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The significance of the differences in soil phosphorus representation and transport procedures in the SWAT and HSPF models and a comparison of their performance in estimating phosphorus loss from an agriculture catchment in Ireland.

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ABSTRACT

Phosphorus transported from agriculture land has been identified as a major source of water pollution in a large number of Irish catchments. Models of this process are required in order to design and assess management measures. This paper reports on the comparison and assessment of two of the most promising physically-based distributed models, SWAT and HSPF, with particular emphasis on their suitability for Irish conditions. The representation of the overall soil phosphorus cycle is similar in both models but there is a significant difference in the level of detail in describing the chemical and biochemical processes in each model. Also there are differences in modeling the mechanisms by which phosphorus is removed from the soil column and either transported in dissolved form with the runoff water or in particulate form attached to eroded or detached sediment. These differences could have a significant influence on performance when using either of the models to simulate phosphorus loss from any catchment. Both models are applied to estimating the phosphorus concentration at the outlet of the Clarianna catchment in north Tiperrary (Ireland). This catchment is small (23km²) and the land use is mainly pasture on grey brown podzolic soils. The results of model calibration are presented along with an assessment of the usefulness of the model outputs as a water quality management tool.

INTRODUCTION

Removal of phosphorus (P) from soil is influenced by various physical and chemical parameters. Whilst the physical parameters control the generation of water fluxes which represents the driving force for P removal, the chemical parameters affect the chemical transformations occurring to the different P forms in the soil and water. Any model to account for P loss from soil should have a structure incorporating a simulation of both the flow generation and the P transformations in order to utilise them in the estimation of P removal. The Soil Water and Analysis Tools (SWAT) model and Hydrological Simulation Program – FORTRAN (HSPF) model both have the required structure though their methods differ in dealing with the flow and phosphorus components. The two models have been used in a study within the European Water Framework Directive (WFD) to quantify the amount of phosphorus transported from an agriculture catchment in Ireland.

Eutrophication in water bodies has been identified as a major threat to water quality in Ireland due, in most cases, to excess phosphorous inputs from agriculture land (McGarrigle et al., 2002, pp. 28). The Clarianna catchment is one of many other catchments where the phosphorus levels in its rivers has markedly increased in the recent years. The catchment area is approximately 23km² and it is located in the middle of Ireland in a land principally occupied by pasture where agriculture and animal rearing practices are dominant. The main soil type in this catchment is grey brown podzolic characterized by a structure allowing good drainage of water in the subsurface layers which in turn enhance the leaching of phosphorus downwards. A limestone aquifer lies beneath the soils.

This paper first describes the main equations used in the SWAT and HSPF model to simulate the soil phosphorus transformations and removal. Moreover the significance of these equations on the overall estimation of the phosphorus loss simulation is assessed based on the results of the application of both models on the Clarianna catchment to predict the flow and the total phosphorus concentrations variables.

In the assessment the predicted values of the two variables are compared with the available observed data at the outlet location of the catchment for the period between (1/12/2001) and (29/07/2003).

PHOSPHORUS COMPONENT IN THE SWAT MODEL

SWAT monitors six different pools of phosphorus in the soil. Three pools are inorganic forms of phosphorus whereas the other three pools are organic forms. Fresh organic P is associated with crop residue and microbial biomass while the active and stable organic P pools are associated with soil humus. The organic phosphorus associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization. Soil inorganic P is divided into solution, active, and stable pools. The solution pool is in rapid equilibrium (several days or weeks) with the active pool while the stable pool is in slow equilibrium with the active pool. Furthermore the model assumes that the runoff water removes the solution P from the top 10cm layer of the soil while the eroded sediment transports the organic and inorganic phosphorus attached to the soil particles. The mathematical relations used by the model to describe the chemical transformations occurring between the various soil phosphorus variables and the removal of phosphorus from soil are presented below.

Mineralization/immobilization of active organic P (P_{min})

$$P_{min} = 1.4 \times \beta \times \sqrt{\gamma_{tmp}} \times \gamma_{sw} \times P_{acor} \quad (1)$$

$$\Rightarrow \begin{cases} P_{acor} : \text{storage of active organic P} \\ \beta : \text{rate coefficient of mineralization} \\ \gamma_{tmp} : \text{nutrient cycle temperature factor} \\ \gamma_{sw} : \text{nutrient cycle water factor} \end{cases}$$

Decaying of fresh organic P (P_{dec})

$$P_{dec} = \delta_{ntr} \times P_{fresh} \quad (2)$$

$$\Rightarrow \begin{cases} P_{fresh} : \text{storage of fresh organic P} \\ \delta_{ntr} : \text{residue decay constant} \end{cases}$$

