

PHYSICALLY-BASED, DISTRIBUTED, CATCHMENT MODELLING FOR ESTIMATING SEDIMENT AND PHOSPHORUS LOADS TO RIVERS AND LAKES: ISSUES OF MODEL COMPLEXITY, SPATIAL AND TEMPORAL SCALES AND DATA REQUIREMENTS.

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1. INTRODUCTION

The Water Framework Directive requires the development of management strategies and specific, detailed, plans to restore Irish rivers and Lakes to “good” status within a specified timeframe. Numerical models will be essential to explore the potential consequences of proposed strategies and to facilitate rational and transparent management decisions. There is a consensus that phosphorus is an important factor in the current degradation of surface water quality and that much of it is transported by water in particulate form or bound with sediment. Distributed catchment models have the required potential to give a good spatial description of the main physical processes involved in the washing off of phosphorus and sediment from catchments and their transport in channels. They are central to the management of the problem in the same way that water itself is central to the mobilisation and transport of the pollutants. Thus, Nasr and Bruen investigated the suitability of off-the shelf, readily available distributed catchment models for this purpose. The models represented a broad range of complexity in spatial descriptions and detail of physical processes. Here, we describe the issues involved in applying these models to Irish catchments and review the important issues of model complexity, appropriate spatial and temporal scales and the problems of data availability and parameter calibration. Even within such a small country, a wide variety of soil, vegetation and topographic conditions are found and these influence the suitability and performance of the models. The project demonstrated that such models can be used in Irish conditions and with useful results.

The work described here is a component of a larger EPA / Teagasc funded ERTDI project and many people contributed to it. The computer modelling work described here was done by Nasr and Bruen at UCD and the data for the three test catchments was collected by teams from the University of Ulster (lead by Phil Jordan) for the Oona catchment; from the University of Limerick (lead by Richard Moles) for the Clarianna catchment and University College Cork (lead by Gerard Kiely) for the Dripsey catchment.

2. PHYSICALLY-BASED MODELS USED IN THE STUDY

We decided to test existing off-the-shelf models first because, if these proved suitable there would be no reason to develop a new model from scratch. Even if existing models did not prove suitable, knowledge of their shortcomings would help subsequently in constructing a better model. Three physically-based distributed models were chosen, SWAT (Arnold et al., 1998), HSPF (as implemented in BASINS) (Bicknell et al., 1997) and SHETRAN, (Ewen et al., 2000). The first two were developed in the USA and have in-build phosphorus modelling components. SHETRAN, developed in the UK, does not currently model phosphorus so Nasr & Bruen (2003) produced a “Grid oriented phosphorus component (GOPC)” which could be used with it. The three 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 normal simulation time step.

3. VARIATIONS OF SPATIAL RESOLUTION IN THE MODELS

The three models chosen for testing have different procedures for representing spatial variation within the catchment.

- (i) SWAT divides the catchment into a number of sub-catchments each of which consists of a number of Hydrologic Response Units (HRU) (Leavesley et al., 1983). An HRU is a unit of area with uniform land use and soil type without reference to their actual spatial position within each sub-catchment.
- (ii) HSPF subdivides the catchment on the basis of land use type. Each land use type can consist of pervious and impervious portions which have different hydrologic behaviour.
- (iii) In SHETRAN/GOPC the catchment is divided into an horizontal orthogonal grid network and in the vertical direction by a column of horizontal layers at each grid square. The channel system is represented on the boundaries of the grid squares.

4. VARIATIONS OF PROCESSES REPRESENTATION IN THE MODELS

The models chosen range from semi-empirical to fully physically-based in how they represented the relevant hydrological processes that control the water and sediment movement on hill slopes and in rivers and the chemical and biochemical processes transforming the phosphorus compounds both in the soil and during its transport by water. The SWAT model uses semi-empirical equations to represent most of these processes. The HSPF model characterises the catchment response to external inputs by changes of water, sediment, and chemical volumes in a series of vertical storages. The fluxes between the various storages and outside to the river reaches are modelled with equations which have parameters determined by measurement and/or calibration. In contrast, SHETRAN/GOPC are examples of fully physically-based models which rely wholly on relationships derived from the actual physical and chemical laws which govern the controlling processes. In order of increasing hydrological complexity, the models would be ranked SWAT, HSPF, SHETRAN and in order of increasing complexity in representing phosphorus processes, HSPF, SWAT, GOPC.

