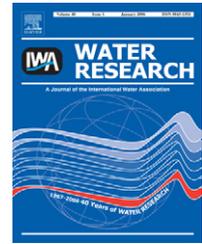
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A comparison of SWAT, HSPF and SHETRAN/GOPC for modelling phosphorus export from three catchments in Ireland

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ABSTRACT

Recent extensive water quality surveys in Ireland revealed that diffuse phosphorus (P) pollution originating from agricultural land and transported by runoff and subsurface flows is the primary cause of the deterioration of surface water quality. P transport from land to water can be described by mathematical models that vary in modelling approach, complexity and scale (plot, field and catchment). Here, three mathematical models (soil water and analysis tools (SWAT), hydrological simulation program–FORTRAN (HSPF) and système hydrologique Européen TRANsport (SHETRAN)/grid oriented phosphorus component (GOPC) of diffuse P pollution have been tested in three Irish catchments to explore their suitability in Irish conditions for future use in implementing the European Water Framework Directive. After calibrating the models, their daily flows and total phosphorus (TP) exports are compared and assessed. The HSPF model was the best at simulating the mean daily discharge while SWAT gave the best calibration results for daily TP loads. Annual TP exports for the three models and for two empirical models were compared with measured data. No single model is consistently better in estimating the annual TP export for all three catchments.

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1. Introduction

The introduction of the Water Framework Directive in Europe (EEC, 2000) required Member States to review water quality problems in all their water bodies. In Ireland, riverine and lake eutrophication due to diffuse pollution has been identified as a major problem (Earle, 2003) and phosphorus (P) is the limiting nutrient controlling eutrophication in inland waters (McGarrigle et al., 2002). Therefore an effective way to tackle eutrophication is to control P inputs, both from point and diffuse sources.

Formerly, P from point sources was the major cause of serious pollution incidents in most Irish rivers (McGarrigle et al., 2002). However, in response to the Urban Wastewater Directive (EEC, 1991) many wastewater treatment plants in Ireland were upgraded to include a tertiary process resulting in a large reduction in pollution from point sources. Now, in many catchments most nutrients entering rivers are from diffuse sources and therefore, this study modelled this influence, concentrating on P transport in three Irish catchments. The catchments were chosen on the basis of availability of the data required by the models and because they

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have different climate, land use and soil types. The modelled variable is total phosphorus (TP) load because of its direct relationship with impacts on receiving waters (Hilton et al., 2006).

According to the DPSIR conceptual framework (Drivers, Pressures, State, Impact and Response) (Irvine et al., 2005) that will guide the selection of modelling techniques in Ireland, it is likely that the most useful models will be of the physically-based or mechanistic types. Three widely used, physically-based, models were selected to cover a range of variation in (i) the complexity of their representation of the physical, chemical, and bio-chemical processes involved in P mobilisation and transport, (ii) the degree of complexity in spatial disaggregation of the catchment, and (iii) the normal simulation time step. The models are: soil water and analysis tools (SWAT) (Arnold et al., 1998); hydrological simulation program-FORTRAN (HSPF) (Bicknell et al., 1997); and Système Hydrologique Européen TRANsport (SHETRAN) (Ewen et al., 2000) coupled with the grid oriented phosphorus component (GOPC) (Nasr et al., 2005). The differences between the three models are discussed here first and then their application to the study catchments. Finally, their flow and TP load simulations are described and assessed and the TP loads compared with empirical models.

2. Differences between the SWAT, HSPF, and SHETRAN/GOPC models

2.1. Processes representation

The models chosen range from semi-empirical to fully physically-based in how they represent the relevant hydrological, chemical and bio-chemical processes transforming the P compounds both in the soil and during its transport by water. The SWAT model uses semi-empirical equations to represent most of these processes. HSPF models the catchment response by changes in water, sediment, and chemical amounts in a series of vertical storages. The fluxes between the various storages and exchanges with the river reaches are modelled with equations that have parameters determined by measurement and/or calibration. In contrast, SHETRAN/GOPC is an example of a fully physically-based model which relies wholly on relationships derived from physical and chemical laws. In order of increasing hydrological complexity, the models are ranked SWAT, HSPF, SHETRAN and in order of increasing complexity in representing P processes, HSPF, SWAT, GOPC.

