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EUTROPHICATION FROM AGRICULTURAL SOURCES – A Comparison of SWAT, HSPF and SHETRAN/GOPC Phosphorus Models for Three Irish Catchments

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Synthesis Report

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by

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1 Objectives

This project has targeted one of the Water Framework Directive (WFD) objectives which focuses on modelling non-point phosphorus loss from rural catchments. It focuses on physically based catchment-scale models which to date have not been applied to model phosphorus losses in Ireland. In the work, three very different catchment models ranging 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 degrees 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 outputs of the three models (including the developed phosphorus component) was examined. This information is useful in providing guidelines for using the models in Irish conditions.

2 Methodology

As shown in Table 2.1, apart from the GOPC component, the SWAT, HSPF and SHETRAN models have been developed in the 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 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.

Figure 2.1 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, a river map, a land-use map and a 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 carry out 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.

Table 2.1. Main features of SWAT, HSPF, SHETRAN and GOPC models.

	Model			
	Soil and Water Assessment Tool (SWAT)	**Hydrologic Simulation Program – FORTRAN (HSPF)**	**Système Hydrologique Européen TRANsport (SHETRAN)**	**Grid-Oriented Phosphorus Component (GOPC)**
Origin	US Department of Agriculture	Stanford University, USA	Collaboration (UK, France and Denmark)	Developed as part of this research
Model type	Semi-empirical	Quasi-physically based	Fully physically based	Conceptual representation of phosphorus processes
Smallest spatial unit	Hydrologic Response Unit (HRU)	Pervious/impervious land segments	Rectangular grid cell (typically 200–300 m)	Rectangular grid cell (typically 200–300 m)
Simulation time step	Day	Minute/hour/day	Minute/hour/day	Minute/hour/day
Flow modelling component	YES	YES	YES	NO (uses SHETRAN output)
Sediment modelling component	YES	YES	YES	NO (uses SHETRAN output)
Phosphorus modelling component	YES	YES	NO (provides GOPC with hydrological variables)	YES