5. VARIATIONS OF TIME RESOLUTION IN THE MODELS

In terms of simulation time step, SWAT is the most constrained, and operates on a daily time step. Both HSPF and SHETRAN/GOPC can simulate at any time step from one minute up to one day. However, the input time series should always be available at intervals equal to or less than the simulation time step.

6. DATA REQUIRED BY THE MODELS

The spatial data required by these models includes a digital elevation model (DEM), land use map, and soil map. In addition, time series of certain meteorological variables, discharge and phosphorus concentrations or loads are also required. The meteorological include rainfall, temperature, solar radiation, relative humidity, and wind speed. For phosphorus modelling, a time series of phosphorus application loads is required. Time series of observed discharge and phosphorus concentrations or loads are vital for calibrating and validating the models.

7. TEST CATCHMENTS

Three catchments were used to test the models, located in three out of the six Irish River Basin Districts (RBDs), Fig. (1). The Clarianna catchment (23 km²) is in county Tipperary, to the north of the Nenagh River catchment which drains the mid-Tipperary region west of Devilsbit mountain. The Dripsey catchment (15 km²) is in County Cork, 25 km northwest of the city of Cork, and drains into the River Lee. The Oona catchment (96 km²) is an international RBD shared between the Republic and Northern Ireland. It is located in County Tyrone and forms a small part of the catchment of the River Blackwater, one of the six major influent rivers of Lough Neagh in Northern Ireland. Most of the Oona catchment is situated in the drumlin belt of Northern Ireland.

For each catchment, the land use and soil maps required by the models have been extracted from the CORINE land use map (CORINE, 1989) and the general soil map of Ireland (Gardiner and Radford, 1980) respectively. Other required data, including a digital elevation model (DEM), weather, discharge and phosphorus data for the three catchments has been collected as part of research projects funded by the Environmental Protection Agency in Ireland.

Detailed descriptions of the structures and parameters of the models can be found in the cited literature and are not repeated here. Many of the model parameters are assigned initial values determined from