2.2. Spatial representation

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

- SWAT divides the catchment into a number of sub-catchments, each of which has a number of hydrologic response units (HRUs) with uniform land use and soil types (without reference to their actual spatial position within the sub-catchment).
- HSPF divides the catchment on the basis of land use alone. Each land use can consist of pervious and impervious parts.

- In SHETRAN/GOPC, the catchment is divided into a horizontal orthogonal grid network and in the vertical direction by a column of horizontal layers at each grid square. Each grid element can have different land use and hydraulic properties. The channel system is represented on the boundaries of the grid squares.

2.3. Temporal resolution

SWAT operates only at a daily time step. Both HSPF and SHETRAN/GOPC can simulate at any time step from 1 min up to 1 day. In all cases, the input time series should always be available at intervals equal to or less than the simulation time step.

3. Study catchments

The Clarianna catchment (23 km²) is located in County Tipperary in an area which is one of the most intensively farmed catchments within the lower Shannon region. The Dripsey catchment (15 km²) is located near the town of Donoughmore in the south of Ireland and ultimately drains into Inniscarra lake, a freshwater lake that in recent years has experienced signs of eutrophication (Scanlon et al., 2004).

The Oona Water catchment (96 km²) is located in County Tyrone and ultimately drains into Lough Neagh which is a water source for Belfast.

4. Data

The model comparisons are based on simulations of daily time series of discharge and TP load at each catchment outlet. Data used in these simulations are summarised in Table 1. Each of the three models has been calibrated for the period from 1/12/2000 to 29/7/2001 in the Clarianna catchment, and from 1/1/2002 to 31/12/2002 in the Dripsey and Oona Water catchments. To allow HSPF and SHETRAN show their best performances, the available time step resolution of the input data has been also employed as a time step of simulation. As SWAT's time step must be one day, daily input time series for it were derived from the available high resolution input data.

The only input of P was assumed to be direct application of fertiliser and animal slurries on the land. In the Clarianna and Dripsey catchments, the total annual P load applied on the soil was taken as 15 kg P ha⁻¹ in line with the National (Teagasc) recommendations (Teagasc, 1998). For the Oona Water catchment, P inputs of 18.9 million kg P to the soil were assumed based on a P balance in Northern Ireland (Jordan, 2003). In each catchment, the estimated value of the total annual P load has been distributed evenly over the 12 months of the year.

The observed TP concentrations at the outlet of the three catchments (Jordan et al., 2005) are summarised in Table 1 and daily TP loads were calculated from these and flow data. The modelled TP is the sum of the dissolved and sediment-attached P load estimates.

Table 1 – Data used in model application

Type of data		Clarianna	Dripsey	Oona water
Digital elevation model	Resolution	20 m × 20 m	20 m × 20 m	50 m × 50 m
Land use	Source	Co-ORDination of INformation on the Environment (CORINE, 1989)		
Soil	Source	Soil map of Ireland (Gardiner and Radford, 1980)		
Weather data (rainfall, temperature, solar radiation, relative humidity, wind speed)	Method	Observed	Observed	Observed
	Time step	15 min	30 min	5 min
Flow discharge	Method	Observed	Observed	Observed
	Time step	15 min	15 min	1 h
Soil phosphorus application regime	Method	Estimated	Estimated	Estimated
Total phosphorus at catchment outlet	Frequency	Annual amount	Annual amount	Annual amount
	Time step	Observed	Observed	Observed
		Concentrations of flow proportional composite samples	Concentrations of flow proportional discrete samples	Daily loads

5. Model calibration and parameter estimation

5.1. Approach used in the calibration

Manual calibration has been used in the vast majority of reported applications of the three models (e.g. Jha et al., 2002; Wang et al., 1999; Bathurst, 1986) although some very limited attempts at automatic calibration have been made (e.g. Eckhardt and Arnold, 2001; Doherty and Johnston, 2003). Despite the considerable effort that has to be made to implement automatic calibration in these studies the results obtained were still within the range of the manually calibrated models.

