EUTOPHICATION FROM AGRICULTURAL SOURCES:
A COMPARISON OF SWAT, HSPF AND SHETRAN/GOPC PHOSPHORUS MODELS FOR THREE IRISH CATCHMENTS

(2000-LS-2.2.2-M2)

Main Report

Prepared for the Environmental Protection Agency
by

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ABSTRACT

Phosphorus has been implicated as the primary cause of the deterioration of surface water quality in Ireland. Extensive water quality surveys revealed that diffuse sources (runoff and subsurface flows) from agricultural land are the major contributors of phosphorus to surface waters. The mechanism of phosphorus movement from land to water can be described by a number of mathematical models that vary in modelling approaches and scales (plot, field and catchment). In this work three efficient mathematical models of diffuse source pollution in general and of phosphorus in particular have been applied, for the first time, to three Irish catchments (Clarianna (Co. Tipperary), Dripsey (Co. Cork) and Oona (Co. Tyrone)) in order to explore the suitability of these models in Irish conditions for future use in implementing the European Water Framework Directive (WFD). The models are: (i) Soil Water Assessment Tool (SWAT), (ii) Hydrological Simulation Programme FORTRAN (HSPF) and (iii) Système Hydrologique Européen TRAnsport (SHETRAN). The first two include phosphorus modelling components while the third can calculate fields of various hydrological variables relevant to phosphorous modelling. For the latter, a generic phosphorus modelling component called Grid Oriented Phosphorus Component (GOPC) has been developed here to model the phosphorus detachment and transport by taking as inputs the hydrological fields produced by any physically-based distributed catchment model such as SHETRAN.

The three models have been successfully transferred to Irish conditions and this required the build up of a database consisting of topographic, land use and soil maps, water quality and weather data. The models application involved two stages. In the first stage, hydrological variables (evaporation, runoff, etc.) within the catchment domains were simulated by each of the three models. The second stage uses the outputs of the first in order to estimate the amount of phosphorus loss from the catchments.

The SWAT, HSPF, and SHETRAN/GOPC models have been calibrated and then compared and assessed on the basis of their ability to fit and reproduce the flow discharges and phosphorus loads and concentrations for the three test catchments. The

findings from the flow and phosphorus calibrations of SWAT and HSPF models were generally consistent with what has been found from previous studies outside Ireland. However, the simple structure of the first order kinetics method used for phosphorus modelling in HSPF has generally impeded the freedom of the phosphorus calibration which was noticeably difficult. Application of the SHETRAN model to the study catchments has illustrated the importance of carefully assigning the parameters related to the soil water modelling, particularly the parameters of the van Genuchten soil-hydraulic function, in order to obtain the best results. The GOPC performance has been found to depend significantly on the SHETRAN model which provided the required hydrological variables.

The flow comparison has showed that in the three catchments, the HSPF model was the best in simulating the mean daily discharges. Moreover discharge simulation from an independent validation run of the three models in the Oona catchment has also demonstrated the superiority of the hydrological component of HSPF. However, the best calibration results for daily total phosphorus loads in the study catchments have been achieved by the SWAT model. However from the validation in the Oona catchment the HSPF has been found better than the other two models, SWAT and GOPC, in simulating the total phosphorus loads. 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. Simulation of the daily dissolved reactive phosphorus loads by the three models in the study catchments has shown big differences between the simulated and the observed data in most of the cases. Results for mean daily total and dissolved reactive phosphorus *concentrations* from the three models were not as good as the results for the *loads* in the three catchments.

1 INTRODUCTION

1.1 Introduction

This is the main report of research project LS-2.2.2 and deals with the assessment of the existing capabilities of distributed, catchment-based, models in relation to simulating phosphorus export from agricultural catchments. It was not the brief of this project to collect field data itself, so it relied on data provided by a parallel project, LS-2.2.1. In this work, three different types of distributed catchment model were applied to three different Irish catchments and their performances compared. Full descriptions of the catchments and of the type of data used can be found in the report from project LS-2.2.1 and are not repeated here. Where detailed descriptions of the models tested are available in the published literature, these sources are cited and the details are not repeated here. Nevertheless, for the sake of readability, brief summary descriptions of the catchments and models are given here.

1.2 Objectives

This project has targeted one of the WFD objectives (EEC 2000) in Ireland which focuses on controlling non-point phosphorus loss from rural catchments which has been identified as a major target for programmes of measures within River Basin Districts. The project focuses on physically-based catchment scale models which to date have not been applied to model phosphorus losses in Ireland. By providing such models it is hoped that they will support the development of more highly targeted measures for the control of phosphorus loss through an improved understanding of the pathways by which phosphorus is lost to water in catchments. 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.

1.3 Methodology

As shown in Table 1.1 apart from the GOPC component the SWAT (Arnold et al., 1998), HSPF (Bicknell et al., 1997) and SHETRAN (Ewen et al., 2000) 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 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.

The GOPC (Nasr, 2004) development was divided into two stages. The first stage focuses on reviewing previous work on phosphorus modelling in order to select the most appropriate processes and mathematical formulation for the GOPC. In addition performance of the numerical scheme used in solving the GOPC equations is thoroughly investigated. The second stage is coding of the mathematical equations

Table 1.1 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	United States Department of Agriculture, USA	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) (> 3% of catchment area)	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

from the selected processes into a FORTRAN computer code that takes account of the required spatial representation (orthogonal grid) of the catchment. Moreover, the GOPC code must integrate with the flow and sediment outputs from SHETRAN model. Thus GOPC uses the same catchment configuration as SHETRAN. Finally to assess the reliability of the GOPC, the simulated results of the phosphorus variables are compared against the observed data.

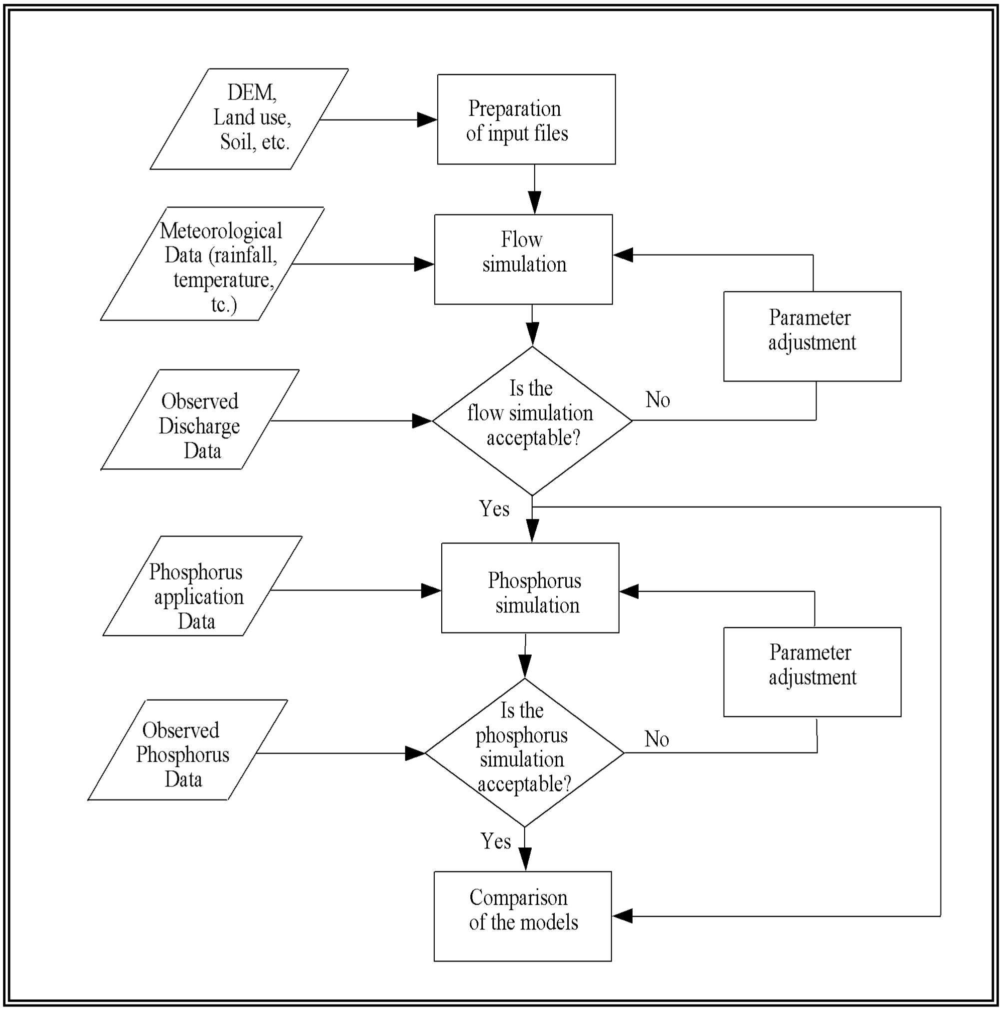


Figure 1.1 Calibration procedure flow chart

(Note: here acceptable means that little further improvement in R^2 or Mean Square Error was possible).

