A COMPARISON OF SWAT, HSPF AND SHETRAN/GOPC PHOSPHORUS MODELS FOR THREE IRISH CATCHMENTS

EXECUTIVE SUMMARY

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**Objectives**

This project has targeted one of the WFD objectives which focuses on modelling non-point phosphorus loss from rural catchments. It focuses on physically-based catchment scale model which to date have not been applied to model phosphorus losses in Ireland. In the work three very different catchment models range from semi-empirical to fully physically-based distributed models have been selected to compare their performances in quantifying phosphorus loss from three different rural catchments (Clarianna, Dripsey, and Oona). The models were selected to be (a) representative of different degree of physical and spatial complexity, and (b) readily available. The models are Soil Water and Analysis Tools (SWAT), Hydrological Simulation Program – FORTRAN (HSPF), and Système Hydrologique Européen TRAnsport (SHETRAN).

The SHETRAN model is the most complex of the three, but does not have a phosphorus modelling component. Because of this, a special phosphorus module was developed as part of this project. The phosphorus component was designed in a generic way so that it can be used with any physically-based distributed hydrological model. Because the modelled catchment should be represented on an orthogonal grid the phosphorus component was named the Grid Oriented Phosphorus Component (GOPC) by the authors.

As part of the model calibration process for each catchment (Clarianna, Dripsey, and Oona), the influence of the most effective parameters on the three models outputs (including the developed phosphorus component) was examined. This information is useful in providing guidelines for using the models in the Irish conditions.

**Methodology**

As shown in Table (1) apart from the GOPC component the SWAT, HSPF and SHETRAN models have been developed in USA and Europe and have not been tested in Irish catchments up to the time of this study. Also from the table it can been seen that the three essential components of phosphorus loss modelling, the flow, sediment, and phosphorus
Table (1) Main features of SWAT, HSPF, SHETRAN and GOPC models

<table>
<thead>
<tr>
<th>Model</th>
<th>Soil and Water Assessment Tool (SWAT)</th>
<th>Hydrologic Simulation Program FORTRAN (HSPF)</th>
<th>Système Hydrologique Européen TRAnsport (SHETRAN)</th>
<th>Grid Oriented Phosphorus Component (GOPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
<td>United States Department of Agriculture</td>
<td>Stanford University USA</td>
<td>Collaboration (UK, France, and Denmark)</td>
<td>Developed as part of this research</td>
</tr>
<tr>
<td>Model type</td>
<td>Semi-empirical</td>
<td>Quasi physically-based</td>
<td>Fully physically-based</td>
<td>Conceptual representation of phosphorus processes</td>
</tr>
<tr>
<td>Smallest spatial unit</td>
<td>Hydrologic Response Unit (HRU)</td>
<td>Pervious/Impervious land segments</td>
<td>Rectangular grid cell (typically 200 – 300 m)</td>
<td>Rectangular grid cell (typically 200 – 300 m)</td>
</tr>
<tr>
<td>Simulation time step</td>
<td>Day</td>
<td>Minute/ Hour/ Day</td>
<td>Minute/ Hour/ Day</td>
<td>Minute/ Hour/ Day</td>
</tr>
<tr>
<td>Flow modelling component</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>(Uses SHETRAN output)</td>
<td></td>
<td></td>
<td>(Uses SHETRAN output)</td>
<td></td>
</tr>
<tr>
<td>Sediment modelling component</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>(Uses SHETRAN output)</td>
<td></td>
<td></td>
<td>(Uses SHETRAN output)</td>
<td></td>
</tr>
<tr>
<td>Phosphorus modelling component</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>(Provides GOPC with hydrological variables)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
components, are already available in the SWAT and HSPF models while the SHETRAN
model contains the first two components only and the third is provided by the GOPC
written for this project. The models vary greatly in (i) the degree of complexity in
disaggregating the catchment spatially, (ii) the complexity of their representation of the
physical, chemical, and biochemical processes involved in phosphorus mobilisation and
transport and (iii) the time step of the simulation. Therefore each of the three Irish study
catchments should be spatially segmented in different ways to meet the requirements of
each model.