Adsorption/desorption between the solution P and the active inorganic P ($P_{ads/des}$)_{sol<->act}

$$P_{(ads/des)_{sol \leftrightarrow act}} = P_{sol} - P_{actads} \times \left(\frac{pai}{1 - pai} \right) \quad (3)$$

$$\Rightarrow \begin{cases} P_{sol} : \text{storage of soluble mineral inorganic P} \\ P_{actads} : \text{active adsorbed inorganic P} \\ pai : \text{phosphorus availability index} \end{cases}$$

Adsorption/desorption between the active inorganic P and the stable inorganic P ($P_{ads/des}$)_{act<->sta}

$$P_{(ads/des)_{act \leftrightarrow sta}} = \beta_{eq} \times (4 \times P_{actads} - P_{stads}) \quad (4)$$

$$\Rightarrow \begin{cases} P_{actads} : \text{storage of active adsorbed inorganic P} \\ P_{stads} : \text{stable adsorbed inorganic P} \\ \beta_{eq} : \text{slow equilibrium rate} \end{cases}$$

Solution P removed in runoff water (P_Q)

$$P_Q = \left(\frac{P_{sol}}{\rho_b \times D \times k_d} \right) \times Q \quad (5)$$

$$\Rightarrow \begin{cases} P_{sol} : \text{storage of soluble P in the top layer} \\ \rho_b : \text{bulk density of the soil} \\ D : \text{depth of the top soil layer} \\ k_d : \text{soil P partitioning coefficient} \end{cases}$$

Removal of P forms associated with the eroded material (P_{sed})

$$P_{sed} = P_{att} \times \left(\frac{SY}{A} \times \epsilon \right) \quad (6)$$

$$\begin{cases} P_{att} : \text{storage of certain P form to be removed with sediment} \\ SY : \text{sediment yield} \\ A : \text{Area of the land} \\ \epsilon : \text{P enrichment ratio} \end{cases}$$

PHOSPHORUS COMPONENT IN THE HSPF MODEL

In the HSPF model, the phosphorus material is assumed to exist in the surface, upper, lower, and groundwater storages. The surface storage receives external phosphorus inputs and releases organic and inorganic adsorbed phosphorus attached to the eroded material and soluble phosphorus dissolved in

the runoff water. All the storages contain three forms of phosphorus, soluble inorganic phosphorus, adsorbed inorganic phosphorus, and organic phosphorus. Only the soluble phosphorus moves from one storage to the other with the aid of the flow flux (infiltration, percolation, interflow, and base flow) and also it can be taken up by plant roots. The mineralisation, immobilisation, adsorption and desorption processes can be simulated with a first order kinetic model which has a general form but with different parameters values for each process. The amount of soluble phosphorus dissolved in the surface runoff is calculated as a fraction of the phosphorus storage in the surface layer. The fraction corresponds to the ratio of the runoff rate to the amount of water stored in the surface layer. Likewise the attached inorganic phosphorus and organic phosphorus removed with the sediment material are calculated as fraction of the storages of both phosphorus forms in the surface layer. The fraction in this case is the ratio of the amount of sediment eroded to the amount in the parent material. The mathematical equations related to the phosphorus simulation in the HSPF model are as follow.

General form of the first order kinetics equation for simulating the adsorption, desorption, mineralization and immobilization fluxes (P_{flux})

$$P_{flux} = P_{stor} \times K \times \theta^{(T-35)} \quad (7)$$

\Rightarrow

- P_{stor} : storage of phosphorus
- K : first order rate parameter for the process
- θ : temperature correction factor for the process
- T : soil temperature

Solution P removed in runoff water (P_Q)

$$P_Q = P_{sol} \times FSO \quad (8)$$

\Rightarrow

- P_{sol} : storage of soluble P in the surface layer
- FSO : fraction of soluble P that transported

Removal of P forms associated with the eroded material (P_{sed})

$$P_{sed} = P_{att} \times \left(\frac{SY}{A} \times \epsilon \right) \quad (9)$$

\Rightarrow

- P_{att} : storage of P to be removed with sediment
- P_{surf} : storage of P in the surface layer
- Ratio: ratio of sediment eroded to that exist in the surface layer

RESULTS

First the flow discharge estimation with the two models (SWAT and HSPF) at the catchment outlet has been calibrated throughout the period of the simulation. This was accomplished by changing the values of the model parameters which have significant effect on the flow generation of each model. After achieving a satisfactory flow simulation the parameters of the best flow calibration were used in all the phosphorus calibration cases. In each of those cases different sets of parameters controlling the soil phosphorus transformations and removal for both models were used until acceptable results were obtained. To facilitate an easy comparison among the performance of the two models in predicting the total phosphorus (TP) concentrations only the best results for the flow and the phosphorus concentrations from the two models are presented. Figure (1) and (2) show the results of the flow and the TP using SWAT and HSPF models respectively. In each figure the observed flow (Q_{obs}) and the estimated flow (Q_{est}) hydrographs were plotted at the top while the observed TP (TP_{obs}) and the estimated TP (TP_{est}) graphs were put at the bottom.