To avoid the complexity and computational demands that arise when using automatic calibration (which would not allow these models to be used in many practical situations) a simple manual strategy was employed to calibrate the parameters of the three models to produce reasonable estimates for both discharges and TP loads. The three models were first calibrated to produce reasonable simulations of the discharge. Then the parameters of the best flow calibration were used without any further change during the P calibration, following the three step strategy proposed by Gupta et al. (2003, p. 11).

5.2. Initial estimates of model parameters (Level Zero estimates)

The main objective for the Level Zero estimates is to populate a default data set of parameters for the three models for each of the three test catchments. The SWAT and HSPF models can automatically produce default values for all model parameters by linking each soil and land use type with corresponding internal tables of default parameters. For the third model, the SHETRAN/GOPC combination, the initial values of the SHETRAN parameters were all taken from guidance given in its user's manual.

5.3. Improving the parameter estimates (Level One estimates)

The effective parameters for flow simulation in HSPF were based on USEPA (2000). For its phosphorous modelling, the method used assumes a first order kinetics equation to represent each of the soil P processes. Each equation contains two parameters, the kinetics rate, which is calibrated manually, and the temperature coefficient, which is maintained at a specified value (USEPA, 2000). For the SWAT model the user's manual guidance was followed to improve the parameter values for flow and nutrient simulation.

The SHETRAN model was developed to be used without calibration due to the physical nature of its parameters which are intended to be obtained from direct measurements. However in most previous applications of this model (e.g. Anderton et al., 2002), some parameters have been calibrated and this has been done here.

To illustrate the complexity of each model in terms of parameter calibration, Tables 2 and 3 give the number of the effective parameters and the methods by which they have been used in the water and P simulations, and also cite the source for the methods. We refer the reader to the user's manual of each model for definitions and descriptions of the parameters and these are not repeated here. However, the number of parameters which can be adjusted for the three models is reported in Tables 2 and 3.

5.4. Adjustment of the parameters (Level Two estimates)

Manual improvement of effective parameters for complex models is difficult to carry out in a reliable and consistent manner due to: (i) large numbers of parameters; (ii) equifinality; (iii) parameter sensitivity, and (iv) uncertainty (Gupta et al., 2003). In this study, however, the manual calibration is to provide results corresponding to practical situations when these models are used by typical users with only a general knowledge of sophisticated calibration techniques. Thus the

Table 2 – Summary of the methods used and parameters required to simulate processes of the water component of SWAT, HSPF, and SHETRAN models

Process	SWAT		HSPF		SHETRAN	
	Method	No. of parameters	Method	No. of parameters	Method	No. of parameters
Interception	Water balance	1	Water balance	—	Rutter et al. (1971/1972)	5
Potential evapotranspiration (E_p)	Monteith (1965)/ Priestley and Taylor (1972)/Hargreaves et al. (1985)	—	User defined E_p	—	User defined E_p / Monteith (1965)	—
Actual evaporation (E_a)	Ritchie (1972)	2	Accounting procedure	4	Feddes et al. (1976)	2
Runoff	SCS (1972)	5	Empirical relations	8	Approximation of St. Venant equation	1
Infiltration	Water balance				Variably-saturated sub-surface model	6
Inter/return flow	Kinematic model	2				
Baseflow	Linear reservoir model	5	Linear reservoir model	2		
Percolation to groundwater	Water balance		Empirical relation	1		
River flow routing	Variable storage/ Musking Um	3	Water balance	—	Approximation of St. Venant equation	1
		Total = 18		Total = 15		Total = 15