Fig. (1) summarises the general procedure for applying each of the three models to each
of the study catchments. Spatial data for each catchment including a digital elevation
model, river map, land use map, and soil map are required by each model to create input
files which will be used to run the model. After preparing the input files, the model will
use weather data (rainfall, temperature, solar radiation, relative humidity, wind speed,
cloud cover) to do the flow simulation. The flow simulation will be repeated by changing
the model parameters and each time the output from the flow simulation will be
compared with the observed flow data until an acceptable simulation is obtained. Starting
with the acceptable flow simulation in addition to the use of external input data required
for phosphorus modelling (fertiliser application) the model will simulate the phosphorus
output. Again some parameters affecting the phosphorus simulation will be adjusted to
find the best simulation. The best flow and phosphorus simulation results from each
model will be used to compare the performances of the three models.

Discussion of the comparison

Comparison between the performances of SWAT, HSPF, and SHETRAN/GOPC in the
three study catchments was based on visual assessment and statistical analysis of the
discharge, total phosphorus, and dissolved reactive phosphorus results. However, the
comparison was summarised in terms of $R^2$ statistics because of its importance in
objectively assessing the models’ performance.
Table (2) includes the best values of this statistics from the application of the three models (SWAT, HSPF, and SHETRAN/GOPC) to Clarianna, Dripsey, and Oona catchments in order to simulate daily discharge, total phosphorus, and dissolved reactive phosphorus. For each catchment, the models with the best $R^2$ during the calibration period have been recorded in the table. In addition the models with the best $R^2$ in the two verification periods in the Oona catchment have been also added to the table. When $R^2$ values were negative no model has been recorded in the table. The HSPF model was the best in simulating the mean daily discharges during the calibration period in the three catchments. Also the HSPF model produced the best mean daily discharges during the
first period of validation in the Oona catchment while the SHETRAN marginally outperformed HSPF during the second period of the validation in the same catchment. The SWAT discharge results were generally acceptable despite occasional deficiencies which they have shown. In the three catchments, the SHETRAN simulation of the flow was always in the third rank. The major deficiency of this model is that the flow hydrographs show recessions that tend to be too step initially and then flatten out too quickly. This implies that the model application needs more investigation to include not only sensitivity analysis to the model parameters and spatial scale but also the structure of the model.

The best model in simulating the total phosphorus load during the calibration period in Clarianna and Oona catchments was SWAT. However, the HSPF was the best during the first and second validation periods in the Oona catchment. In a study on a catchment in the USA, SWAT was good during calibration whereas HSPF was good during the validation in simulating phosphorus loads, an outcome which is similar to our results from the Oona catchment. In the Dripsey, the best results for the total phosphorus load during the calibration period have been obtained from GOPC. Generally in each model, the failure in simulating the total phosphorus loads is associated with a failure in the flow simulation which can be observed in the flow hydrographs. This indicates that the hydrological part of each model is important in getting good simulation for the non-point phosphorus source pollution because hydrological variables are involved in modelling the soil phosphorus processes and transport of phosphorus and hence affecting the amount removed from the soil and reaching the streams. Results of the mean daily total phosphorus concentrations from the three models were not as good as the results of the loads in the three catchments. Only in one case (Clarianna catchment), $R^2$ has a positive value for total phosphorus concentration and this value was obtained from SWAT during the calibration period.
Table (2) Summary to the best Nash-Sutcliffe coefficients ($R^2$) obtained from results of applying SWAT, HSPF, and SHETRAN/GOPC models to the Clarianna, Dripsey, and Oona catchments

<table>
<thead>
<tr>
<th></th>
<th>Clarianna catchment</th>
<th>Dripsey catchment</th>
<th>Oona catchment</th>
<th>Validation (First period)</th>
<th>Validation (Second period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calibration</td>
<td>Calibration</td>
<td>Calibration</td>
<td>Validation (First period)</td>
<td>Validation (Second period)</td>
</tr>
<tr>
<td>Best model</td>
<td>$R^2$</td>
<td>Best model</td>
<td>$R^2$</td>
<td>Best model</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Discharge</td>
<td>HSPF 0.95</td>
<td>HSPF 0.74</td>
<td>HSPF 0.91</td>
<td>HSPF 0.90</td>
<td>SHETRAN 0.80</td>
</tr>
<tr>
<td>Total phosphorus load</td>
<td>SWAT 0.59</td>
<td>GOPC 0.51</td>
<td>SWAT 0.56</td>
<td>HSPF 0.59</td>
<td>HSPF 0.77</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>SWAT 0.55</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>concentration</td>
<td>SWAT 0.55</td>
<td>No useful value</td>
<td>No useful value</td>
<td>No useful value</td>
<td>No useful value</td>
</tr>
<tr>
<td>Dissolved reactive</td>
<td>HSPF 0.70</td>
<td>GOPC 0.46</td>
<td>GOPC 0.56</td>
<td>GOPC 0.39</td>
<td>-</td>
</tr>
<tr>
<td>phosphorus load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissolved reactive</td>
<td>-</td>
<td>No useful value</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>phosphorus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>concentration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Simulation of the daily dissolved reactive phosphorus loads by the three models in the study catchments can be hardly acceptable due to the big differences between the models results and the observed data in most of the cases. However, the best $R^2$ values during the calibration period in Clarianna and Dripsey were achieved by HSPF and GOPC respectively. Also the GOPC was the best in the Oona catchment during the calibration period and the first validation period while no model showed a significantly good performance in the second validation period. The mean daily dissolved reactive phosphorus concentrations from the three models have shown big discrepancies from the observed data and as a result all three models have failed to produce positive $R^2$ values for the dissolved reactive phosphorus concentration.