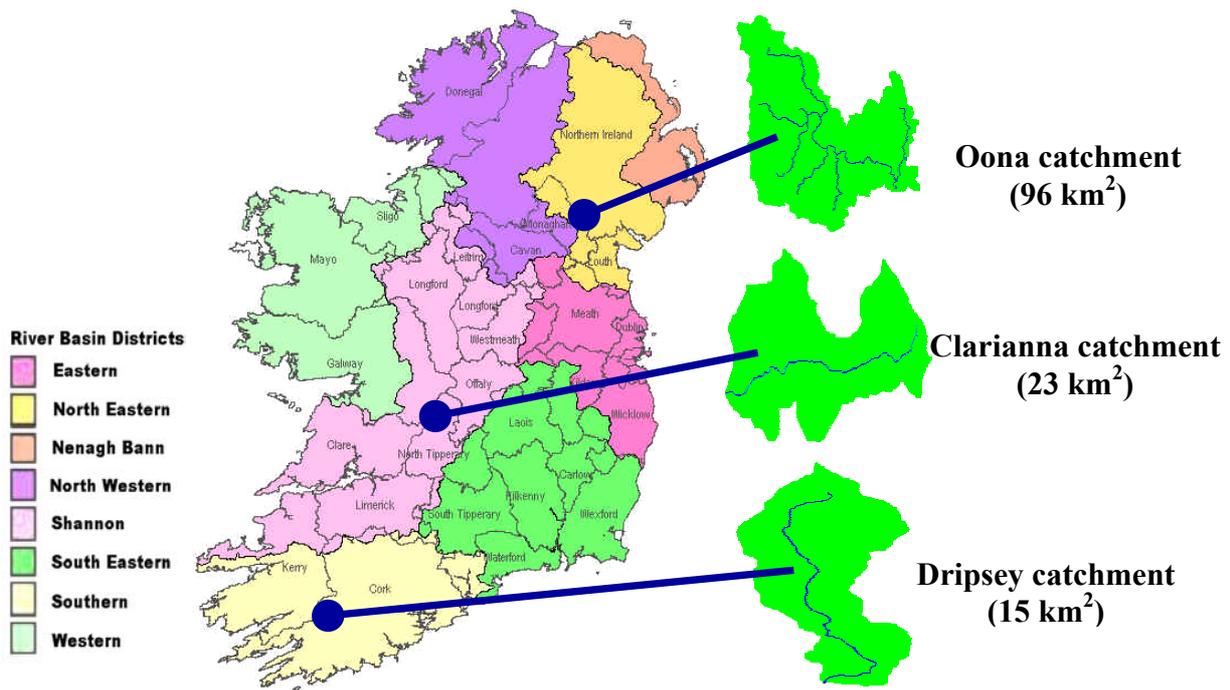


Figure (1) Location of test catchments

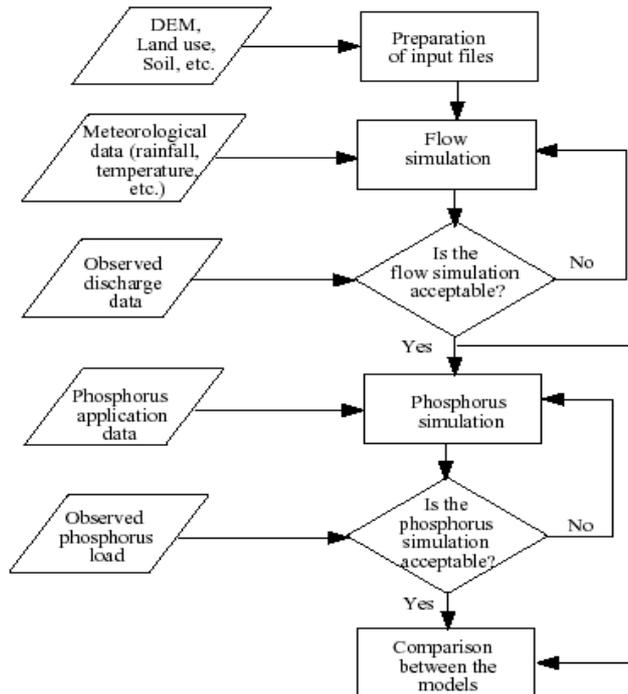


Figure (2) Manual calibration procedure

the basic topographic, soil and land use data. However, in some cases, better performance can be achieved by adjusting (calibrating) them for the specific catchment. Here this is done manually in two stages, Fig. (2). First the parameters which influence runoff and water flow from the catchment are adjusted until as good a fit as reasonably possible to the observed hydrograph is obtained. Then the parameters relating to the phosphorus modelling are adjusted to match the observed loads as well as

reasonably possible. For each of the three study catchments all three models have been manually calibrated to produce estimates for discharge, total phosphorus, and dissolved reactive phosphorus.

8. IMPLEMENTING THE MODELS

8.1. Swat

SWAT2000, the most recent version so far, is used here. The preparation of all the inputs files has been done using the AVSWAT interface. Because of the Clarianna's relative uniformity, no division into sub-catchments has been made. The average slope of the lumped catchment was 0.03, the length of the main channel in the lumped catchment was 12.7, and the slope of the main channel was 0.001. To allow for some spatial variations, the lumped catchment has been divided into three HRUs each of which has same soil type but with different land use type. The dominant HRU is composed of pasture on Grey Brown Podzolic soil and represents 83% of the total area. Its parameters are expected to have a significant influence on the flow and the phosphorus simulations.

The Dripsey catchment was divided into three sub-catchments, two of them were further divided into two HRUs while the third one was represented by a single HRU.

The Oona catchment has eight main streams and therefore it has been divided into eight sub-catchments. One of the sub-catchments has been divided into three HRUs while three other sub-catchments have been divided into two HRUs. The remaining four sub-catchments have all one HRU and therefore the total number of HRU in the catchment is thirteen.

8.2. HSPF

The same procedure used in SWAT to divide the study catchment into sub-catchments was also applied in HSPF. Therefore the same shape and characteristics for the sub-catchments and stream networks were obtained. In all catchments more than 75% of the land area is occupied by pasture. Range land is the next most common and occupies more than 10% of the area in all catchments. In the Clarianna and Dripsey only, agriculture land comes third with an area occupying more than 5%. Urban areas are only a very small proportion of each catchment. There are wetlands in the Clarianna and Oona catchments while there are forests in the Dripsey and Oona catchments. Both the wetland and the forest occupy small areas. In the Oona catchment a very small area is occupied by lakes.