Table 3 – Summary of the methods used and parameters required to simulate processes of the phosphorus component of SWAT, HSPF, and GOPC models

Process	SWAT		HSPF		GOPC	
	Method	No. of parameters	Method	No. of parameters	Method	No. of parameters
Soil P processes (adsorption/desorption, mineralisation/immobilisation, plant uptake)	Mass balance	6	First order kinetics equation	5	Mass balance	7
Leaching of P	Empirical relation	1	Mass balance	—	Advection equation	1
Dissolution of P in runoff water	Empirical relation	1	Mass balance	—	Empirical relation	1
Overland transport of dissolved P	Linear reservoir model	—	Not simulated by this model	—	Mass balance	2
Subsurface transport of dissolved P	User defined concentration	1	Mass balance	—	Advection equation	1
Transport of attached or particulate P	Empirical relation	1	Mass balance	—	Empirical relation	1
		Total = 10		Total = 5		Total = 13

models are compared in terms of their likely performances in reality rather than their potential best performances if unlimited calibration resources were available.

A systematic approach to manual calibration has been followed in this study where for each model and in each catchment, one parameter was changed at a time and the

resulting shapes of the hydrograph in the flow calibration or load graphs in the P calibration were visually compared with the observed. In addition, the Nash–Sutcliffe index (Nash and Sutcliffe, 1970) was also calculated for each model run. In the flow calibration, first the focus was on visually matching the peaks, then on matching the flow recessions and finally on the low flow values. This requires sequential adjustment to the particular parameters in the models that influence each of the three components of the hydrograph. The P calibration followed a similar procedure where the focus was first on the high values, then on the low values, and finally on the overall shape of the simulated time series.

6. Comparison criteria

The three models are compared both on their daily and annual results. Two criteria are used to assess the models in simulating the daily discharges and TP loads. Firstly, for each catchment, the flow hydrograph was plotted together with the rainfall hyetograph so that the flow simulation and its consistency with rainfall can be observed and the daily TP results were superimposed on the graph. This allows a direct visual appreciation of the influence of the hydrological modelling on the transport of P. Importantly, it also reveals many systematic aspects of the model performance such as tendencies to over or under estimate, which are seasonal or related to flow or rainfall, and tendencies to match high peaks but not low ones. These tendencies would be difficult to detect with a single numerical index.

The second criterion is based on two numerical measures: the Nash–Sutcliffe index (R^2); and the fraction of the mean of the squares of the errors due to bias (B%MSSE). These are calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^n (x_i - \hat{x}_i)^2}{\sum_{i=1}^n (x_i - \bar{x})^2}, \quad (1)$$

$$\text{B\%MSSE} = \frac{(\bar{x} - \bar{\hat{x}})^2}{\sum_{i=1}^n (x_i - \bar{x})^2 / n}, \quad (2)$$

where x_i is the observed value, \hat{x}_i is the value estimated by a model, \bar{x} is the mean of the observed values, $\bar{\hat{x}}$ is the mean of the estimated values, and n is the number of data values.

The R^2 index describes the ability of the model to explain the variability in the data, while the B%MSSE index describes the model's ability to match the central tendency (mean) of the data. A good model is one that has a good visual match to the observed data, with a value of R^2 close to one, and a small value of B%MSSE.

7. Comparison with simple empirical models

The three physically-based models are compared with two empirical models specifically developed to estimate annual TP export. The first, (DM) is derived from an equation developed by Daly et al. (2006) specifically for use in Irish conditions and the second model is an export coefficient model (ECM) (Johnes, 1996) used in the UK.

