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The Soil and Water Assessment Tool is widely used to predict the fate and transport of phosphorus (P) from the landscape through streams and rivers. The current in-stream P submodel may not be suitable for many stream systems, particularly those dominated by attached algae and those affected by point sources. In this research, we developed an alternative submodel based on the equilibrium P concentration concept coupled with a particulate scour and deposition model. This submodel was integrated with the SWAT model and applied to the Illinois River Watershed in Oklahoma, a basin influenced by waste water treatment plant discharges and extensive poultry litter application. The model was calibrated and validated using measured data. Highly variable in-stream P concentrations and equilibrium P concentration values were predicted spatially and temporally. The model also predicted the gradual storage of P in streambed sediments and the resuspension of this P during periodic high-flow flushing events. Waste water treatment plants were predicted to have a profound effect on P dynamics in the Illinois River due to their constant discharge even under base flow conditions. A better understanding of P dynamics in stream systems using the revised submodel may lead to the development of more effective mitigation strategies to control the impact of P from point and nonpoint sources.

THE FATE AND TRANSPORT of nutrients in streams and rivers is an important environmental concern. Phosphorus (P) in particular is linked to primary productivity in freshwater aquatic systems (Schindler et al., 2008). Excessive primary productivity may result in impaired waters that cannot support assigned designated usages. The U.S. Environmental Protection Agency (USEPA) maintains a listing of impaired water bodies according to section 303(d) of the Clean Water Act. Nationally, excessive nutrients were the fourth leading cause of water quality impairment (USEPA, 2010).

One method to mitigate water quality impairment is the development of total maximum daily loads (TMDLs). This method seeks to identify pollution sources within a watershed and allocate acceptable levels of pollution to each individual source. This may require the use of tools such as The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) or Hydrological Simulation Program—Fortran (HSPF) (Bicknell et al., 1997). These models simulate landscape processes, which result in nutrient delivery to water bodies, and lotic nutrient cycling and transformations, which occur in stream and rivers. With increasing pressure from the USEPA to develop and enact TMDLs, tools like SWAT and HSPF are more frequently used. The continued development of these models will better support these water quality programs.

Phosphorus input from the landscape must be considered in conjunction with in-stream P behavior to generate effective remedial strategies (McDowell and Sharpley, 2003). In-stream processes include sediment sorption and desorption, precipitation and dissolution, microbial and algal uptake, and floodplain and wetland retention (Haggard and Sharpley, 2006). These in-stream processes result in significant modification of P loads and forms transported downstream (Mulholland and Webster, 2010; House, 2003).

The current in-stream submodel contained within SWAT is based on the QUAL2E (Brown and Barnwell, 1987). QUAL2E simulates the growth and settling of algae in the stream system. SWAT considers two forms of P in the in-stream submodel:

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Abbreviations: EPC, equilibrium P concentration; HSPF, Hydrological Simulation Program—Fortran; NSE, Nash Sutcliffe efficiency; SRP, soluble reactive P; SWAT, Soil and Water Assessment Tool; TMDL, total maximum daily load; WWTP, waste water treatment plant.

mineral and organic. These labels are often misunderstood. Mineral P refers to soluble forms, including soluble mineral and soluble organic P forms. Organic P represents particulate forms, including organics like algae cells and sediment-bound P. The SWAT in-stream submodel predicts soluble P uptake by algae during growth, transforming it to particulate forms contained within the algal cells in the water column. Growth may be light or nutrient limited. Benthic sediment is also a source of soluble P; the quantity is based on the streambed area and a constant benthic sediment soluble P source rate specified by the user. These routines are optional; users may disable in-stream nutrient transformations, making soluble nutrient transport conservative through the stream system.

These in-stream routines have been shown to accurately predict P transport by many researchers. There are many examples in the literature of acceptable P predictions at the monthly or annual scales; Gassman et al. (2007) list 14 such studies. The simulation of nutrient dynamics at the daily scale, which is one objective of this study, is more difficult. Gassman et al. (2007) lists five studies successful at that level. Grizzetti et al. (2003) calibrated and validated SWAT for daily estimated total P loads, with Nash-Sutcliffe efficiency (NSE) values ranging from 0.54 to 0.74 on the Vantaanjoki watershed in Finland over a period of 9 yr. Glavan et al. (2011) used SWAT to predict daily ortho-P concentrations in the Axe watershed in the United Kingdom, with excellent results in a highly point source-impacted reach using the existing routines.

