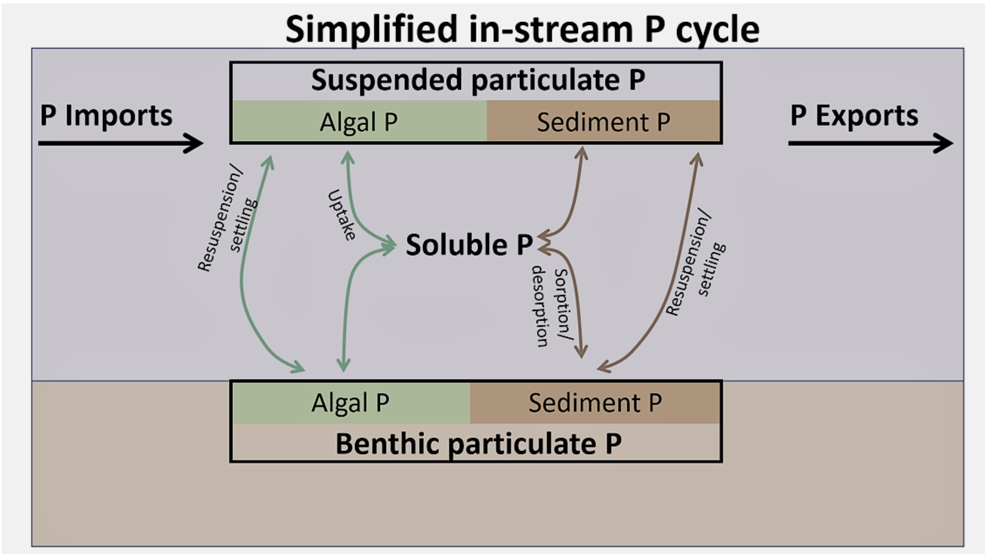

Figure 3. A proposed modified in-stream P cycle

Conclusions & References

The limitations of the existing water quality algorithm with SWAT can direct modifications within SWAT source code to enhance the ability of SWAT to simulate in-stream processes.

The modified revision of SWAT for simulating in-stream water quality will be tested at local and regional scales to test its efficacy.

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