8.3. SHETRAN/GOPC

For all the study catchments, an orthogonal grid has been created for each catchment with a cell size of 200 x 200 m². Each of the existing land use types in each of the study catchments have been categorised to be in one of the generic groups that have parameters in the SHETRAN user's manual. Most of the elements in the land use grid of each catchment are grass land. Arable land occupies a considerable number of elements (more than 10%) in the land use grid of each catchment. Other types including urban land and deciduous forest can be found in a few elements of the land use grids of the Dripsey and Oona catchments. Also a few elements in the land use grid of the Clarianna catchment are occupied by urban land.

9. RESULTS

9.1. Clarianna catchment

Flow: A visual comparison between hydrographs of observed and estimated discharge from the three models (Fig. (3)) shows that HSPF has produced a hydrograph closest to the actual one, capturing most of the peaks except for some discrepancy in the falling limb. On the other hand, the hydrograph from SWAT is not as good and shows a significant underestimation of one of the largest observed peaks. The SHETRAN model failed to simulate one of the major peaks in the observed hydrograph and doesn't match the recessions after any of the peaks.

The average flow estimates from SWAT and HSPF models are very close to the observed values while SHETRAN's average is slightly lower, Table (1). The standard deviation is higher for HSPF for the observed data and is lower for SWAT and SHETRAN. This means that the HSPF output has more variability than the observed flow series and that of the other models. For flows, the best results for

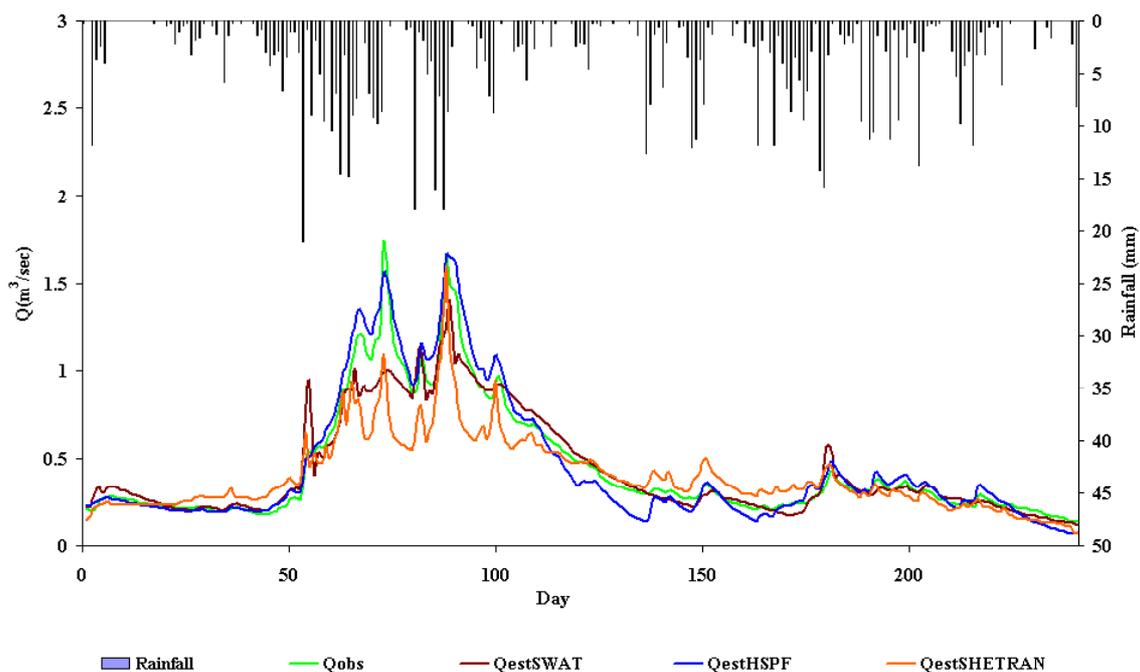


Figure (3). Flow modelling in the Clarianna catchment

Sum of Squares of Errors (SSE), Correlation coefficient, and R^2 , are for HSPF model and the shape of the flow hydrograph has confirmed this. The corresponding values for SWAT are generally better than the case of SHETRAN and this also agrees with the resulted shapes of the hydrographs from the two models.