Other researchers have expressed the need for an improved in-stream nutrient submodel in SWAT. Grunwald and Qi (2006) found that SWAT replicated streamflow well but found shortcomings in the nutrient routines, as documented by poor to moderate performance simulating N and P loads. The authors also note that data deficits likely contributed to the poor performance. Migliaccio et al. (2007) coupled SWAT with a full QUAL2E model and compared their combined ability to predict nutrient losses with SWAT, with and without the in-stream components active. They found no significant differences in monthly nutrient predictions between the three models and concluded that the in-stream processes in SWAT do not enhance the predictive capability of the model. This study was conducted on a monthly basis; daily comparison may yield different results. Other researchers have opted to develop simplified in-stream P submodels and incorporate them directly into SWAT. Santhi et al. (2001) encoded a simple first-order decay function for soluble P in simulation of the Bosque River watershed in central Texas. These researchers concluded that the SWAT in-stream components did not adequately represent systems dominated by periphyton like the Bosque River because algae in SWAT are assumed to reside in the water column. The authors used a first-order decay function using reach length and flow rate as a surrogate for travel time and a user-specified degradation coefficient. Other research by Stewart et al. (2006) in the Bosque River achieved satisfactory monthly P predictions without the modification by Santhi et al. (2001).

There are alternatives to QUAL2E that have been developed to predict P in-stream processes. Viney et al. (2000) presented a simple in-stream particulate P model based on sediment deposition and streambed degradation, requiring only three parameters in calibration and treating soluble P as a conservative

solute. Wade et al. (2001) simplified the P and macrophyte model presented by Ham et al. (1981) through a sensitivity analysis reducing the number of parameters from 14 to 10, 9 of which were significant with respect to P. The most important parameters are those linked with storage of total P in the streambed and the exchange of soluble reactive P (SRP) between the pore water and the overlaying water column (Wade et al., 2001). Based on the importance of these parameters, better representation of streambed storage and SRP interactions with the water column should be considered in SWAT.

The SWAT model is widely used to predict P losses from the landscape, where measured P data collected from streams and rivers for calibration and validation have been subjected to in-stream modification. Edge-of-field P loss data could be used to directly calibrate upland P losses, but these data are relatively rare and expensive to collect. It is important that the in-stream submodel properly accounts for changes in P loads and forms between the upland areas and downstream sampling sites because this has direct bearing on the quality of load predictions from upland areas.

The SWAT model can be calibrated to measured loads at a gauge site by altering the upland or channel parameters. There are many paths to a calibrated model, each of which may result in a different set of input parameters. Each combination may be equally successful according to commonly used statistical metrics evaluated at a single gauge but may predict very different upland and channel processes.

This research focuses on the development of an alternative to the existing QUAL2E-derived in-stream P routines. These routines have performed well in many regions but may not be equally applicable to all areas. The impetus for this research was the need to predict changes in P management required to meet in-stream P concentration standards in the Illinois River Watershed in Oklahoma. The existing in-stream P submodel does not adequately represent the in-stream processes associated with sestonic algae systems common in this region of the Ozarks. The in-stream standard to be evaluated in the Illinois River requires the accurate prediction of daily P concentrations under current and proposed conditions and emphasizes accurate predictions during baseflow conditions. To facilitate this research, an appropriate in-stream P submodel was needed that can accurately represent these processes at a daily timescale. This research and the evaluation of the standard are fully documented in Storm et al. (2006, 2010). This study focuses on the development of the in-stream submodel and presents the Illinois River study as an example application of the proposed revised approach. The specific objectives are (i) to develop a submodel that can predict instream P concentrations on a daily basis, (ii) to integrate the submodel into the SWAT code and test it for proper function, and (iii) to test the revised SWAT model in the Illinois River Basin. Work is underway to incorporate this submodel into the standard release version of SWAT.