8. Results

8.1. Discharge performance

The hydrographs of observed and estimated discharge (Figs. 1a, 2a, 3a) show that, in general, none of the models is able to replicate the entire shape of the hydrographs throughout the simulation period. However, HSPF is the best at matching the discharge hydrographs and SWAT performed better than SHETRAN. The noticeable weakness in SHETRAN is its failure to adequately model the flow peaks and recessions. Most of its estimated peaks are either very much higher or lower than the observations and also the estimated flow recession is not as flat as the observed.

The numerical criteria for the flow simulations from each model are compared in Table 4. The best results for R^2 are 0.95, 0.74, and 0.91 and for the HSPF model in the Clarianna, Dripsey, and Oona, respectively. The R^2 for SWAT (0.91) is better than for SHETRAN (0.74) in the Dripsey. However, SHETRAN has an R^2 of 0.8 which is better than the 0.73 for SWAT in the Oona. The B%MSSE values for all three models in Clarianna are all low and this means that the bias in estimating the mean of the observed flow was not the major source of error. In the Dripsey and Oona, the B%MSSE value for HSPF is high compared to SWAT and SHETRAN with the latter giving the best results for B%MSSE for these two catchments.

8.2. Daily TP results

Figs. (1b, 2b, 3b) show the TP results. SWAT performed quite well in all three catchments. The GOPC TP load performance is second, despite the problems with the flow estimates. It is quite surprising that HSPF was the worst for TP load in the three catchments although it was best for discharges. The main reason for this could be its smaller scope for calibration due to the fewer number of P parameters, as show in Table 3, and this indicates the limited capability of the first order kinetics equation used in the P simulation by HSPF.

The numerical criteria for TP loads are summarised in Table 4. In the Clarianna, the value of R^2 for SWAT (0.59) is the best while the corresponding value for GOPC (0.40) is the worst of the three models. HSPF has the highest B%MSSE while the other two models have low values, indicating that their bias is less significant. In the Dripsey, the best R^2 value of 0.51 is obtained from the GOPC model while the HSPF model value was the worst (0.22). All three models have low B%MSSE values indicating an overall acceptable bias performance in this catchment. In the Oona, SWAT has the best R^2 (0.56) while its B%MSSE value is second best to the HSPF value. The GOPC has the worst R^2 (0.23) and B%MSSE values.

8.3. Annual TP export results

Table 5 shows the observed and modelled values of annual TP export from each catchment. In the Clarianna, SWAT and GOPC are the best of the five models. Both empirical models greatly overestimated the TP export while HSPF