Figure 1.1 is a flow chart summarising 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 are used to run the model. In addition to the spatial input files, the model requires weather data (rainfall, temperature, solar radiation, relative humidity, wind speed, cloud cover) for the flow simulation. The flow simulation is repeated with different model parameters and each time the output is compared with the observed flow data until little further improvement (in R^2 and Mean Square Error) is possible. The resulting flow simulation together with input data on fertiliser applications are used to simulate the phosphorus output from the catchment. Parameters affecting the phosphorus simulation are manually adjusted to find the best simulation. Automatic optimisation procedures, which may have difficulty with complex models, were not used. The best flow and phosphorus simulation results from each model will be used to compare the performances of the three models. Sufficient independent data for model validation was available for the Oona catchment and this was done. There wasn't sufficient data for model validation in the other catchments.

1.4 Organisation of the report

As the main research theme of this study is to assess the physically-based catchment modelling approach in quantifying the phosphorus loss from agricultural catchments in Ireland, it is of vital importance to start this report by discussing the most significant issues relative to modelling phosphorus loss. Therefore Chapter Two of the report is devoted to two main issues about catchment water quality modelling. These issues include the principles and approaches of soil phosphorus modelling. Moreover all elements involved in the process of the phosphorus loss will be reviewed. Brief description for each of the models (SWAT, HSPF, SHETRAN, GOPC) used in this study is also presented in the chapter.

The implementation of the models for the catchment data is documented in Chapter Three. This includes description of the fitting of the models to three catchments and discussion of the calibration of each model in the three catchments. The results of the flow and phosphorus simulations are presented and discussed in Chapter Four. In addition a comparison of the performance of the three models on each catchment is given. The conclusions, which are extracted from the whole research work as well as the recommendations for further work, are also included in the Chapter Four.

2 REVIEW OF CONCEPTS AND APPROACHES TO CATCHMENT WATER QUALITY MODELLING WITH SPECIAL EMPHASIS ON PHOSPHORUS

2.1 Introduction

The aim of the present study is to evaluate and compare the performances of three models in order to use them in the Water Framework Directive implementation in Ireland. Such models are required to assess various catchment management alternatives which will be implemented in order to reduce the impacts of non-point source pollution on water bodies. The most important impact is eutrophication which has been identified as a major water quality problem in Ireland. Thus this chapter starts with an overview of the eutrophication problem in Ireland followed by a general discussion about the two principal causes of the eutrophication, point and non-point source pollution. Then it focuses on nutrients coming from non-point sources and phosphorus in particular. Finally this Chapter discusses the empirical and the physically-based approaches for modelling non-point source pollution.

2.2 Eutrophication problem in some Irish fresh waters

A major cause of eutrophication is the excessive amount of nutrients (mainly nitrogen and phosphorus) in a water body. The relative concentrations of phosphorus and nitrogen in a water body determine which nutrient is the governing (limiting) factor for eutrophication. This is sometimes decided according to the Redfield ratio (Pierzynski et al., 2000) defined as the ratio of the nitrogen to the phosphorus in the water body (N:P) and accordingly, if it is greater than (16:1) the phosphorus would be the limiting factor, while a lower value implies that nitrogen is of great importance. However, phosphorus is generally important in fresh water ecosystems since it is often the nutrient in shortest supply and thus often controls the rate of eutrophication (Srinivasan et al., 1996). For example Lough Neagh, into which the Oona catchment drains, was assessed by Parr and Smith (1976) using bioassays prior and after a phosphorus removal programme in the catchment area. The findings of the assessment affirmatively showed that phosphorus is the only critical nutrient for algal growth in Lough Neagh. The influence of phosphorus on eutrophication was also studied by Young et al. (1999) in three rivers in the UK. They demonstrated with the aid of regression analysis that phosphorus was not the limiting factor for algae growth. The finding agreed with the levels of phosphorus concentrations in the three rivers which appeared to be much greater than levels likely to be limiting.

Whether the limiting factor for eutrophication is phosphorus or nitrogen, the only way to prevent eutrophication from progressing to an unacceptable condition is to control nutrient inputs, both from point and non-point sources.

2.3 Point source pollution

Point source pollution enters a water body at a discrete location (Mander and Forsberg, 2000) making it relatively easy to estimate the amount of polluted materials from these sources. The effluent from these systems has different origins including municipal, industrial, agricultural and combined sewer overflows (Krenkel and Novotny, 1980). Normally there are variations in both the daily and the seasonal load of point source pollution depending on the amount of water consumed by different sectors in the community and on rainfall.

In Ireland, nutrients coming from point sources are considered to be the major cause of serious pollution cases in rivers (McGarrigle et al., 2002). These cases are always associated with disposal of improperly treated wastewater to fresh waters. However, in response to the Urban Wastewater Directive (EEC, 1991) many wastewater treatment plants in Ireland have been upgraded to include a tertiary process and this has resulted in a large reduction of point source nutrients entering the rivers. For example some of the existing wastewater treatment plants in the three catchments, Boyne, Liffey and Suir, studied in the Three Rivers Projects (MCOS, 2002), have received major upgrading. This in turn has influenced the point sources contribution which was estimated to represent only 25%, 22% and 29% of the total river loads in the Boyne, Liffey and Suir catchments respectively. Earlier, Foy and Lennox (2000) noticed a significant reduction in sewage derived phosphorus after 1980 due to the implementation of a phosphorus reduction programme at the largest treatment works in the River Main catchment in Northern Ireland.

Previous studies by the Irish EPA revealed that point source pollution in Irish rivers draining agricultural land is not comparable to diffuse or non-point pollution loss to these rivers and this is the case in the three catchments studied in this work. In the Lough Derg/Ree project, the source of pollution in three mini-catchments including the Clarianna catchment has been managed to reduce nutrient losses to surface waters, the point sources pollution was found to not be significant due to the dominance of the diffuse or non-point source pollution from agriculture land (KMM, 1998). Likewise, studies on fresh waters in the Oona catchment area, e.g. Lough Friary (Jordan et al., 2002), Lough Erne (Zhou et al., 2000), and Lough Neagh (Foy, 1992) in Northern Ireland, indicated that non-point source pollution from agriculture land is the major contributor to these waters. In the Dripsey catchment the effect of point source pollution has not been reported, however, according to the recent national water quality survey (McGarrigle et al., 2002) the main river in this catchment has been classified as unpolluted at the location(s) surveyed, and is not affected by any serious point source pollution. Similarly, the Clariana River does not have any important point sources within the catchment such as towns or industrial discharges. Therefore, this study concentrates on non-point sources of phosphorus and the three catchments chosen for study do not have any significant point sources of pollution. Accordingly, the following review and study work focussed on the non-point or diffusive pollution case only.

2.4 Non-point source pollution

“Non-point source pollution is the introduction of impurities into a surface water body or an aquifer, usually through a non-direct route and from sources that are spatially diffuse in nature” (Leeds et al., 1992). The pollution is difficult to track and characterise though it has been increasingly recognised as a significant problem. The pollutant substances contributing to non-point sources are originally organic compounds measured as COD or BOD, total phosphorus, ammonia and nitrate nitrogen, total nitrogen, pesticides, lead, copper, cadmium, zinc and chromium (Novotny, 1995).

The two major nutrients from agricultural land that cause eutrophication are nitrogen and phosphorus. Nevertheless, phosphorus is typically the more critical nutrient in inland and non-saline waters (Brogan et al., 2001). Nitrate levels in Irish rivers and lakes are generally lower than those of most other European countries due to the predominance of pasture as opposed to tillage as the main agriculture land use (EPA, 2004). Thus in Ireland it is more important to control phosphorus than nitrogen. The main sources of phosphorus from agriculture land are soils, animal wastes (urine and faeces), and plants (Nash and Halliwell, 2000). Other potential sources of phosphorus include urban and industrial runoff, pesticides, effluent from feedlots, and weathering of rock material (Viney et al., 2000). Among all the sources, soil phosphorus has an extremely important influence on non-point source pollution modelling and accordingly it is the major concern of this study.