Materials and Methods

Submodel Description

The instream submodel consists of two primary components (Fig. 1). The first component represents the deposition and scour of particulate P to and from the streambed. This particulate P includes sediment-bound P and algal P. The second component

Fig. 1. In-stream submodel overview. EPC, equilibrium phosphorus concentration.

represents the transformations of soluble P to particulate P and interactions with benthic sediments and attached biota. These components are intended to represent a combination of biotic and abiotic processes. Soluble P interactions with the streambed cover adsorption and release by sediments and uptake by stationary organisms such as periphyton. The particulate routine may latter scour sediment and periphyton into the water column and transport them downstream. No attempt is made to simulate algal uptake separately from abiotic processes.

Soluble Phosphorus In-Stream Submodel

Phosphorus loss pathways in SWAT are limited to surface runoff only. Phosphorus can be transported in lateral flow and in groundwater (Carlyle and Hill, 2001; Heathwaite and Dilsb, 2000), but surface and near-surface processes are usually the primary sources of P in stream discharge (Viney et al., 2000). The SWAT model does not track lateral or groundwater contributions of soluble P to streamflow. SWAT generates upland loads of soluble P only during runoff events, yet measured streamflow data clearly show that soluble P is present at significant concentrations even under base flow conditions. To accurately match measured stream P concentrations, SWAT needs an in-stream process to buffer and store soluble P between runoff events and release it during base flow conditions.

Although benthic sediments are often associated with particulate P, they also behave as both a source and a sink for soluble P in the water column (Hoffman et al., 2009; Ekka et al., 2006) and act as an important buffer for soluble P in streams. One measure of the interaction between soluble P in the water column and benthic sediments is the equilibrium P concentration (EPC) (Froelich, 1988). The sediment EPC is the concentration in the aqueous phase at which there is no net sorption or desorption from benthic sediments.

Equilibrium P concentration is a function of many factors, including sediment particle size and composition, solution cations, and P content (Ekka et al., 2006). Solution cations and sediment composition are not considered in SWAT, whereas sediment particle size distribution functions are being tested. Once these routines are adequately tested, the in-stream P submodel may be linked with sediment transport. This leaves P loads as the primary factor, which can be used to estimate EPC in SWAT. Due to the

dynamic equilibrium between benthic sediment and the water flowing over them, the P content of benthic sediment is highly dependent on the concentration of soluble P in the stream. For example, streams that receive waste water treatment effluent typically have much greater EPC downstream of the discharge as compared with upstream (Ekka et al., 2006).

To use the EPC concept in SWAT, a method to estimate EPC for each reach must be devised. Typically, EPC is measured using sediment samples in the laboratory; here EPC must be estimated each day by the model and is assumed to be a characteristic of the entire channel. Given spatial differences in P loading, EPC should vary by reach. Under baseflow conditions, EPC is often highly correlated with the concentration of soluble P in the water column (Klotz, 1988). For this reason, we derive the model estimates EPC daily for each reach in the basin based on the concentration and timing of soluble P entering each reach. The equation used to derive EPC is given as

$$EPC = \frac{\sum_{t=1}^{-DI} SP_t * [1 + (t/DI)]}{\sum_{t=1}^{-DI} 1 + (t/DI)} \quad [1]$$

where EPC is the estimated EPC on day t in mg L^{-1} , SP_t is the soluble P concentration on day t in mg L^{-1} , and DI is the period of influence in days (user specified). Equilibrium P concentration is calculated as a weighted average of soluble P concentration entering the reach for many days before the current day. The weight is based on a period of influence parameter DI, which varies from near 1 for recent days and approaches 0 at DI days in the past. In this way, yesterday's soluble P concentration has more effect on today's EPC estimate than a concentration from a month ago. Values of DI ranging from 100 to 500 d produced predictions consistent with typical in-stream total P concentration variability. This range is similar in magnitude to the lag in stream response seen by other researchers. Haggard and Stoner (2009) evaluated changes in sediment EPC after sudden reduced P input from a wastewater treatment plant (WWTP) in the Lake Eucha basin. They observed a slow decrease in sediment EPC after the reduced P input from upstream, and sediments became a source of P to the water column. Equilibrium P concentration slowly declined over the next 14 mo (420 d) in the absence of scouring events. The default for this parameter is 365 d; better values may be obtained via calibration with several years of measured data.