DISCUSSION

Generally the simulated flow hydrograph from SWAT is not in good agreement with the measured one and is worse than what is obtained from HSPF model. The general trend in TP prediction with SWAT is that there was nearly constant low TP base values associated with the base flow while there was high TP values taking place during the runoff storms. The constant low TP base values could be the result of the assumption of a constant phosphorus concentration in the base flow resulting in an inaccurate estimate of the P load contributed by the base flow. Essentially, this means that the model ignores the soil phosphorus movement in the lateral dimension and considers it in the vertical direction only. In addition to the inadequate simulation of the TP values associated with the low flows all of the high TP values fall

below the observed values which could reflect the general tendency of the model to underpredict at high flows. There are few high TP values appearing near to the end of the low period. These values are difficult to relate to any of the surface hydrological mechanisms which transport the phosphorus and they were not expected. Despite the fact that simulated flow values were significantly comparable to the observed (in the case of HSPF model) the estimation of the TP values was not as good as the flow. Alternatively the model produced high TP values during the initial period which does not match any observed value. Moreover apart from one point all the other point with high TP values were underestimated by the model. Similar to SWAT, the model did not reproduce the high TP values associated with low flows at the end of the simulation period.

The total phosphorus concentrations were calculated from both model by summing the average daily loads of the phosphorus delivered with the runoff water (soluble P) and the eroded sediment (attached inorganic P and organic P) divided by the average daily flow discharge at the outlet location. The amount delivered with the sediment is always the most important in the calculation of the phosphorus loss since the phosphorus solubility is limited. Therefore the chemical transformations which occur to the various phosphorus forms at the soil, especially those affecting the storages of the organic phosphorus and attached inorganic phosphorus, have great influence in the phosphorus removal. The equation in SWAT used to account for the mineralisation process depends on both the temperature and moisture content of the soil. In contrast the corresponding equation in the HSPF model depends only on moisture content neglecting the effect of temperature. Likewise the adsorption and desorption processes are temperature dependant in HSPF model while in SWAT they only depend on a rate coefficient. The difference in the way of describing the chemical transformations in the two models in addition to the flow prediction might impact on the phosphorus removal and hence produce the difference in results.

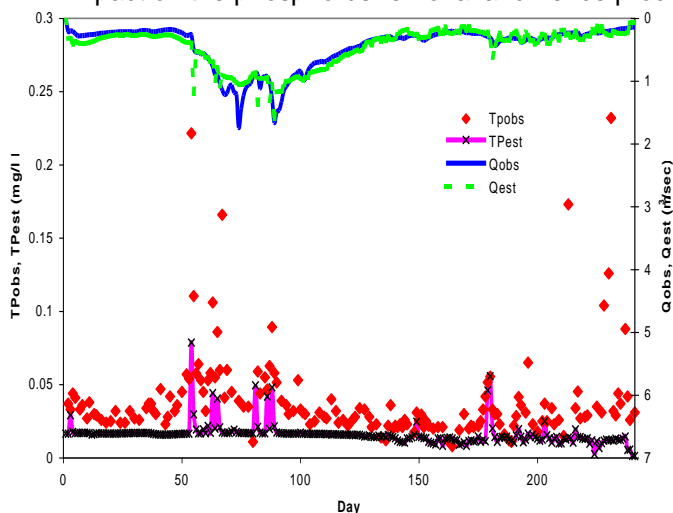


Figure (1) Simulation of the flow and the TP SWAT model

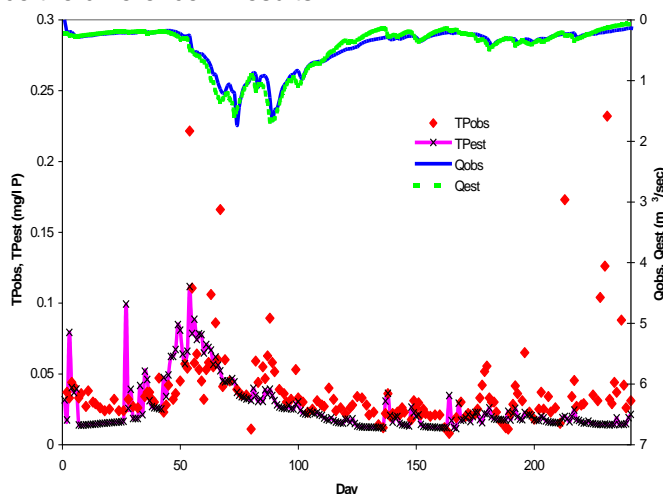


Figure (2) Simulation of the flow and the TP HSPF model

CONCLUSION

The SWAT and HSPF models were applied to the Clarianna catchment in Ireland to estimate the phosphorus loss to the channel reach. Different simulations for the flow and total phosphorus resulted from the two models. The difference in the mathematical representation of the chemical transformations between the soil phosphorus variables in addition to the flow prediction could be the main cause of the difference in the phosphorus simulation with the two models

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