2.5 Phosphorus in soil

The inputs of phosphorus to a typical agricultural soil are chemical fertilisers, which contribute to the inorganic phosphorus in the soil, and the by-products from agricultural, municipal and industrial areas. Another source of phosphorus input to the soil is crop residues which contribute to both the organic and inorganic phosphorus pools. When phosphorus inputs to agricultural soils exceed outputs in plant biomass and agricultural produce then phosphorus in fertiliser material that is added to the soil tends to be retained and may accumulate from year to year (except for very small areas of sands and organic soils which are relatively poor at retaining phosphorus). As a result of this many soils now contain higher phosphorus levels than required for plant growth (Sharpley et al., 1994; Novais and Kamprath, 1978; Tunney et al., 2000).

Phosphorus can be found in the soil in dissolved, colloidal, or particulate forms with the particulate form being dominant (Stevenson and Cole, 1999). Usually the different forms of the phosphorus in the soil, considered as pools, interact and there is movement of phosphorus between these pools. This phosphorus movement in and out of the soil represents the soil phosphorus cycle (Cole et al., 1977; Barrow and Carter, 1978; Cox et al., 1981; Seligman and Keulen, 1981).

The soil phosphorus cycle in Figure 2.1 (Doody et al., 2005) shows that soil inorganic phosphorus is available in different forms including soluble phosphorus and both labile and stable inorganic phosphorus. Phosphorus in soluble form can be sorbed to the soil mineral particles and it can also be precipitated as stable inorganic phosphorus. Both processes are usually indicated by phosphorus fixation. Phosphorus in mineral particles can be desorbed through a process known as desorbtion.

Moreover, more soluble phosphorus is added through the mineral dissolution that transforms the phosphorus from the inorganic stable form into soluble form. Organic soil phosphorus can exchange soluble phosphorus through two opposite processes, mineralisation and immobilisation. Both reactions are mediated by soil microorganisms and phosphorus uptake by plant roots alone or in association with mycorrhizal fungi.

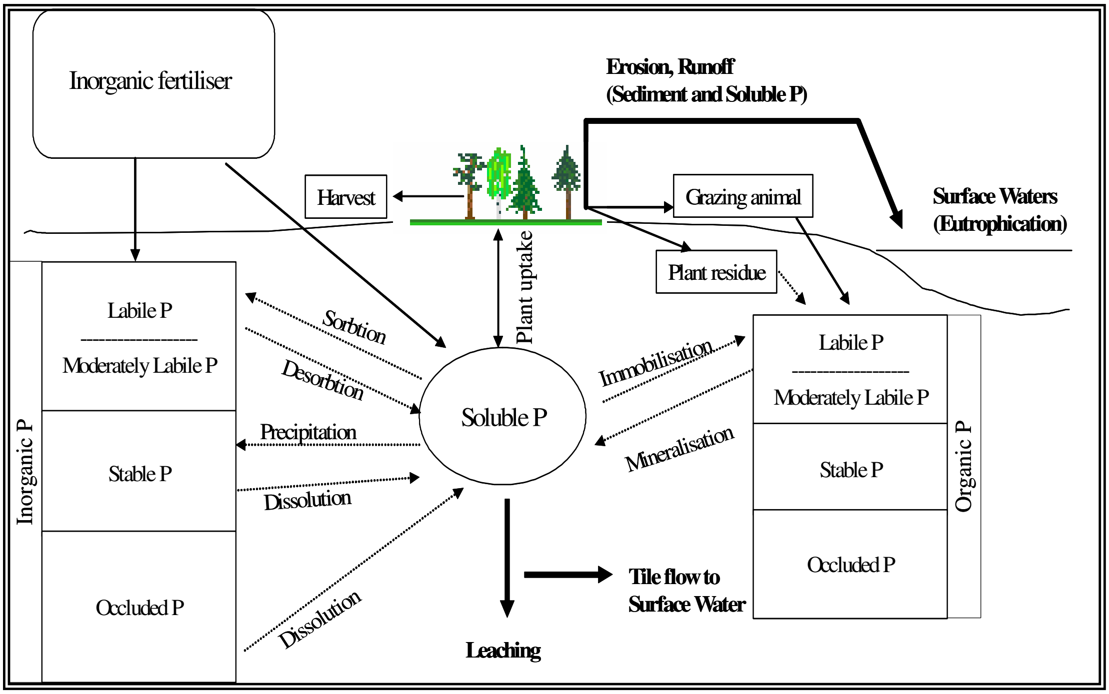


Figure 2.1 The soil phosphorus cycle (Doody et al., internal project document).

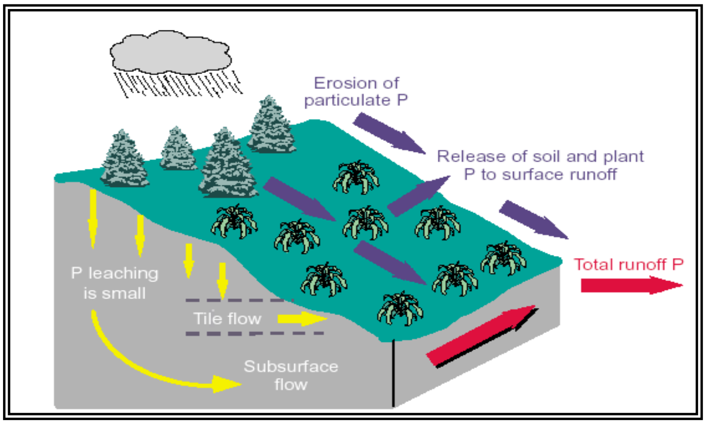


Figure 2.2 Pathways of phosphorus to water bodies (Sharpley et al., 1999).

All forms of phosphorus are susceptible to removal through several mechanisms of water transport over and under the land surface (Figure 2.2). Therefore phosphorus transport is highly affected by the same factors controlling the various water transport mechanisms in a typical catchment. Slope, soil texture and structure, land use, proximity to drainage network and vegetation control the hydrological transfer of phosphorus to water and are included in different ways in each of the models. In addition field drains from agricultural land also discharge phosphorus directly into surface waters via drainage pipes or mole drains (Brogan et al., 2001). Once phosphorus reaches a stream through surface and subsurface pathways, in-stream processes, different from those of the overland and subsurface, usually control its transport to downstream points. Therefore it is possible to differentiate between three mechanisms of phosphorus transport; surface and subsurface transports (in land phase) and the in-stream transport.

2.6 Surface water transport of soil phosphorus

Runoff water dissolves and carries phosphorus from the upper layers in the soil and this is always associated with the removal of fine particles from soils enriched with phosphorus. The mechanisms involved in soluble phosphorus transport are straightforward, and include an initial desorption or dissolution of phosphorus bound by soil particles, followed by water movement from source soil to a stream or river that later intercepts a sensitive water body. The process takes place in the most upper layer, 2 cm, of the soil profile (Cample and Edwards, 2001). Rainfall and the subsequent runoff in storm events provide the energy required to entrain the finer and lighter particles in the soil, thus it is not surprising that clays and organic matter, soil constituents with relative low bulk densities, are preferentially transported in runoff. Sediment particles in runoff have generally higher concentrations of phosphorus (and other nutrients) than the original soil. This enrichment is caused by the greater sorption capacity of the finer-sized clay particles and the relatively higher concentrations of phosphorus in organic matter, relative to silt and sand particles.

2.7 Subsurface water transport of soil phosphorus

In addition to the intrinsic soil phosphorus, the infiltration process assists in bringing more phosphorus material to the soil from the land surface. Normally soils with higher cracking potential are characterised by large crack volumes that accelerate the removal of water with the dissolved phosphorus from the surface to the lower soil horizons where it will join the lateral flow or tile flow and finally reach the surface water (Dils and Heathwaite, 1996). Besides the phosphorus transported with interflow, infiltration also contributes to removing phosphorus from the soil downward to the groundwater which in turn delivers some phosphorus to the surface water through baseflow (Groenendijk, 2002; Pierzynski et al., 2000). In general, transport of particulate phosphorus by subsurface flow is insignificant.