Table (1) Assessment of calibration results for the period 1/12/2001 - 29/07/2002 - Clarianna catchment

Clarianna catchment	Discharge (m^3/sec)				Total phosphorus (kg P/day)			
	Observed	SWAT	HSPF	SHETRAN	Observed	SWAT	HSPF	GOPC
Number of days	241	241	241	241	143	143	143	143
Average of values	0.44	0.43	0.45	0.40	1.82	1.55	0.93	1.63
Standard Deviation	0.33	0.29	0.38	0.22	2.43	1.53	1.22	1.26
Correlation coefficient		0.96	0.99	0.92		0.79	0.84	0.65
Sum of Squares of Errors		2.46	1.22	6.60		341.53	455.95	501.82
R^2		0.91	0.95	0.75		0.59	0.45	0.40

Total phosphorus: Fig. (4) shows the results of the total phosphorus simulation from all models. Note that at the end of the simulation period there are high total phosphorus values which none of the three models have reproduced. These correspond to a period of dredging of the river and are ignored in the model comparison. Discounting this period, the SWAT model has performed quite well generally except for some high measured total phosphorus values which could not be matched by the model because of its failure to adequately simulate the corresponding flow peak. The GOPC performance with TP is second to SWAT 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. It is quite surprising to notice that the HSPF performance for TP was the worst although it has the best performance in simulating the flow hydrograph. All the total phosphorus values simulated by this model are systematically lower than the actual values which means that the model has a response lower than the other two models. The main reason for this result could be the much simpler nature of the phosphorus component in the HSPF model compared to the same components in SWAT and GOPC.

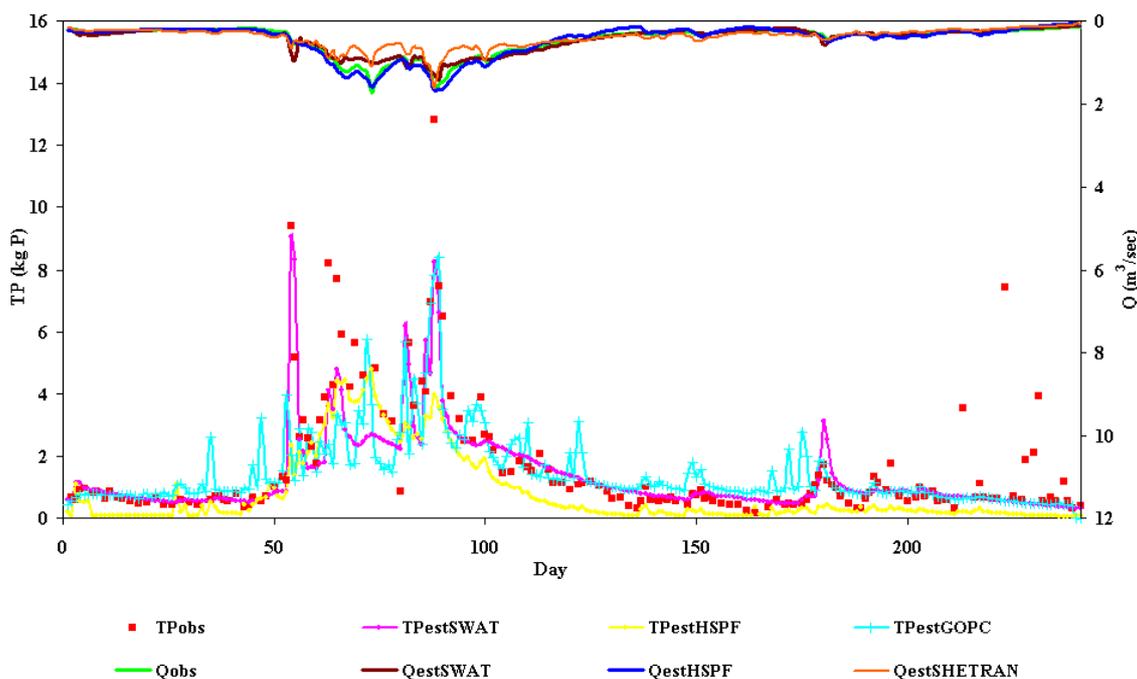


Figure (4) TP modelling in the Clarianna catchment

9.2. Dripsey catchment

Flow: As with the Clarianna, the HSPF flow simulation for the Dripsey is generally best with SWAT second and SHETRAN third. A noticeable weakness in the SWAT simulation is the overestimation of the flow recession.