In all cases, the three models are better at simulating phosphorus loads than concentrations. Also the simulation of total phosphorus is better than the dissolved reactive phosphorus and this confirms the necessity of including the dissolved reactive phosphorus in the calibration since the calibration of the total phosphorus alone is not sufficient to produce acceptable values for both components. Furthermore the poor concentrations results obtained with using parameters calibrated for loads suggests that the models should be independently calibrated for the concentrations if good estimates are required.

**Conclusions**

The conclusions, which can be made regarding the performance of the models, include:

- In the three catchments, the HSPF model was best in simulating the mean daily discharges. Moreover discharge simulation from independent validation runs of the three models in the Oona catchment have also demonstrated the superiority of the HSPF. Discharge results from SWAT and SHETRAN were generally acceptable despite occasional deficiencies described above.

- Nevertheless, the best simulation for the daily total phosphorus loads in the study catchments was by the SWAT model. However in the validation runs for the
Oona catchment the HSPF was best. Generally the results of total phosphorus loads from the GOPC in the three catchments were quite good and this model has reproduced some observed values better than the best model, SWAT. Results of the mean daily total phosphorus concentrations from the three models were not as good as the results of the loads in the three catchments.

- Simulation of the daily dissolved reactive phosphorus loads and concentrations by the three models in the study catchments were not acceptable.

- All three models have shown good performance in simulating phosphorus loads compared to concentrations. This could be attributed to the fact that daily average values of the simulated concentrations have been compared with instantaneous values of observed concentrations that do not represent the actual average daily values.

- Some modelling limitation factors have been identified

**Recommendations**

For the further improvements of the phosphorus loss simulation in the study catchments using SWAT, HSPF, and SHETRAN/GOPC models, some suggestions has been proposed. These include:

- Combining the flow simulation of HSPF model with the SWAT or GOPC phosphorus component is expected to produce a new catchment model which will be better than using either of the individual models to simulate the phosphorus loss.

- Adding an in-stream water quality module to the GOPC to strengthen the capability of this model in simulating the phosphorus loss from a catchment.

- Activating the chemical in-stream processes of SWAT and HSPF models in order to achieve the maximum capacity of the models.

- Improving the flow simulation in each model as much as possible as this is expected to improve the phosphorus simulation.
• Applying the models to the study catchments after fragmenting them into smaller units in order to identify contaminant “hot spots” and study the models sensitivity to spatial scales.

• To ensure that the total phosphorus is properly simulated, it must be partitioned into its components (particulate and dissolved) in order to be separately modelled.

• Using phosphorus data as much as possible from a continuous water sampling (flow-weighted or time-weighted) in order to use data which is more robust when compared with the models outputs.

• Using actual data for phosphorus application to the soil as inputs to the models so that the uncertainty in defining phosphorus inputs can be minimised.

• Generally the phosphorus predictions from the three models were very sensitive to the parameters related to the soil sorption process. Therefore values of these parameters should be obtained from laboratory analysis of soil samples from the three catchments.

Finally it is highly recommended to develop a decision support tool consisting of SWAT, HSPF, and SHETRAN/GOPC models and multi-criteria analysis to support the evaluation of various catchment management strategies in line with the WFD requirements. This tool can assist the engineer/manager to link between the scientific information and the effective and efficient management strategies to ensure the maximum benefit for the environment with minimum economic impact on the ongoing activities in the catchment. Then decision makers can utilise the information provided by the decision support tool to seek an effective way to regulate pollution through obligatory abatement policies.