2.8 In-stream transport of phosphorus

Phosphorus exists in a dissolved and particulate state within a stream system. Temporal and spatial changes of these two phosphorus forms in a river occur due to a combination of physical, chemical and biochemical processes (Rauch et al., 1998; Runkel and Bencala, 1995). Therefore by examining the characteristics of water flow, sediment transport and chemical reactions occurring in a stream system, the movement of phosphorus through a stream can be understood. These considerations usually render the study of the in-stream phosphorus dynamics very complex. Add to this complexity the fact that macrophytes and benthic algae in the stream interact with phosphorus during its transport and hence they must be considered. The interaction of moving phosphorus in stream with bed sediment and other substances results in loss (retention) and/or gain (release) in the amount of phosphorus received from the land phase.

The in-stream transport of phosphorus is not covered in the modelling work in this study due to the complexity of modelling in-stream phosphorus transport. However, it will be assumed that the phosphorus material received from the land phase gains and loses equal amount of phosphorus during its in-stream transport and hence the available phosphorus data at the outlet of each catchment can be compared directly with the total amount of the estimated phosphorus load from the land phase. Accordingly the catchments chosen are relatively small to reduce the effect of in-stream processes on the results. Catchments with lakes are not considered either as they generally act as a sink for phosphorus.

2.9 Approach to modelling non-point source loss from the catchment

As shown in Figure 2.3, modelling approaches to non-point source loss from catchments can be classified into two main types, (i) empirical (data-derived) relationships and (ii) physically-based (process-based or mechanistic) modelling.

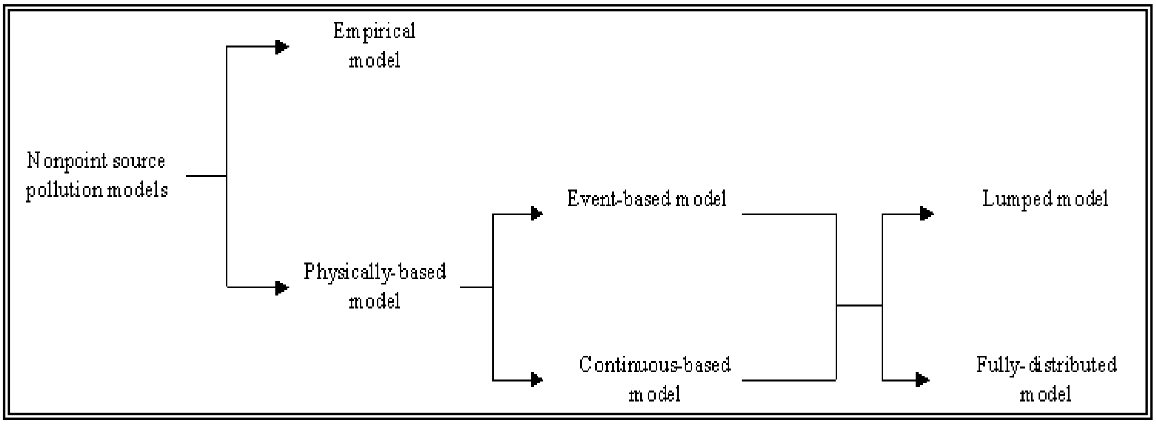


Figure 2.3 Classification of non-point source pollution models.

When reliable data are available covering long period of time an empirical model can be established to relate certain water quality parameters with other catchment characteristics. There is no unique empirical non-point source pollution model that can be used absolutely to deal with problems different from the one which the model has been developed for. A variety of results can, however, be obtained from such models. The physically-based approach can be looked at as a descriptive modelling approach, that is modelling with the objective of achieving a better understanding of the physical and chemical processes involved in non-point source pollution transport and fate. Moreover it is possible to differentiate between two types of physically-based models, as shown in Figure 2.3, according to the time scale of the resulted outputs, namely continuous and event oriented models (Novotny, 1986). Regardless of whether the model is event-based or continuous, the parameters required by each can be used as an additional feature to differentiate between physically-based models. Therefore a model can be either based on the lumped or distributed parameters (Figure 2.3) and this in turn controls the spatial discretisation of the catchment.

In general the physically-based models vary in their structure and approach of non-point source pollution modelling, particularly the three main components (water, sediment, and phosphorus) required for modelling phosphorus loss. In addition to the models, SWAT, HSPF, SHETRAN, and GOPC used in the present study, some other popular models can be found in Donigian and Huber (1991) and Donigian et al. (1995a). A brief review for each of these models is given below.

2.10 SWAT model

SWAT is a continuous model working at the basin scale to look at the long term impacts of management and also timing of agricultural practices within a year on water, sediment, and agriculture chemical yields in large ungauged basins (Arnold et al., 1998). The model consists of a number of interconnected components which are capable of describing most of the water transport processes involved in the non-point source pollution modelling using readily available data from ungauged catchments. In addition the model has many other relationships to simulate transportation of sediment, nutrients (nitrate and phosphorus), pesticides, bacteria.

The smallest unit in the spatial scale of SWAT model is the Hydrologic Response Unit (HRU) which has a uniform land use and soil type without referencing to its spatial positioning within each sub-catchment. In SWAT model, the water balance of each HRU is represented by four storage volumes; snow, soil profile (0-2m), shallow aquifer (typically 2-20 m), and deep aquifer (>20 m) (Arnold et al., 2000). The water hydrology component of the model simulates most of the hydrological processes occurring during the water movement in its path to the outlet of the catchment, Figure 2.4.

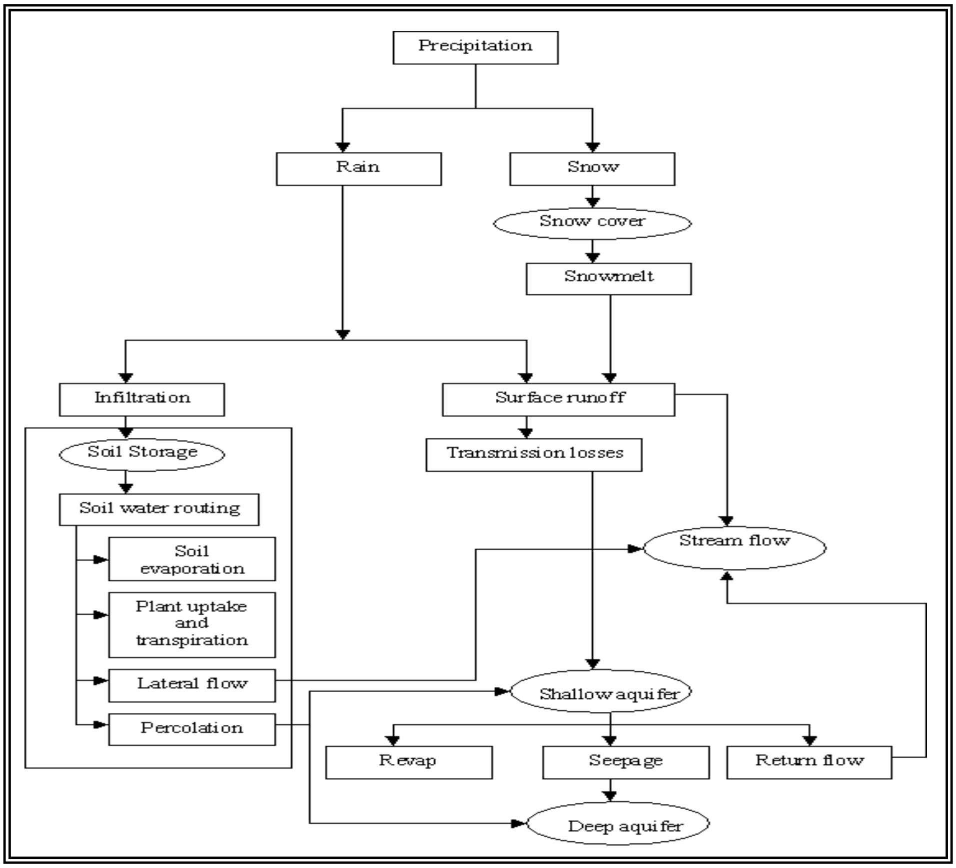


Figure 2.4 Pathways of water movement in SWAT (Neitsch et al., 2001).

