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Modelling phosphorous loss from agriculture catchments: a comparison of the performance of SWAT, HSPF and SHETRAN for the Clarianna catchment

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Abstract
Much research in Europe at present has been directed at generating and assessing modelling tools for use in catchment management, driven by the requirements and schedule of the Water Framework Directive. A logical first step is to assess the suitability of existing models for this task so that any resources used in generating new models can be targeted at actual modelling needs. Crucial questions, relating to the model structure and complexity and spatial and temporal scales required must also be addressed. This paper reports a comparison of the performance and suitability of three "off-the-shelf" distributed catchment models, each with a different level of complexity, applied to modelling phosphorous losses from the Clarianna catchment in Ireland. In this paper, the performance of three such models (SWAT, HSPF and SHETRAN/GOPC) is compared, both in estimating discharges and phosphorous loads in the Clarianna catchment. The flow comparison has showed that the HSPF model was the best in simulating the mean daily discharges. However, the best calibration results for daily total phosphorus loads in the study catchment has been achieved by the SWAT model.

Keywords: Flow simulation; GOPC; HSPF; Phosphorus; SHETRAN; SWAT

Introduction
Eutrophication has been identified as the major threat to water quality in Ireland due, in most cases, to excess phosphorous inputs (McGarrigle et al., 2002). The phosphorous transported from agriculture land has been found to contribute a significant amount of phosphorous to the river reaches of the Irish catchments. Therefore models of this process are required in order to design and assess management measures as part of the objectives of the European Water Framework Directive (WFD) which represents the deriving force behind the work described in this paper. Accordingly three wide spectrum physically-based distributed catchment models, HSPF (Bicknell et al., 1997), SWAT (Arnold et al., 1998), and SHETRAN (Ewen et al., 2000), have been selected for testing their ability to model phosphorous loss from the Clarianna catchment in Ireland. The models vary greatly in (i) the degree of complexity in disaggregating the catchment into smaller units and (ii) the complexity of their representation of the physical processes involved.

In terms of spatial disaggregation, the HSPF model is the simplest, followed by the SWAT model and the SHETRAN model is the most complex. However in terms of physical representation of the water fluxes, SWAT is the simplest, followed by HSPF and SHETRAN is the most complex. Both the HSPF and the SWAT models can model the phosphorous loss directly as they contain phosphorous-specific components in their structure. On the other hand the SHETRAN model is able to produce the required hydrological variables for a Grid Oriented Phosphorous Component
(GOPC) developed by Nasr et al. (2003) to be used for modelling the phosphorus loss. This paper represents a comparison and assessment of the three models with particular emphasis on their suitability for Irish conditions through applying them on the Clarianna catchment.

**Clarianna catchment**
The Clarianna catchment is located in county North Tipperary (Ireland) to the north of the Nenagh sub-basin in the big Shannon Basin. The catchment is relatively small with an area of 23 km$^2$ approximately. The main stream in the catchment feeds into the lower reaches of the Nenagh River. The principal soil type is a grey brown Podzolic (Fig (1-a)), the parent material consisting of a gravelly limestone till with some shale and sandstone. The soil is well drained, well structured and shows a friable brown to dark brown gravelly loam surface. With good management the soil of the catchment is highly productive for grass and pasture occupies the largest area compared to other crops in the catchment (Fig (1-b)).

![Soil and land use maps - Clarianna catchment](image)

**Figure (1) Soil and land use maps - Clarianna catchment (county North Tipperary, Ireland)**

**Application of HSPF, SWAT, SHETRAN/GOPC models to the Clarianna catchment**
The availability of spatial data (digital elevation model (DEM), land use map and soil map) for the Clarianna catchment has greatly facilitated the application of SWAT, HSPF, and SHETRAN/GOPC models. Other available data including weather, discharge and phosphorus data in the catchment was collected as part of a research project (LS2000.2.2.1.) funded by the Environmental Protection Agency in Ireland. The weather data is required as input to the three models for flow simulation and it includes rainfall, temperature, solar radiation, relative humidity, and wind speed. The equivalent input data required for the phosphorus modelling includes phosphorus application loads to the soil. This data was not available for this catchment and hence it had to be estimated with the aid of the available guidance of nutrient advice for phosphorus and potassium fertiliser application to Irish soils (Tegasc, 1998). On the other hand the available observed discharge and phosphorus data can be used in assessing the flow and the phosphorus modelling by the three models.

For each of the three models the flow discharge simulation at the catchment outlet has been calibrated for the period from 1/12/2000 to 18/6/2001. This was obtained by changing values of the model parameters which have most effect on the flow estimation for each model. After achieving a satisfying flow calibration the parameters of the best flow calibration were used in all the phosphorus calibration cases. The flow outputs from the models were assessed by comparing them to the observed values at the Ballyanny station located at the catchment outlet. There is no available sediment record to evaluate the sediment results from the models. Instead, the models have been
calibrated to produce estimates of the phosphorus loads which can be compared to the available data. The phosphorus simulation was obtained directly from the HSPF and SWAT models while the flow and the sediment outputs of the SHETRAN model were inserted into the GOPC to estimate the phosphorus loads.

To enable an easy comparison among the performance of the three models in estimating the phosphorus loss only the best results for the flow and the phosphorus loads from the three models are presented in this paper.