Table 2 shows the comparative statistics. The average flows from HSPF and SHETRAN are close to the observed. HSPF has a slightly higher average while SHETRAN slightly over. HSPF's standard deviation is closest to that of the observed flow and it has the best values of correlation coefficient and R^2 .

Table (2) Assessment of calibration results for the period 1/1/2002 - 31/12/2002 - Dripsey catchment

Dripsey catchment	Discharge (m ³ /sec)				Total phosphorus (kg P/day)			
	Observed	SWAT	HSPF	SHETRAN	Observed	SWAT	HSPF	GOPC
Number of days	365	365	365	365	166	166	166	166
Average of values	0.50	0.55	0.61	0.49	10.36	8.26	9.22	8.37
Standard Deviation	0.54	0.51	0.56	0.59	17.16	14.06	4.75	10.20
Correlation coefficient		0.86	0.89	0.84		0.69	0.55	0.74
Sum of Squares of Errors		29.05	27.55	37.56		$2.7 \cdot 10^4$	$3.8 \cdot 10^4$	$2.4 \cdot 10^4$
R^2		0.72	0.74	0.64		0.44	0.22	0.51

Total phosphorus: The SWAT model is reasonably good at simulating the total phosphorus load in the Dripsey catchment, Fig (5). Most of the total phosphorus load values have been simulated in the SWAT simulation. The GOPC simulation for the total phosphorus loads is also good except for the remarkable underestimation of the peak values at around 300 days during the period of simulation. The reason for this underestimation is obviously related to the failure of SHETRAN to simulate the corresponding flows during the same period and this demonstrates the necessity of having a good estimation of the flow by SHETRAN in order to have a good estimation of total phosphorus with the GOPC model. HSPF, despite being best in simulating the flows, shows a consistent underestimation for all total phosphorus values above 20 kg. This means that a good flow estimation is not sufficient to

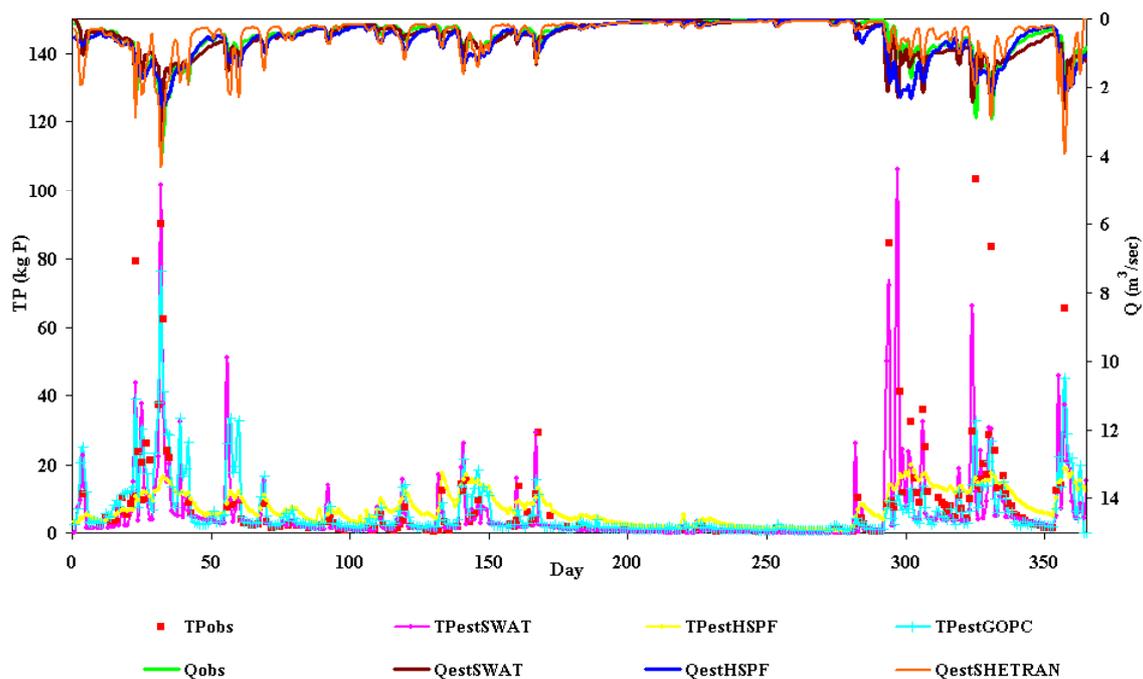


Figure (5) TP modelling in the Dripsey catchment

produce a good total phosphorus estimation and shows up the phosphorus modelling limitations in the HSPF model.