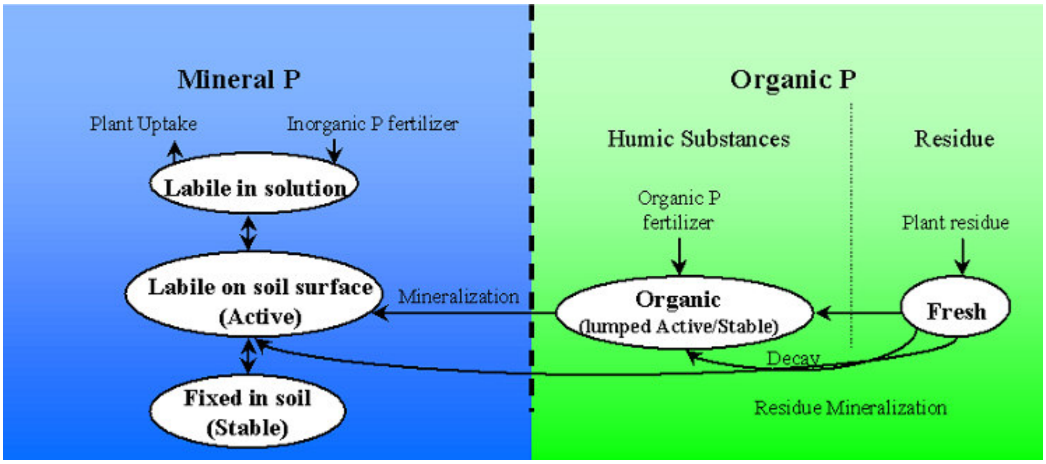


Figure 2.5 Soil phosphorus cycle in SWAT (Neitsch et al., 2001).

In addition to water movement, chemical and sediment materials are generated from their sources at the local space in the HRU and then transported with the runoff water to the tributary channels. They can be routed further downstream to the main channel in the sub-catchment and thereafter to the outlet point through the main catchment's channel. The soil phosphorus cycle in the model is described by Figure 2.5.

2.11 Hydrologic Simulation Program – FORTRAN (HSPF) model

In the model, the catchment area is divided into different land segments each of which is assumed to react uniquely to any external inputs. The land segments do not necessarily have to be contiguous but still they can be connected to each other depending on the catchment topography. Any land segment in the catchment may be either fully or partially pervious and therefore it can consist of pervious and impervious portions which have different hydrologic behaviour. While the pervious land has a capacity to allow enough infiltration to influence the water budget, the impervious land has no significant infiltration effect on the water budget. One or more land segments can drain into the same surface water body. The HSPF has a flexible approach which copes with any type of surface water body whether it is a river, channel, or a completely mixed lake/reservoir. Basically there are three main modules in HSPF, namely PERLND, IMPLND, and RECHRES, to simulate water, sediment, and chemical processes in the pervious land, the impervious land, and the surface water body respectively.

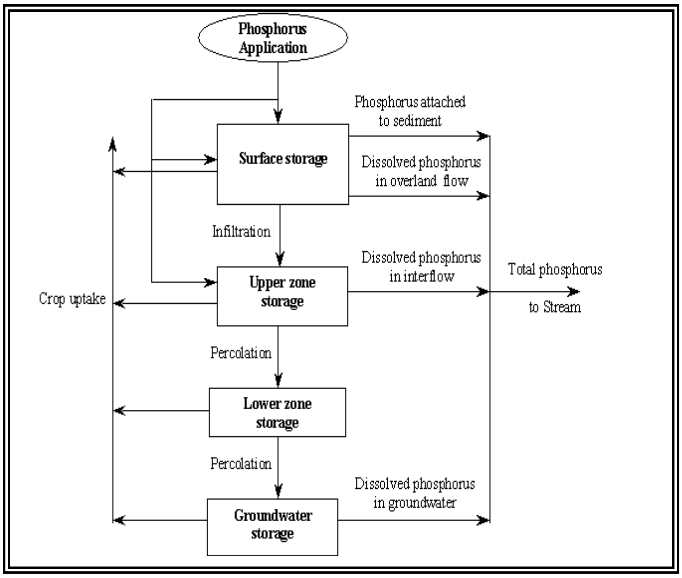


Figure 2.6 Modelling of phosphorus transport in HSPF model.

Movements, chemical and biochemical reactions for various elements including phosphorus can be simulated in agri-chemical section of PERLND module. Figure 2.6 summarises the pathways of phosphorus movements from the soil.

2.12 SHETRAN Model

In the SHETRAN model the spatial distribution of catchment parameters, rainfall input and hydrological response is achieved in the horizontal direction through the representation of the catchment by an orthogonal grid network and in the vertical direction by a column of horizontal layers at each grid square. The model can be characterised by its comprehensive nature and capabilities for modelling subsurface flow and transport (Ewen et al., 2000). The subsurface is treated as a variably saturated heterogeneous porous medium, and fully three-dimensional flow and transport can be simulated for combinations of confined, unconfined and perched systems. The unsaturated zone is modelled as an integral part of subsurface flow. Subsurface flow and transport are coupled directly to surface flow and transport. Further addition to the existing components in the version of SHETRAN derived from the SHE model were continued to include three major new components, a sediment component, a contaminant transport component and a nitrogen transformation component.

2.13 Grid Oriented Phosphorus Component (GOPC)

The Grid Oriented Phosphorus Component (GOPC) for modelling the phosphorus loss from agriculture land was developed by the authors to incorporate accounting procedures for simulating the changes in the soil phosphorus variables and in the surface phosphorus variables caused by overland flow. The GOPC has been written for any rectangular grid, and can be used with any hydrological model which provides the required variables. In the present study, SHETRAN is used as a supplier of the hydrological variables for the GOPC. However note that the GOPC works independently from SHETRAN, i.e. it is not incorporated in SHETRAN.

Following the soil phosphorus cycle described earlier, the soil phosphorus state variables in the GOPC consist of the soil soluble phosphorus (SSP), the fresh organic phosphorus (FROP), the fixed organic phosphorus (FXOP), the easily soluble inorganic phosphorus (ESIP), and the fixed or insoluble inorganic phosphorus (FIP). The phosphorus in overland flow is carried in two forms, dissolved phosphorus (DP) and particulate phosphorus (PP). In total there are five state variables for the soil phosphorus and two more state variables for the two phosphorus forms that exist in overland flow. The internal interactions between the soil phosphorus state variables and the overland phosphorus state variables as well as the external interaction between them for the proposed procedure are illustrated in Figure 2.7. Moreover, Table 2.1 summarises the description of the phosphorus fluxes between the various storages. For each variable in the GOPC, a mass balance equation is formulated to link the rate of change of the storage with the input and the output fluxes. The mass balance equations for all the soil phosphorus states variables are ordinary differential equations while all of the overland flow phosphorus states variables are represented with partial differential equations.

The outputs calculated by the GOPC can be divided into two groups. First the soil phosphorus group and these are particularly important if observed data for some or all of the simulated soil phosphorus variables are available. The output results in this group represent average values over the soil profile for the five soil phosphorus pools. In the second group, loads and concentrations of the overland phosphorus variables are estimated. Phosphorus received by the river comprises of three components, subsurface soluble phosphorus, overland dissolved phosphorus and overland sediment attached phosphorus.