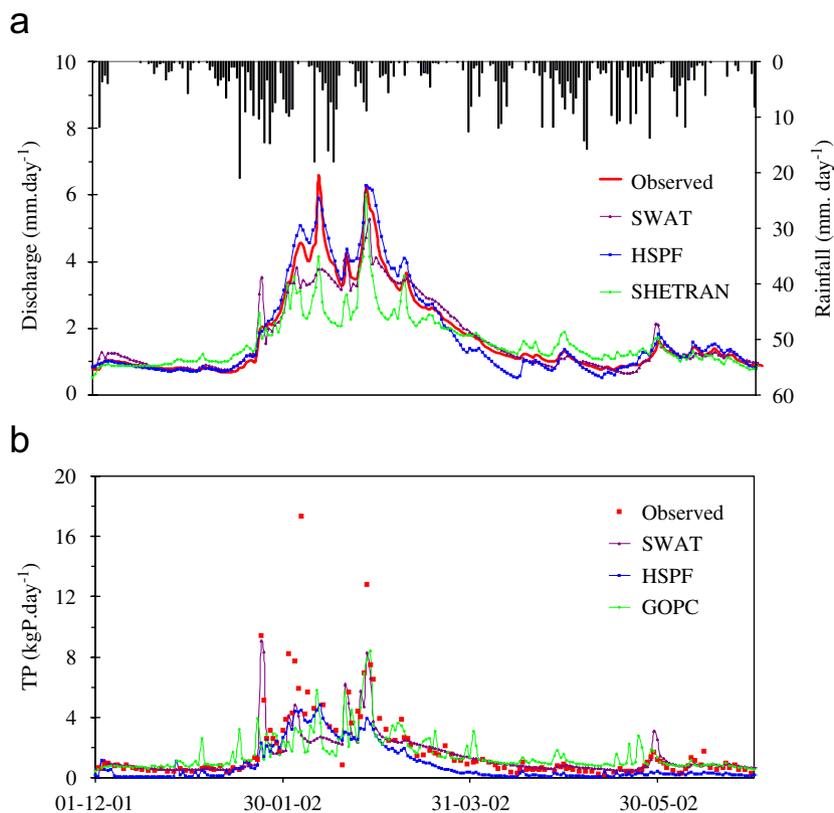


Fig. 1 – Clarianna catchment: results of the three models: (a) flow and (b) total phosphorus load.

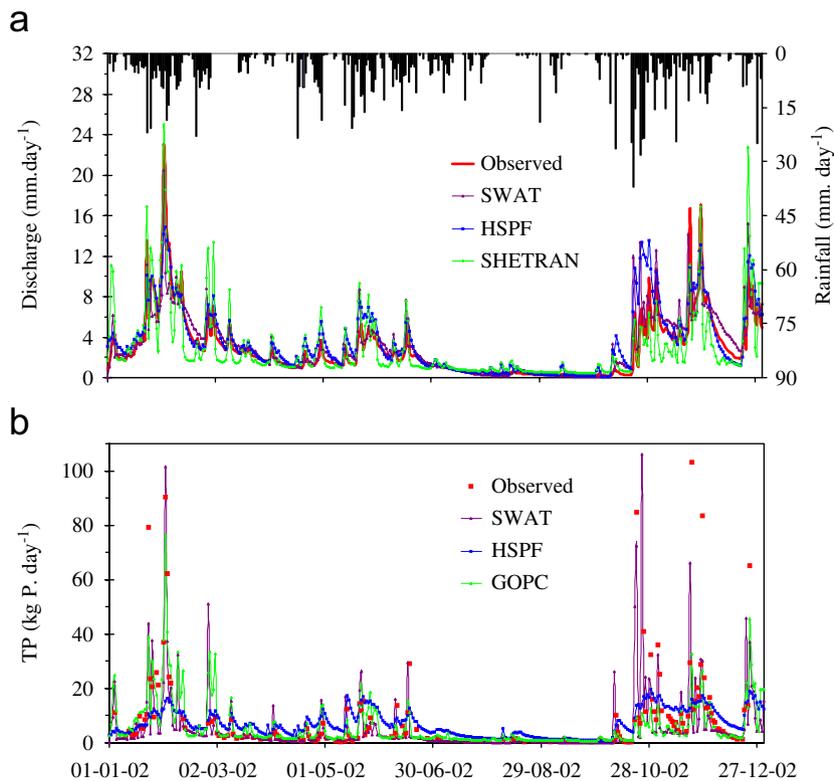


Fig. 2 – Dripsey catchment: results of the three models: (a) flow and (b) total phosphorus load.