Stream flow and P loading are dynamic; the soluble P in the water column will deviate from the EPC on any given day. The sorption and desorption of soluble P from benthic sediments are not instantaneous. We assume these processes obey first-order kinetics depending on their contact time. Similar kinetics have been described by House and Warwick (1998). Travel time in the reach was used as a surrogate for contact time. The direction of transformation is based only on the difference between the current soluble P concentration in the water column and the EPC concentration. If EPC is greater, P moves from the streambed (if sufficient P is available) to the water column. If EPC is less, P moves from the water column to the streambed. The magnitude of the difference, the travel time, and a rate constant are used to determine the magnitude of the transformation.

If $EPC > SP_m$:

$$SP_{out} = EPC + (SP_{in} - EPC) \exp^{-K_{out} TT} \quad [2]$$

If $EPC < SP_{in}$:

$$SP_{out} = EPC + (SP_{in} - EPC) \exp^{-K_{in} TT} \quad [3]$$

where SP_{in} and SP_{out} are the concentrations of soluble P entering and leaving the reach in $mg\ L^{-1}$, K_{in} and K_{out} are the soluble P transformation coefficients into and out of the benthic sediments in h^{-1} (both user specified, 0.1 default), and TT is the travel time in the reach in hours. To represent the uptake of soluble P by algae in the water column, soluble P is transformed to particulate P in the water column according to the following equation:

$$SP_{trans} = SP_{in} * (1 - \exp^{-SPT*TT}) \quad [4]$$

where SP_{trans} is the concentration of P transformed from soluble to particulate forms, and SPT is the soluble to particulate transformation coefficient (user specified, default 0.01).

Particulate Phosphorus In-stream Submodel

Particulate P is assumed to comprise all nonsoluble forms of P. This includes abiotic forms associated with sediments and biotic forms, such as mobile organisms and periphyton. The particulate routines described here allow for a buildup of P in the stream system through deposition from the water column and a periodic resuspension and flushing of P from the system during high flow events. Flushing of P from stream systems has been noted in high-frequency (10 min) measured P data by Jordan et al. (2005). The link between discharge condition and P deposition and mobilization has been identified in other such intensive sampling studies. Bowes and House (2001) found retention of particulate P during base flow and a remobilization of particulate P during high flow conditions for the River Swale watershed in the United Kingdom. The streambed P pool (Fig. 1) is tracked by stream reach and acts as a source and sink for P deposition and scouring. The amount of P stored in the streambed pool at any instant depends on previous flow activity and P transformations. Bowes and House (2001) further found a mobilization of P during low to medium discharge in the River Swale watershed, which is contrary to previous research for the same river (House and Warwick, 1998). Bowes and House (2001) postulated that antecedent conditions may play an important role in P dynamics. By tracking P stored in streambed sediments, antecedent conditions are considered by the proposed submodel.

The particulate P submodel is purposefully separated from the sediment deposition and streambed and bank erosion routines of the SWAT model. There is a great deal of uncertainty in the estimates of channel sediment contributions in even a well calibrated SWAT model. This is often the result of a lack of data with which to gauge the relative contribution of upland and channel sediment sources during the calibration process. Particulate P in the water column may be scoured from the streambed or deposited, depending on flow conditions. Unlike sediment, the modification of streamflow due to in-stream processes is relatively minor. Scour and deposition are based on the fraction of bankfull discharge reached on any particular day. The fraction of bankfull discharge is calculated as:

$$F_{bf} = Q/Q_{bf} \quad [5]$$

where F_{bf} is the fraction of bankfull discharge in the reach, Q_{bf} is the streamflow in $m^3\ s^{-1}$ at bankfull conditions, and Q is the streamflow in $m^3\ s^{-1}$. Bankfull discharge in SWAT is calculated

by assuming a trapezoidal channel profile and using channel dimensions derived from GIS or user inputs. The particulate P submodel is based on three user inputs: F_{eq} , F_{dep} , and F_{scr} , where F_{eq} is the fraction of bankfull discharge at which scour and deposition of particulate P is at equilibrium, F_{dep} is the fraction of bankfull discharge flow at which there is 100% deposition of particulate P in the water column, and F_{scr} is the fraction of bankfull discharge at which all P is scoured from the streambed. Although F_{eq} may be adjusted between 0 and 1, the recommended range is 0 to 0.25. If $F_{bf} < F_{eq}$, deposition of particulate P occurs; if $F_{bf} > F_{eq}$, P is scoured from the streambed if available.