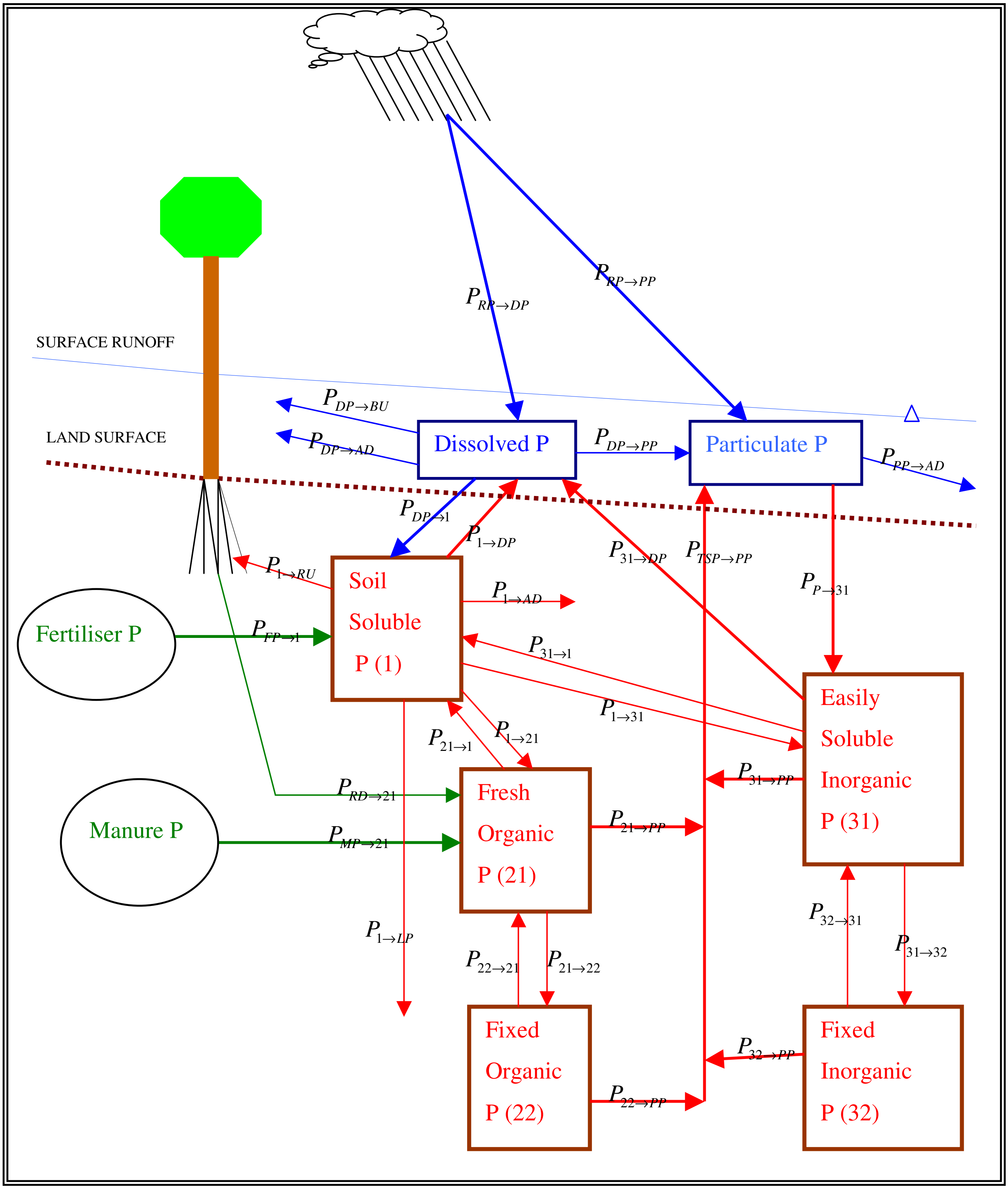


Figure 2.7 The GOPC conceptual representation for phosphorus processes occurring in the soil and during transport (Nasr, 2004).

Table 2.1 Description of the phosphorus fluxes in the GOPC (Nasr, 2004).

Code in Figure 2.7	Flux (gP. m^{-2} min^{-1})
$P_{FP\rightarrow 1}$	**Input of fertiliser to the soil soluble phosphorus storage**
$P_{DP\rightarrow 1}$	**Infiltration of dissolved phosphorus from the overland flow into the soil**
$(P_{21\rightarrow 1} - P_{1\rightarrow 21})$	**Net flux of the mineralisation/immobilisation processes**
$P_{1\rightarrow RU}$	**Root Uptake of phosphorus from the soil soluble phosphorus**
$P_{1\rightarrow LP}$	**Loss of soil soluble phosphorus by the leaching process**
$P_{1\rightarrow AD}$	**Advection transport of soil soluble phosphorus**
$P_{1\rightarrow DP}$	**Dissolution of soil soluble phosphorus in the overland water**
$(P_{1\rightarrow 31} - P_{31\rightarrow 1})$	**Net flux of the adsorption/desorption processes**
$P_{MP\rightarrow 21}$	**Input of manure and other sources of organic phosphorus to the soil fresh organic phosphorus**
$P_{RD\rightarrow 21}$	**Input of phosphorus from the decayed roots to the soil fresh organic phosphorus**
$P_{21\rightarrow 22}$	**Decaying of the soil fresh organic phosphorus that added to the soil fixed organic phosphorus**
$P_{22\rightarrow 21}$	**Decomposing of the soil fixed organic phosphorus that added to the soil fresh organic phosphorus**
$P_{21\rightarrow PP}$	**Input from the soil fresh organic phosphorus detachment to the particulate phosphorus**
$P_{22\rightarrow PP}$	**Input from the soil fixed organic phosphorus detachment to the particulate phosphorus**
$P_{FP\rightarrow 1}$	**Input of fertiliser to the soil easily soluble inorganic phosphorus storage**
$P_{PP\rightarrow 31}$	**Input of the particulate phosphorus deposition from overland flow water to the soil easily soluble inorganic phosphorus storage**
$(P_{31\rightarrow 32} - P_{32\rightarrow 31})$	**Net flux of the precipitation/desorption processes between the soil easily soluble inorganic phosphorus and the soil fixed inorganic phosphorus**

$P_{31 \to PP}$	**Input from the soil easily inorganic phosphorus detachment to the particulate phosphorus**
$P_{31 \to DP}$	**Desorption of soil easily inorganic phosphorus that enters the overland flow dissolved phosphorus**
$P_{32 \to PP}$	**Input from the soil fixed inorganic phosphorus detachment to the particulate phosphorus**
$P_{RP \to DP}$	**Input of phosphorus from the rainfall water to the overland flow dissolved phosphorus**
$P_{DP \to PP}$	**Adsorption of the overland flow dissolved phosphorus into the overland flow particulate phosphorus**
$P_{DP \to BU}$	**Loss of the overland flow dissolved phosphorus due to biological uptake in the overland flow water**
$P_{DP \to AD}$	**Advection of the overland flow dissolved phosphorus**
$P_{TSP \to PP}$	**Total input from the soil detached phosphorus to the overland flow particulate phosphorus**
$P_{RP \to PP}$	**Input of phosphorus from the rainfall to the overland flow particulate phosphorus**
$P_{PP \to AD}$	**Advection of the overland flow particulate phosphorus**

3 IMPLEMENTATION OF SWAT, HSPF, AND SHETRAN/GOPC ON THE STUDY CATCHMENTS

3.1 Introduction

The performance of each of the three tested models is assessed for three Irish catchments (Clarianna, Dripsey, and Oona) which have been chosen due to the availability of the data needed by the models and because they represent different climates, land use and soil type. This variety may help in identifying the model which performs better in the Irish conditions if exists. The three study catchments are located in three out of the seven Irish River Basin Districts and International River Basin Districts (RBDs and IRBDs) in which the European Water Framework Directive management will be implemented or partly implemented b the Republic of Ireland in conjuction with Northern Ireland. Looking at the catchment locations in the Irish RBDs map, Figure 3.1, the Clarianna catchment is approximately in the middle of Ireland, in county Tipperary which is located in the Shannon RBD, the Dripsey catchment is in the Southern RBD in county Cork, and the Oona catchment is in the North Eastern RBD in county Tyrone. The latter is an international RBD shared between the Republic and Northern Ireland. Both the Clarianna and the Oona catchment are some distance from the coast while the Dripsey catchment is within 25 km of the coast.

The geographic location of the catchments influences the amount of rainfall in each because, in Ireland, the main factors in shaping the climate are the westerly atmospheric circulation of middle latitudes and the Atlantic Ocean which lies to the north, west and south of the country (Rohan, 1986). Therefore when projecting the three catchments onto the map of the long-term average annual rainfall in Ireland (Figure 3.2) the annual average rainfall in the Clarianna and Oona catchments is 1000 mm while the Dripsey catchment has an annual average of 1200 mm. These figures compatible with the shorter term averages for their measuring period given by Kiely et al. (2005) who reported values of 925, 1470, and between 800 to 1000 mm for annual rainfall values in the Clarianna, Dripsey, and Oona respectively. Likewise average values for evaporation loss in the study catchments can be obtained from the map of average estimated actual evapotranspiration as a percentage of annual rainfall

(Mills, 2000), Figure 3.3. Multiplying the percentage values of actual evapotranspiration in Figure 3.3 by the corresponding rainfall values in Figure 3.2 indicates that the annual evapotranspiration is 480 mm in the Clarianna and Dripsey catchments while in the Oona catchment this value varies between 360 mm and 440 mm. The above evapotranspiration values are slightly higher than those reported by Kiely et al. (2005).