**Discussion of the results**

In all figures, the observed flow (Qobs) and the estimated flow (Qest) hydrographs are displayed at the top while the observed TP (TPobs) and the estimated TP (TPest) graphs are at the bottom. This arrangement could help in determining the effect of the flow simulation on the phosphorus one. The simulation time covers the period between 1/12/2001 and 18/6/2002. Each figure will be discussed individually.

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

**Figure (2):** Most of the peak values in the flow hydrograph were well captured by the HSPF model while a small number were not well estimated. Generally the shape of the simulated flow hydrograph resembles the actual one except for some discrepancy during the falling limb. Although the simulated flow values were significantly comparable to the observed the model estimation for the TP was not as good as the flow. The model produced TP values during the initial period which do not match any observed value. This may be a model “spin-up” problem relating to initial conditions. High TP values observed during the high flow period were poorly simulated by the model as most of the high TP values were underestimated. During the falling limb and the low flow periods the observed TP values were commonly low. The trend of the simulated TP during those periods follows the observed trend and with simulated values not much different from the observed. The good simulation of the hydrology as it has been observed in the flow prediction by the model was not sufficient to accurately model all the TP values. Many other factors might influence the TP prediction. The most important would be the amount of phosphorus transported from the soil especially when knowing that the land use type in the catchment is grassland which contains different sources of phosphorus inputs. (e.g. fertilisers, animal manure, etc..) which are difficult to quantify.
Figure (3): The simulated flow hydrograph from SWAT is not in good agreement with the measured one and is much worse than HSPF. The peak values are either under or over predicted except for one of the three highest which is estimated accurately by the model. An unusual feature in the flow prediction is the relatively high simulated value at the rising point of the hydrograph. This could be caused by a high rainfall event associated with high prediction of soil moisture which assists in producing more overland flow. The model exhibits good simulation to most of values in the recession limb and during the low flow period. The general trend in the TP prediction is that there was nearly constant low TP base values associated with the base flow while there were high TP values taking place during the runoff storms. The constant low TP base values is probably due to the model assumption of a constant phosphorus concentration in the base flow. Essentially, this means the model ignores soil phosphorus movement in the lateral dimension and considers it in the vertical direction only. The model behaves better than SWAT during the high TP values. Despite the observed high TP values were not accurately simulated, the trend of the simulated values is similar to the observed. The hydrology effect on the TP simulation by SWAT model seems to be obvious especially for the high flow values which the model failed to simulate and, as a result, the associated TP values were also not simulated properly.

Figure (4): During the initial period, the SHETRAN model generated flows comparable with the actual ones. After the initial period the predicted flows generally followed the measured values except for a single very large estimated peak, which was not reflected in the data. The model performed well in simulating the flows in the rising limb followed by under estimation of most of the values. The model again worked well during the falling limb, but failed again to match the measured flows during the early part of the low flow period. Subsequent low flows were well simulated by the model. The hydrological variables simulated by SHETRAN constituted an input to the GOPC which has been used to estimate the TP loads. There is an underestimation of the high values of TP associating with the high flows. Since the high flows were generally under predicted by SHETRAN it can be expected that the runoff volume, contributing to this flow, was also not precisely estimated and likewise the associated sediment load. Therefore the effect of the improper hydrological simulation in producing the flow peaks had a shadow on the GOPC performance resulting in TP values lower than the real ones. Similar to SWAT, the GOPC has produced trend similar to the observed during the high TP values. The low TP values from the GOPC generally
matched the observed values and this demonstrates the good accounting of the soil phosphorus dynamics by this model.

![Figure (4) Simulation of the Flow with SHETRAN model and the TP with GOPC](image)

**Comparison between the three models performances**

The visual comparison between hydrographs of observed and estimated discharge by the three models reveals that HSPF has produced a hydrograph which is the best in resembling the actual one except for some discrepancy during the falling limb. On the other hand the resulted hydrograph from SWAT is not as good as the one from HSPF. The worst hydrograph shape was obtained in the case of SHETRAN model when compared to the other two models.

Regarding the performance of the models in simulating the total phosphorus values, SWAT model has performed quite good generally except for some high total phosphorus values which could not be matched the model and the reason for this can be attributed to the failure of the model to adequately simulate the flow peak corresponding to this total phosphorus value. It is quite surprising to notice that the HSPF performance was generally worse than SWAT although it has the best performance in simulating the flow hydrograph. The GOPC performance was poor and again the deficiency in simulating some of the total phosphorus values is related to the corresponding deficiency in the flow simulation by SHETRAN model.

**Conclusion**

Three physically-based distributed catchment models, HSPF, SWAT, and SHETRAN/GOPC, were applied to the Clarianna catchment in Ireland to estimate the phosphorus loss from the land to the channel reach. The models vary in their complexity of representing the spatial scale of the catchment and hydrological detail. HSPF and SWAT simulate the flow and the phosphorus directly whereas the SHETRAN feeds the GOPC with the required hydrological values for phosphorus modelling as a post-process. In terms of the flow simulation, the HSPF model proved itself to be superior to the other two models for all cases (low and high flows). In contrast SWAT was the best in simulating the TP values.
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