The second parameter, F_{dep} , is required to predict P deposition. The value of F_{dep} must be less than F_{eq} and may be less than 0, indicating that 100% deposition never occurs even if there is no flow. The amount of deposition on any given day is a linear function, which calculates the fraction of particulate P that is deposited.

$$PP_{out} = PP - PP \times \frac{(F_{bf} - F_{dep})}{F_{eq} - F_{dep}} \quad [6]$$

where PP_{out} is the particulate P concentration leaving the reach, and PP is the particulate P concentration in the reach water column. If P is deposited, the quantity is added to the streambed P pool for that reach.

During higher flow conditions, P may be scoured from abiotic sediments and from biotic sources like periphyton. Phosphorus scoured from the benthic environment is limited to the quantity in the streambed P pool, which is tracked separately for each reach in the watershed. Like the deposition routine, the scour routine requires one additional parameter, F_{scr} . The following equation is used:

$$PP_{out} = PP_{in} + BP_{con} \times \frac{(F_{bf} - F_{eq})}{F_{scr} - F_{eq}} \quad [7]$$

where BP_{con} is the concentration of benthic P in the water column if 100% of the benthic P were released. During model testing, it was found that limiting scouring to 50% of the total streambed pool on any single day provided better results, and this limit was added to the in-stream submodel code. Any P scoured from the streambed is removed from the benthic pool for that reach. Once the P in the streambed pool of a reach is exhausted, no further scouring of P is allowed. F_{dep} , F_{eq} , and F_{scr} have default values of 0, 0.1, and 0.9, respectively.

Model Testing

Model testing is a vital component of model development because we need to ascertain if there is any predictive advantage in using the proposed submodel over the existing in-stream P submodel. It is difficult to evaluate the proposed submodel against the existing QUAL2E-based submodel using measured data because both models require calibration. Any difference between the model's predictions would be attributed to the model routines and to the quality of the calibration process. Because the submodels use differing input parameters, and thus differing calibrations, such comparisons would not isolate effects of the model routines.

A comparison between the two submodels was made using suggested default parameters with a simple, single-sub-basin, single-reach SWAT model. The goal of this analysis was to examine model

function and how the model responds to change from a theoretical perspective. Figure 2 illustrates in-stream P concentration as predicted by the existing and proposed submodels. Two scenarios are presented: (i) a point-source-free stream and (ii) a stream affected by a point source that is reduced from 5 to 0.05 mg P L⁻¹ during the simulation. Using default parameterization, the QUAL2E submodel seems to predict very low in-stream concentrations between runoff events. In SWAT, P from the landscape is delivered primarily during storm events; during baseflow conditions, input to the reach are often negligible. The SWAT model was also tested without any active in-stream P submodel and produced similar trends (not shown). In contrast, the buffering provided by the EPC approach of the proposed submodel stores P from runoff events in stream sediments for release during baseflow conditions, reducing concentration variability.

The second scenario tests the ability of these in-stream submodels to respond to changes in the system without reparameterization. Figure 2 shows the response of both models to a drastic reduction in point source P loading. The current routines offer little buffering ability. A dramatic rise in concentration is predicted by the current submodel resulting from reduced flow during a dry period. Because the point sources discharge a constant 5 mg L⁻¹ and the flow is reduced, there is less dilution effect. Here storm events generate a negative response in concentration. The new in-stream submodel is more strongly buffered; during the same period, in-stream concentration shows only a small increase. On 1 January, the point source is nearly eliminated, and the existing QUAL2E submodel immediately falls into a new state, with no sign of legacy effects. A similar response can be seen in data presented by Glavan et al. (2011), who obtained very good results using the existing submodel. Wastewater dischargers accounted for approximately 50% of ortho-P sources in their study basin. The

submodel responded to the midsimulation implementation of P removal by wastewater discharges but seems to underpredict for a couple of years as the monitoring data settled slowly to a new equilibrium P regime. The new EPC-based submodel predicts a much smaller instant response followed by a long trend of declining concentrations as a new equilibrium is slowly reached.