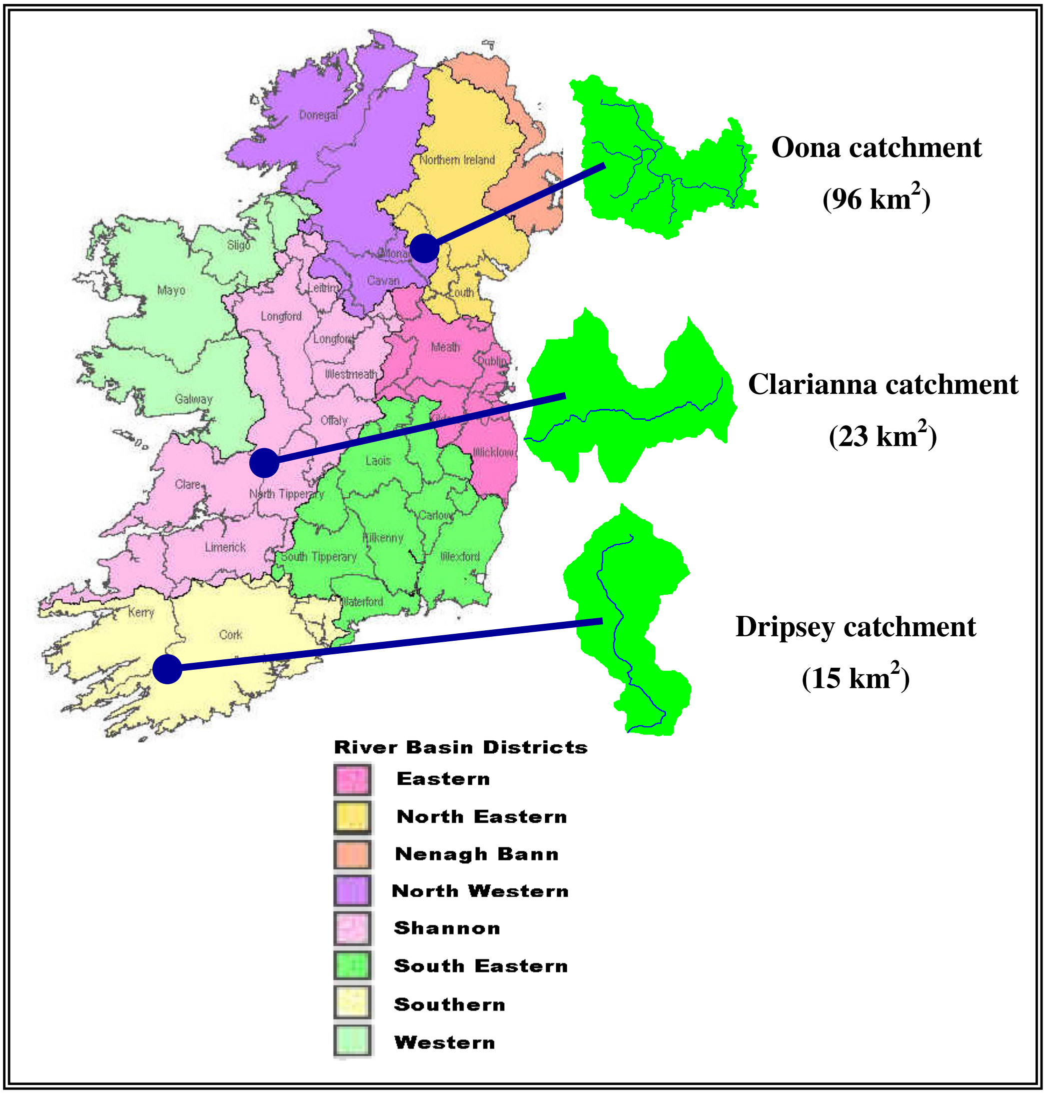


Figure 3.1 Location of the study catchments in the Irish River Basin Districts map (RBDs map adapted from http://www.wfdireland.ie/).