9.3. Oona catchment

Flow: For the Oona, the hydrographs of SWAT and HSPF are a better simulation of the actual observed flow than the hydrograph from SHETRAN. Both SWAT and HSPF simulate the peaks well while SHETRAN consistently underestimates these peaks. Nevertheless SHETRAN gives a good simulation of the low flows.

Here, the average flows estimated by all three models are greater than the observed, Table 3. However, SWAT and HSPF have higher standard deviations and SHETRAN lower. HSPF gives a very good fit with a correlation coefficient of 0.97 and R^2 of 0.91.

Table (3) Assessment of calibration results for the period 1/1/2002 - 31/12/2002 – Oona catchment

Oona catchment	Discharge (m ³ /sec)				Total phosphorus (kg P/day)			
	Observed	SWAT	HSPF	SHETRAN	Observed	SWAT	HSPF	GOPC
Number of days of data	365	365	365	365	365	365	365	365
Average of values	2.38	3.00	2.88	2.70	75.33	91.19	70.46	34.30
Standard Deviation	3.25	3.54	3.54	2.04	140.55	140.51	87.34	29.41
Correlation coefficient		0.90	0.97	0.96		0.79	0.60	0.87
Sum of Squares of Errors		1*10 ³	0.4*10 ⁴	0.8*10 ⁴		3.2*10 ⁶	4.6*10 ⁶	5.5*10 ⁶
R^2		0.73	0.91	0.80		0.56	0.36	0.23

Total phosphorus: The good flow simulation by SWAT model has been reflected in its performance in simulating the total phosphorus loads. Fig. (6) demonstrates the superiority of SWAT compared to the other two models in achieving acceptable total phosphorus results although some of the total phosphorus peak values have not been well captured. Again, being the best model in the flow simulation was not sufficient for HSPF to outperform SWAT in the total phosphorus simulation. Nevertheless HSPF was not so bad with lower total phosphorus values close to those from SWAT but could not match SWAT for the highest total phosphorus values. The GOPC is obviously affected by the bad simulation of the flow peaks by SHETRAN and hasn't done well at simulating the high total