A sensitivity analysis was performed to evaluate how proposed in-stream submodel parameter selection alters in-stream total P concentrations over time. The sensitivity analyses were performed on the single-reach, point-source-free model described earlier by altering a single parameter from default to examine the resulting change in model output. The results of the sensitivity analysis are given in Fig. 3. A 3-mo period is shown to allow change in each scenario to be visible. The parameters DI and K_{out} primarily effected concentrations under base flow conditions; K_{in} , F_{dep} , and F_{eq} altered concentrations during storm events; and F_{scf} had no effect during the test period examined, presumably due to the lack of events large enough to cause scour during this 3-mo test period. These data may assist a user during calibration of the in-stream submodel by illustrating how parameter changes effect concentrations under differing flow regimes. For example, if the submodel underpredicts during base flow conditions in a point-source-free reach, K_{out} should be increased. If the underprediction is independent of flow regime, reducing SP_{trans} may be effective in achieving calibration.

Model Application

Study Area Description and History

The Illinois River Basin covers approximately 4600 km² and is divided nearly equally by the Oklahoma/Arkansas border (Fig. 4). The Illinois River is one of Oklahoma's most valued scenic rivers and is a popular recreational destination offering camping, canoeing, and swimming. Overall, the basin is comprised primarily of pasture

Fig. 2. In-stream total P concentration as predicted by SWAT using the existing QUAL2E-based routine and the new in-stream P model.

Fig. 3. Predicted total P in-stream concentration with parameter modifications from default values. DI, period of influence in days; F_{dep} , fraction of bankfull discharge flow at which there is 100% deposition of particulate P in the water column; F_{eq} , fraction of bankfull discharge flow at which there is no deposition/scour; K_{in} and K_{out} , soluble P transformation coefficients into and out of the benthic sediments in h^{-1} ; SP_{trans} , the concentration of P transformed from soluble to particulate forms.

and forest, but the Arkansas portion of the basin contains several rapidly expanding urban areas. The primary agricultural activities include cow-calf operations and poultry production. The basin contains an estimated 1900 poultry houses, generating 192,000,000 kg of poultry litter (a mixture of manure and bedding) annually. This material is used as a low-cost fertilizer to increase pasture productivity and has resulted in elevated soil P in some pastures within the basin. Poultry production and WWTP effluent are thought to be a significant source of P (Storm et al., 2006; Haggard, 2010).

Oklahoma and Arkansas have disputed water quality in the Illinois River Watershed since 1982. The conflict reached the U.S. Supreme Court in 1992, which ruled that the state of Arkansas was required to abide by Oklahoma water quality standards in shared watersheds (Soerens, 2003). In 2002, Oklahoma passed a numeric water quality standard for scenic rivers. This standard set an upper limit for in-stream total P at 0.037 mg L^{-1} , measured as a 30-d geometric mean. Arguments as to the suitability and attainability of that standard immediately ensued. The need to assess the attainability of this standard was a driving force in the development of this in-stream P component. In 2006, the State of Oklahoma filed suit

against seven poultry companies operating in the basin, seeking damages and injunctive relief. This litigation was unresolved as of 2011. The USEPA is currently developing a TMDL for the Illinois River, which is scheduled for completion in 2012 (Flores, 2009). Work by Haggard (2010) has shown that P concentrations and loads have been decreasing in the Illinois River near the Oklahoma-Arkansas border since 2003.

Fig. 4. Location of the Illinois River Basin and stream gaging sites used for calibration/validation of the SWAT model.