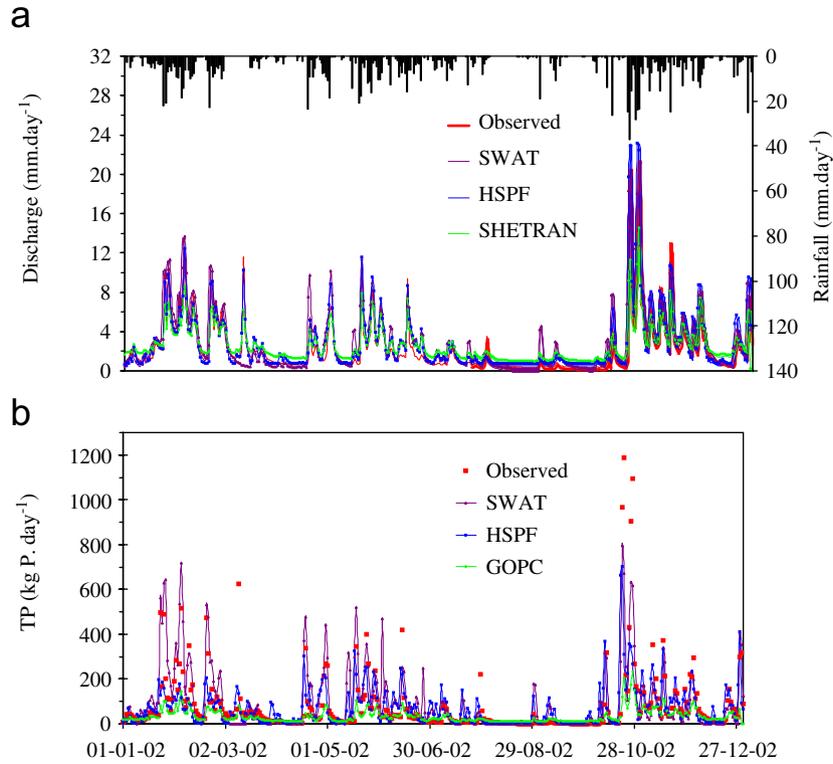


Fig. 3 – Oona water catchment: results of the three models: (a) flow and (b) total phosphorus load.

Table 4 – Values of R^2 and B%MSSE for the flow and phosphorus in the three study catchments

Flow	Observed	Clarianna			Observed	Dripsey			Observed	Oona water		
		Estimated				Estimated				Estimated		
		SWAT	HSPF	SHETRAN		SWAT	HSPF	SHETRAN		SWAT	HSPF	SHETRAN
No. of days	241	241	241	241	365	365	365	365	365	365	365	365
R^2	—	0.91	0.95	0.75	—	0.72	0.74	0.65	—	0.73	0.91	0.80
B%MSSE	—	0.01	0.03	0.07	—	0.03	0.15	0.001	—	0.13	0.25	0.05
<i>Total phosphorus</i>												
		SWAT	HSPF	GOPC		SWAT	HSPF	GOPC		SWAT	HSPF	GOPC
No. of days	143	143	143	143	166	166	166	166	365	365	365	365
R^2	—	0.59	0.45	0.40	—	0.44	0.22	0.51	—	0.56	0.36	0.23
B%MSSE	—	0.03	0.25	0.01	—	0.03	0.01	0.03	—	0.03	0.001	0.11

Table 5 – Values of total phosphorus export (kg P annum^{-1}) in the three study catchments

Catchment	Observed	Estimates from each model				
		SWAT	HSPF	GOPC	DM	ECM
Clarianna	289	231	136	243	448	420
Dripsey	1719	1371	1530	1389	640	1512
Oona	27496	33285	25717	12519	22152	15046

underestimates. In the Dripsey, all models except DM are comparable with the observations, with HSPF being the best. In the Oona, SWAT is the only model that overestimated the TP export although the result is still acceptable. HSPF and DM also give acceptable results, although lower than the ob-

served, whereas the GOPC and EM significantly underestimate.

The results from the three physically-based models are better than the results from the two empirical models. This is not surprising because the empirical models are fitted to a

larger number of different catchments and are an average of the responses over a larger area and have much less catchment-specific information.

9. Conclusions

In the three catchments, the HSPF model was best in simulating the mean daily discharges. Discharge results from SWAT and SHETRAN were acceptable despite occasional deficiencies. Nevertheless, the best simulation for daily TP loads in the study catchments was by SWAT. The TP performance of the SHETRAN/GOPC combination was good although hampered by its discharge simulation. In terms of TP export, no single model was best for all three catchments, however the three physically-based models gave annual TP export estimates closer to the measurements than the two empirical models. In the short term, we recommend using SWAT for TP load estimation.

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