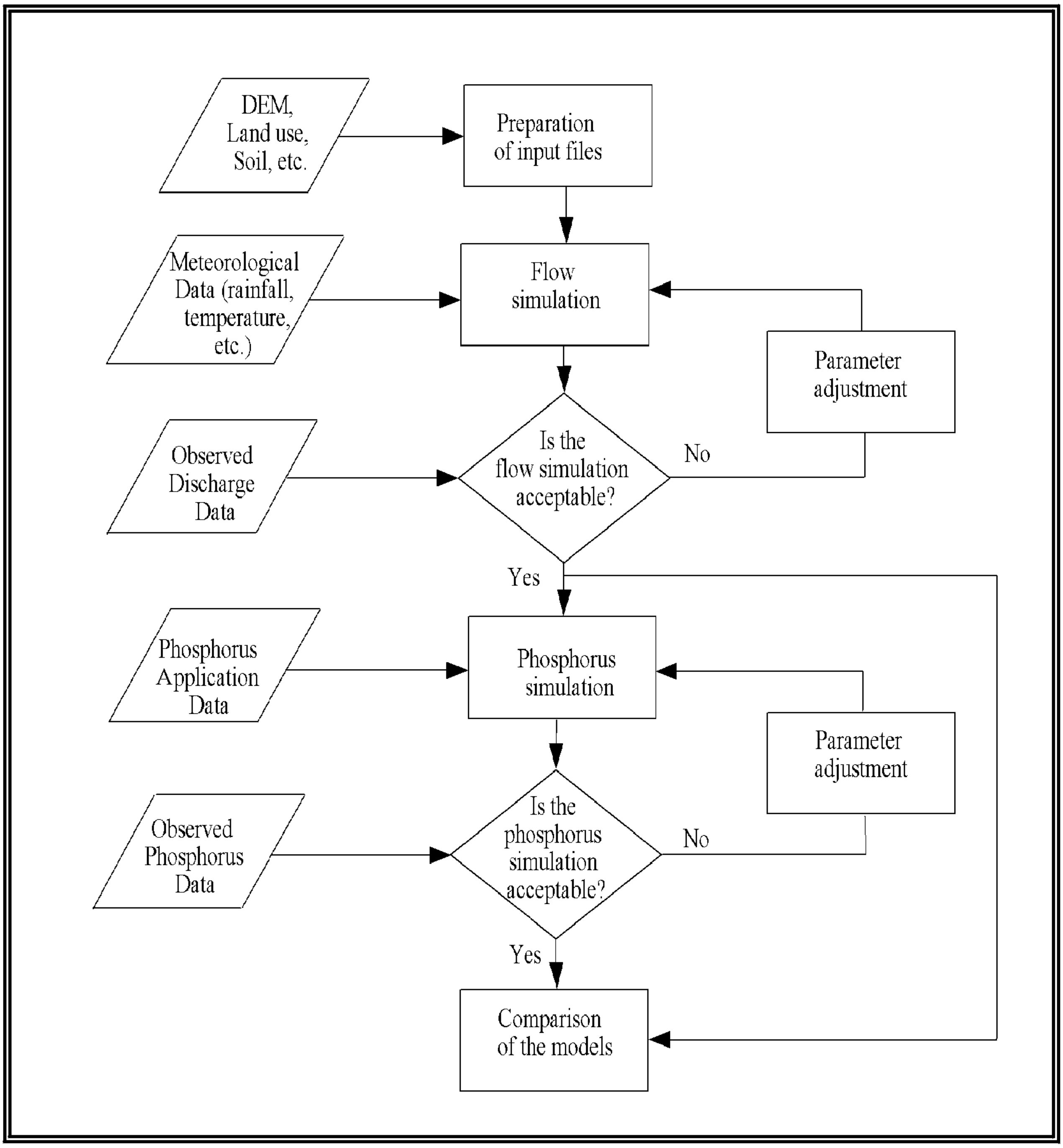

Figure 2.1. Flow chart for the procedure of the application of each of the three models (SWAT, HSPF and SHETRAN/GOPC) to each of the study catchments.

3 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' performances.

Table 3.1 includes the best values of the statistics from the application of the three models to the Clarianna, Dripsey and Oona catchments in order to simulate daily discharge, total phosphorus and dissolved reactive phosphorus. Typically, these are calculated from 365 daily values for the Oona and Dripsey and 200 daily values for the Clarianna. For each catchment, the models with the best R^2 value during the calibration period have been recorded in the table. In addition, the models with the best R^2 value in the two verification periods in the Oona catchment have also been 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 steep 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 to the structure of the model.

The best model in simulating the total phosphorus load during the calibration period in the 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 (the Clarianna catchment), has R^2 a positive value for total phosphorus concentration and this value was obtained from SWAT during the calibration period.

Simulation of the daily dissolved reactive phosphorus loads by the three models in the study catchments is hardly acceptable due to the big differences between the model 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 model 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 estimates of concentrations obtained with parameters calibrated for loads suggests that the models should be independently calibrated for concentrations if good estimates of concentrations are required.

Table 3.1. Summary of 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.

	Clarianna catchment		Dripsey catchment		Oona catchment					
	Calibration		Calibration		Calibration		Validation (first period)		Validation (second period)	
	Best model	R^2	Best model	R^2	Best model	R^2	Best model	R^2	Best model	R^2
Discharge	HSPF	0.95	HSPF	0.74	HSPF	0.91	HSPF	0.90	SHETRAN	0.80
Average daily total phosphorus load	SWAT	0.59	GOPC	0.51	SWAT	0.56	HSPF	0.59	HSPF	0.77
Average daily total phosphorus concentration	SWAT	0.55	–	No useful value	–	No useful value	–	No useful value	–	No useful value
Average daily dissolved reactive phosphorus load	HSPF	0.70	GOPC	0.46	GOPC	0.56	GOPC	0.39	–	No useful value
Average daily dissolved reactive phosphorus concentration	–	No useful value	–	No useful value	–	No useful value	–	No useful value	–	No useful value

4 Conclusions

The conclusions, in respect of the performance of the models, include:

- **Flow simulation:** (very good) In the three catchments, the HSPF model was the best at simulating the mean daily discharges and this was also confirmed with the validation runs for the Oona catchment. The discharge results from SWAT and SHETRAN were generally acceptable despite occasional deficiencies described above.
- **Total phosphorus:** (reasonably good) The best simulation for the daily total phosphorus loads in the study catchments was given 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 model 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.
- **Dissolved reactive phosphorus:** (bad) Simulation of the daily dissolved reactive phosphorus loads and concentrations by the three models in the study catchments was not acceptable.
- **Phosphorus concentrations:** (not good) All three models are better at simulating daily phosphorus loads than concentrations. From the point of view of eutrophication of waterbodies, the load delivered to the waterbody is the more important parameter.
- Some modelling limitations have been identified and described.

5 Recommendations

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

- Combining the flow simulation of the 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 model to strengthen the capability of this model in simulating the phosphorus loss from large catchments.
- Activating the chemical in-stream processes of the 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 to 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 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 independently from laboratory analysis of soil samples from the three catchments, instead of calibration.

It is highly recommended that this work be extended to develop a decision support tool consisting of the best components of the SWAT, HSPF and SHETRAN/GOPC models and multi-criteria analysis to support the evaluation of various catchment management strategies to support 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.