Data Sources

Several SWAT modeling efforts have been undertaken on the Illinois River (Storm et al., 2006, 2010) using some form of the in-stream component. The construction of the SWAT model for the Illinois River presented is detailed in Storm et al. (2010). A variety of data was used to develop the model, including (i) 30-m National Land Cover Dataset (NLCD) (Homer et al., 2004); (ii) 10 m (1/3 arc-second) USGS digital elevation model data; (iii) State Soil Geographic Database (STATSGO) soils data (USDA, 1991); (iv) observed daily precipitation and minimum and maximum temperatures provided by the National Oceanic and Atmospheric Administration (NOAA) Cooperative Weather Network and the Oklahoma Mesonet (NCDC, 2012); (v) ponds digitized from USGS 7.5 min quadrangle maps, with parameters derived from the National Inventory of Dams data for structures in the Illinois River Basin (U.S. Army Corp of Engineers, 2010); (vi) commercial fertilizer usage based on Oklahoma Department of Agriculture and Arkansas State Plant Board estimates; (vii) poultry house location data collected by the Oklahoma Attorney General's Office; (viii) soil test P data from the Oklahoma State University Soil, Water, and Forage Analytical Laboratory and the University of Arkansas Soil Testing Laboratory; and (ix) municipal WWTP discharges obtained from the Oklahoma Department of Environmental Quality and directly from each treatment facility.

Calibration/Validation

The model was calibrated for streamflow at four locations (Fig. 4) for the period 1990 to 2006. Nash Sutcliffe efficiencies ranged from 0.81 to 0.97 for annual, from 0.75 to 0.88 for monthly, and from 0.26 to 0.50 for daily streamflow comparisons. The upland portion of the SWAT model was calibrated to average annual values by adjusting parameters that govern P loss from the landscape. Additional information and upland parameter adjustments are given in Storm et al. (2010). The in-stream model was then calibrated to P loads and concentrations for the period 1997 to 2006 at three sites. During this process, only in-stream model parameters were adjusted. There were no data with which to separately calibrate the upland and in-stream components. The model was calibrated using 30-d geometric mean in-stream P concentrations, the same method used to evaluate the 0.037 mg L⁻¹ P standard. The resulting NSE values ranged from 0.42 to 0.67 for total P. The model was subsequently evaluated based on predicted total and soluble monthly P loads. These comparisons yielded coefficients of determination greater than 0.64.

Although there are no universally accepted standards to judge model performance as acceptable (Loague and Green, 1991), several researchers have suggested values. Ramanarayanan et al. (1997) judged the model performance as satisfactory or acceptable if the monthly NSE was greater than 0.4. Santhi et al. (2001) assumed that a monthly NSE greater than 0.5 indicated acceptable model performance when calibrating SWAT. Moriasi et al. (2007) suggested that monthly NSE values greater than 0.5 were satisfactory for streamflow, based on an in-depth analysis of previous hydrologic modeling studies. In general, NSE values decrease at lesser comparison intervals. The model performed similarly during the validation period (1980–1989). Given these criteria, the model performance was deemed satisfactory.

Results and Discussion

The SWAT model was developed to evaluate policy scenarios that have the potential to meet the 0.037 mg L⁻¹ criteria. These policy scenario–related results are described by Storm et al. (2010) and are not presented here. The calibration and validation of the in-stream submodel for existing conditions yielded a set of in-stream parameters that give some insight into the functionality of the proposed submodel. In the calculation of EPC for each reach, the period of influence DI was calibrated at a value of 250. This implies that EPC for a given reach is significantly affected by P concentrations within the last 250 d. The soluble P transformation coefficients into and out of the benthic sediments in h⁻¹ (K_{in} and K_{out}) were calibrated to 0.15 and 0.0001, respectively. This indicates that in the Illinois River, sediment typically acts as a sink for soluble P. This may be due to the quantity of soluble P discharged by WWTPs during the study period. Other research indicates that removal of such constant P discharge results in sediment suddenly becoming a net source of soluble P (Haggard et al., 2004; Haggard and Stoner, 2009). Soluble to particulate transformation coefficient h⁻¹ was calibrated to a value of 0.01. This is particularly interesting when compared with K_{in} , which was calibrated to 0.15. Although these parameters are not directly comparable, these processes share similar first-order kinetics. The much greater value for K_{in} suggests that interaction between SRP in the water column and the streambed is more important than interactions between SRP and particulate P within the water column. This implies that the primary mechanism for soluble P retention in this system is direct adsorption by stream sediments and uptake by attached biota, not transformation to particulate forms in the water column.