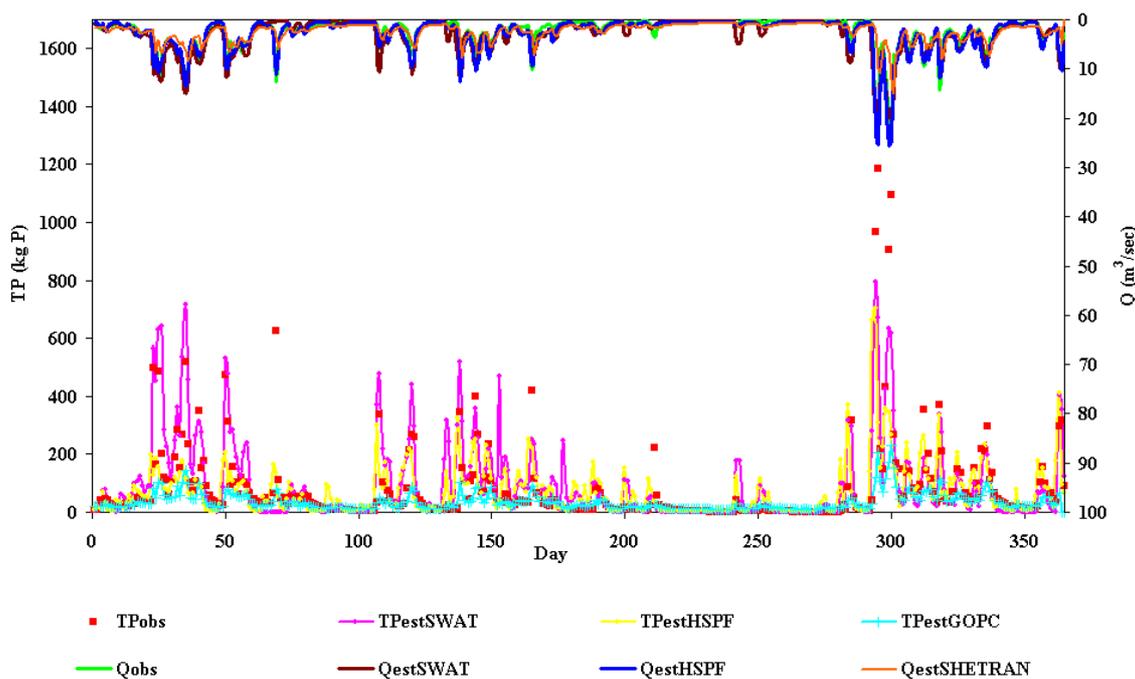


Figure (6) TP modelling in the Oona catchment

phosphorus values. However, the GOPC simulation of the low total phosphorus values are in good agreement with the observed and similar to the other two models.

Table (3) displays the results of the statistical analysis for the total phosphorus loads simulated by the three models. The average of total phosphorus loads from SWAT is much higher than the observed value whereas the GOPC result is much lower. SWAT has a standard deviation almost equal to the observed values. HSPF has values lower than the observed for the average and standard deviation. The best correlation coefficient was 0.78 in the case of GOPC model while the best R^2 was 0.56 in the case of SWAT model.

The results given here are for model calibration. Where sufficient independent data was available, validation tests were also performed, but are not reported here.

10. CONCLUSIONS

- Existing distributed physically-based models can be applied in Irish conditions with the available data.
- These models, with some manual calibration, gave reasonable simulations of TP load from agricultural non-point sources for the catchments tested.
- The HSPF model, in the Basins package was the best model for simulating discharges.
- Despite not being as good as HSPF at flow modelling, SWAT outperformed it at modelling total phosphorus loads. The GOPC performed well in some cases only.

11. REFERENCES

- Arnold, J. G., Srinivasan, R., Muttiah, R.S., Williams, J. R. 1998. Large area hydrological modelling and assessment Part I: Model development. *Journal of the American Water Resources Association* 34(1), 73-89.
- Bicknell, B. R., Imhoff, J. C., Donigian, A. S., Johanson, R. C., 1997. Hydrological Simulation Program – FORTRAN (HSPF), User's Manual For Release 11. EPA – 600/R-97/080. U.S. Environmental Protection Agency, Athens, GA.
- CORINE program, 1989. Land Cover Project, The Nomenclature. Commission of the European Communities, Directorate-General Environment Nuclear Safety and Civil Protection, Rue de la Loi 200, B-1049 Brussels, Belgium.

Ewen, J., Parkin, G., O'Connell, E., 2000. SHETRAN: Distributed basin flow and transport modelling system. *Journal of Hydrologic Engineering* 5(3), 250-258.

Gardiner, M.J., Radford, T., 1980. *Soil Associations of Ireland and their land use potential (Explanatory Bulletin to Soil Map of Ireland 1980)*. Published by An Foras Taluntais, 19 Sandymount Avenue, Dublin 4.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., Saindon, L.G., 1983. *Precipitation-runoff modelling system: user's manual*. United States Geological Survey, Water-Resources Investigation Report 83-4238, pp. 207.

Nasr, A., Taskinen, A., and Bruen, M., 2003. Developing an independent, generic, phosphorous modelling component for use with grid-oriented, physically-based distributed catchment models. In Bruen, M. (ed.) *Proc. of the 7th International IWA Specialised Conference on Diffuse Pollution and Basin Management*, Dublin, Ireland. Vol. 1, pages 1.89-1.94.

12. ACKNOWLEDGEMENTS

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Table (2) Assessment of calibration results for the period 1/1/2002 - 31/12/2002 - Dripsey catchment

Dripsey catchment	Discharge (m ³ /sec)				Total phosphorus (kg P/day)			
	Observed	SWAT	HSPF	SHETRAN	Observed	SWAT	HSPF	GOPC
Number of days	365	365	365	365	166	166	166	166
Average of values	0.50	0.55	0.61	0.49	10.36	8.26	9.22	8.37
Standard Deviation	0.54	0.51	0.56	0.59	17.16	14.06	4.75	10.20
Correlation coefficient		0.86	0.89	0.84		0.69	0.55	0.74
Sum of Squares of Errors		29.05	27.55	37.56		2.7*10 ⁴	3.8*10 ⁴	2.4*10 ⁴
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Oona catchment	Discharge (m ³ /sec)				Total phosphorus (kg P/day)			
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