The particulate P in-stream parameters F_{bp} , F_{eq} , and F_{scr} (fraction of bankfull discharge flow at which there is 100%

Fig. 5. Map of model predicted equilibrium phosphorus concentration (EPC) and waste water treatment plant (WWTP) P loads during the study period in the Illinois River basin.

deposition, no deposition/scour, and 100% scour of particulate P) were calibrated as 0.01, 0.15 and 0.8, respectively. These values indicate increased scouring at higher flows and no net scouring/deposition at flows equal to 0.15 of the bankfull discharge. Bankfull discharge in SWAT is calculated from stream cross-sections derived from drainage area only and contains significant uncertainty. The scouring of particulate P in this area is supported by Galloway (2008), who noted greater chlorophyll a concentrations during high flow as compared with baseflow conditions at several sites in the Illinois River watershed and proposed scouring of periphyton as the source.

The model was not calibrated to EPC data, but it did predict temporal and spatial trends that are consistent with other studies in the region (Ekka et al., 2006; Haggard and Stoner, 2009). The model predicted different EPC values by reach in response to total P loads. The SWAT model based reaches on sub-basin boundaries (one reach per sub-basin). Typical reach lengths ranged from 5 to 15 km. Equilibrium P concentration was generally greater in reaches receiving or downstream from effluent dischargers. Figure 5 is a map of mean EPC values across streams in the basin. Equilibrium P concentration is greater immediately downstream from point sources, and the value depends on the average load discharged by each WWTP. Equilibrium P concentration decreases with increasing distance downstream the source, which would be expected based on Ekka et al. (2006) in this basin. The average value of EPC was 0.165 mg L^{-1} but ranged from 0.002 to 1.37 mg L^{-1} . Ekka et al. (2006) observed EPC values ranging from 0.01 to 6.9 mg L^{-1} . Soluble P has been shown to decrease with distance downstream in other Ozark basins (Haggard et al., 2005), and dissolved P in the water column is correlated with sediment EPC (Haggard and Stoner, 2009). Figure 6 illustrates the effect of point sources on EPC. Equilibrium P concentration in this point source-impacted reach is more than one order of magnitude greater than a similar nonimpacted reach. Seasonal variability in EPC is also apparent. Equilibrium P concentration in the point source-impacted reach varies in a regular annual cycle, which is likely a result of reduced dilution of the effluent discharged into the stream during summer base flow conditions. In contrast, the nonimpacted reach appears to have less seasonality and appears to be directly out of phase with the point source-impacted reach. Because EPC in nonimpacted reaches depends on the introduction of new P into the system during runoff events, we would expect EPC to be greater after modest runoff events that are too small to flush the system.

The model predicts a gradual accumulation of P in the streambed sediments in the river and a periodic flushing of the P associated with sediments to Lake Tenkiller. The introduction of a stream P benthic storage pool allows for a gradual buildup of P in the system and periodic flushing of stored P from the system. Figure 7 illustrates this effect

Fig. 6. Equilibrium phosphorus concentration (EPC) in point source-impacted and point source-free reaches as predicted by SWAT.

by source. The spike in monthly P load during December 1992 is greater than the average annual load. Even relatively constant contributions of point sources build up in the stream and are flushed by these events, as shown by the spike in point source contributions during this event. The model indicated that four such large events occurred from 1990 to 2006. During this period, point source contributions were the largest single source of the total P in the Illinois River 89% of the time, even though 60% of all P reaching Lake Tenkiller is from nonpoint sources. The model indicates that P concentrations in the water column during base flow are dominated by WWTP discharges. The constant discharge of point sources is predicted to have a profound effect on P concentration in the system. Haggard (2010), Haggard et al. (2004), and Ekka et al. (2006) showed that effluent discharge had a large influence on P concentration in receiving streams and in the Illinois River. The dramatic effects of point source discharges (and their subsequent reduction in 2003) on stream P has been observed using measured data in the neighboring Lake Eucha watershed (Haggard and Stoner, 2009).

Fig. 7. SWAT predicted monthly P loss by source for the Illinois River Basin. Data presented by source for period 1992 to 1994. NPS, nonpoint source.

In general, the P submodel predictions fit our conceptual understanding of P dynamics. A better representation of the P dynamics in the Illinois River and other rivers in watershed planning tools like SWAT may lead to the development of more effective mitigation strategies to control the impact of P from point and nonpoint sources.

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