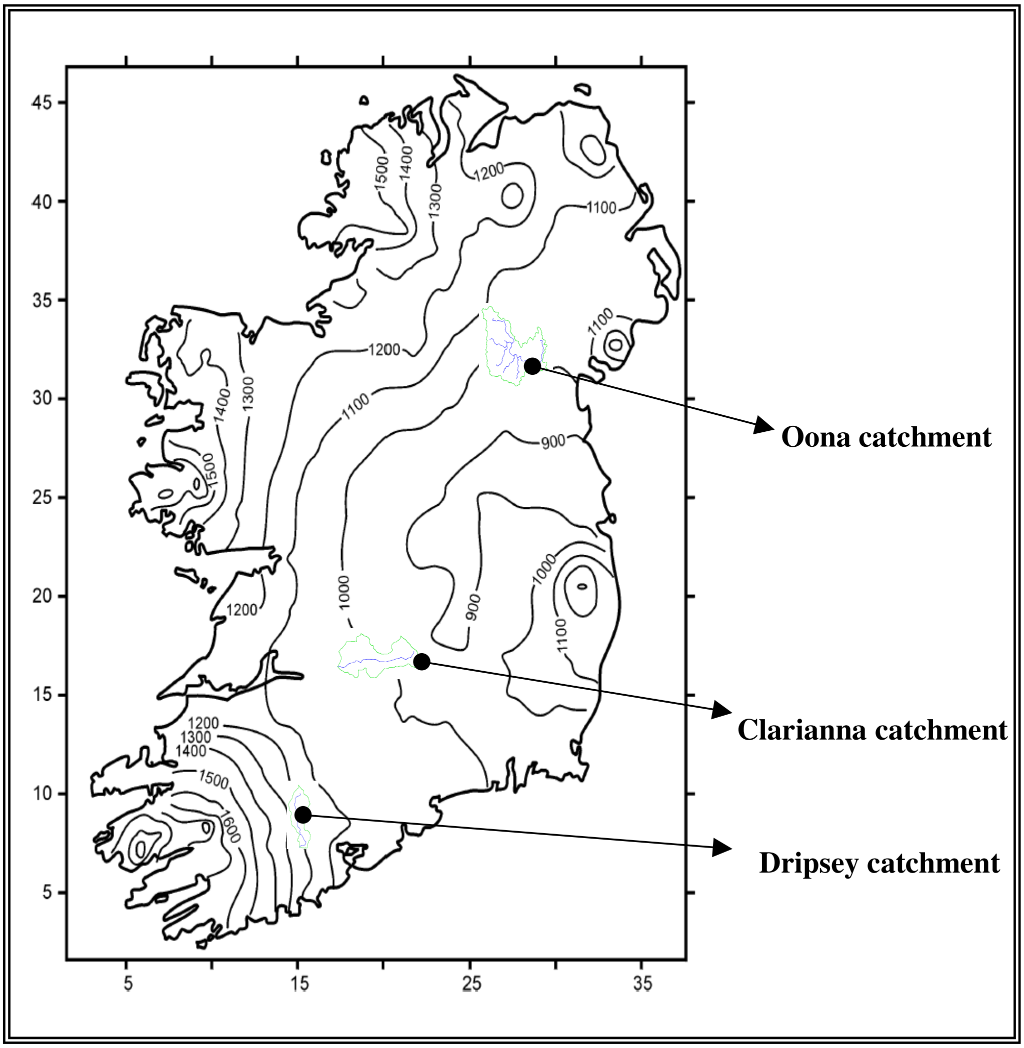


__Figure 3.2 Projection of the study catchments on a map of the average annual rainfall (Mills, 2000).__

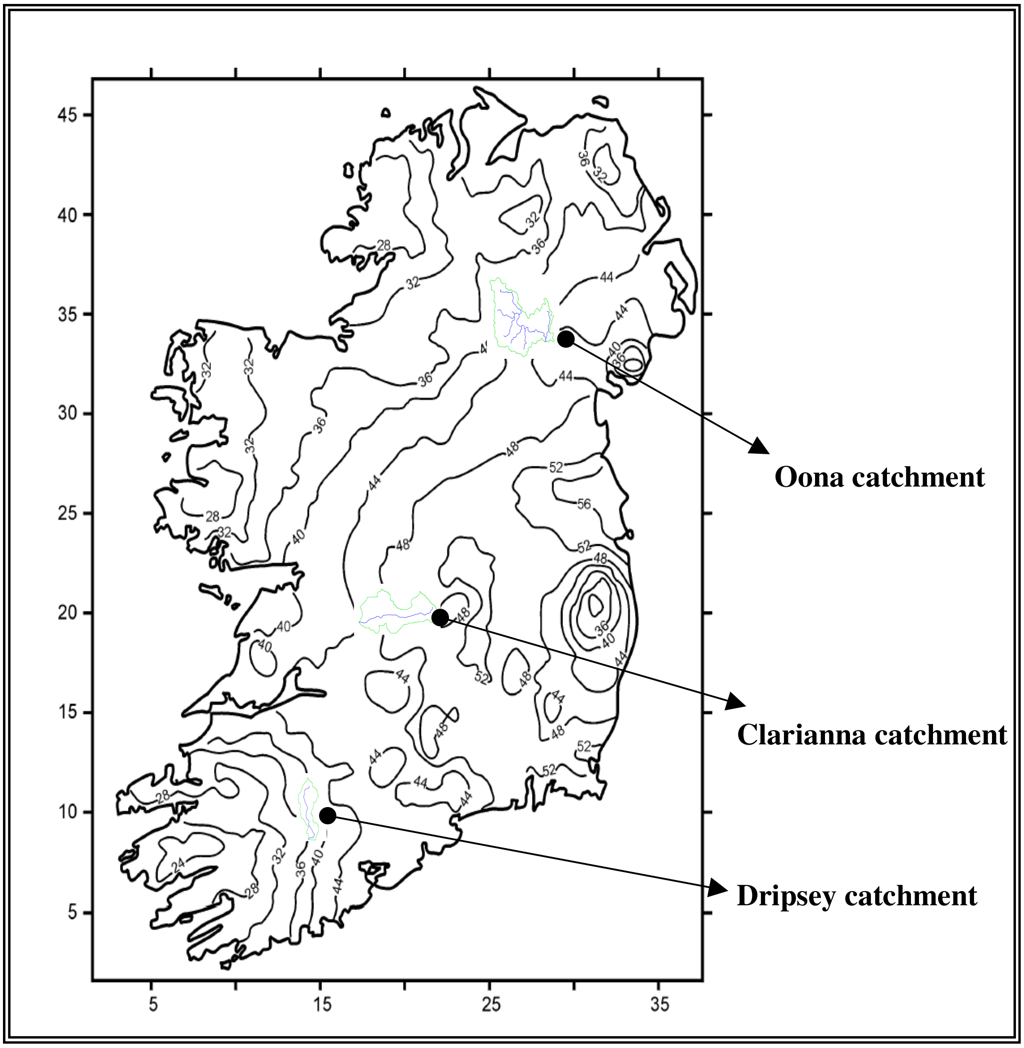


Figure 3.3 Projection of the study catchments on a map of the annual average estimated evapotranspiration as a percentage of annual rainfall (Mills, 2000).

A significant contribution to non-point source pollution and particularly phosphorus has been attributed to the activities associated with grassland in Ireland. The main land use type in the three study catchments is generally the grassland with pasture as a principal activity though other types of crops are also grown. Another factor is the significant amount of rainfall which represent the driving force for the transport of phosphorus from the catchments. In addition, other hydrological related variables like soil properties, topography, weather and climate conditions play important roles in the processes of transporting the phosphorus from the soil and hence raising the phosphorus levels in the main streams of the catchments. These catchment characteristics are discussed for each of the study catchments in the following sections.

3.2 Data used in implementing the models on the study catchments

The availability of spatial data for the three study catchments (Clarianna, Dripsey, Oona) has greatly facilitated the implementation of SWAT, HSPF, and SHETRAN/GOPC models in each of the catchments. The spatial data includes a digital elevation model (DEM), land use map, and soil map. The DEM for the Clarianna and the Dripsey catchment are available at a good resolution, 20 by 20 m, while the one for the Oona catchment has a resolution of 50 by 50 m. The map scales used were the best readily available for each catchment. We did not investigate the use of coarser scales. The land use map has been extracted from the CORINE land use map (CORINE, 1989) which classifies the land according to the dominant use. Four major land classes (agriculture, forest, urban, and wetland) have been categorised each of which has a number of subclasses. The general soil map of Ireland (Gardiner and Radford, 1980) has been used to obtain the soil map for each catchment. Each polygon in the soil map represents certain soil type which composes of a combination of some of the great soil groups in the country. These groups are soils having the same kind, arrangement and degree of expression of horizons in the soil profile and they also have close similarity in soil moisture and temperature regimes and in base status (Coulter et al., 1998).

In addition to the spatial data, other meteorological data including rainfall, temperature, solar radiation, relative humidity, and wind speed, is required to build the input files used in running the three models. These data in the three catchments was collected as part of a partner research project, in the large scale Environmental Research and Technical Development Innovation programme project entitled Agricultural Eutrophication (LS-2.1.1.) funded by the EPA and Teagasc under the Irish National Development Plan.

3.3 Fitting of the models on the study catchments

Fitting of the models on the study catchments consists of three steps. The first step is mainly preparation of the database used in estimating the physical parameters related to topography, soil and land use for each model. The second step is needed to perform the spatial discretisation of the catchments into smaller units. For the three catchments, the spatial subdivision in each model was done in accordance with the available recommendations from previous international (but not Irish) studies on sensitivity of the models to the spatial scale. However, in the case of the HSPF model where these studies are not found the spatial discretisation matched as much as possible the ones used in previous applications of this model. Finally in the third step, configuration of each unit in the spatial discretisation is defined.

3.3.1 Fitting the SWAT model

The version of SWAT, which has been used in testing the model in the study catchments (Clarianna, Dripsey and Oona), is SWAT2000, the most recent version so far. The preparation of all the input files to run the model on the study catchments has been done using the ArcView SWAT (AVSWAT) GIS interface (Srinivasan and Arnold, 1994). There are enough data on each catchment to enable the model to simulate the flow and the phosphorus variables.

Most of the required properties in the soil database of the SWAT model have been compiled from an explanatory bulletin of the soil map of Ireland (Gardiner and Radford, 1980), the SWAT user's manual (Neitsch et al., 2001) and other sources, as described below. The saturated hydraulic conductivity, soil hydrologic group, porosity, and water content at both field capacity and wilting point for each soil type were obtained from tables (Rawls et al., 1993; Neitsch et al., 2001) relating them with the soil texture. The field capacity and the wilting point water contents were then used to calculate the available water content as the difference between the two values. The moist bulk density and the soil erodibilty factor were estimated from the equation cited by Neitsch et al. (2001).

The AVSWAT interface was used to input the CORINE land use maps of the study catchments and convert them into the SWAT types by using a user-defined table. Any land use type in the CORINE map without an exact corresponding type in the SWAT database has been linked to a most probable type in the database. The nomenclature definitions of the existing land use types in the CORINE map (CORINE, 1989) has been used to establish the comparison with the SWAT database and hence reducing the subjectivity in allocating the SWAT land use type to those in the CORINE land use.

The weather data required to run SWAT are all available for the study periods. However, it was necessary also to generate synthetic weather data for making runs outside the period of the observed data, e.g. to assist with specifying suitable initial conditions. Since there is no station in the vicinity of the three catchments with long time series data which can be used to estimate the monthly statistics required by the built-in weather generator, data from two stations in the same regions of the three catchments have been used. The station at Cork airport is close to the Dripsey catchment while station at Birr is close to both the Clarianna and the Oona catchment. The sources of the data of the two stations were the MET ÉIREANN web site (http://www.met.ie/) and summarised by Rohan (1986). The data obtained from the two stations include monthly averages of rainfall, maximum and minimum temperature, solar radiation, wind speed and relative humidity.

To define the configuration of the study catchments in SWAT, the available DEMs were used first to delineate the shape of each catchment and its main streams. Then, where appropriate, each catchment has been divided into a number of sub-catchments and after that the land use and the soil maps have been used to define separate HRUs within each sub-catchment. The Clarianna catchment has not been divided into any sub-catchments because of its geological and landuse uniformity. Hence a lumped catchment was used with average slope of 0.03 (m/m), length of the main channel of 12.7 km and the slope of the main channel of 0.001 (m/m). In contrast the Dripsey was divided into three sub-catchments according to the three measuring points in this catchment. The Oona catchment has eight main streams and these streams were used to divide the catchment into eight sub-catchments. The HRUs subdivision have been accomplished using land use threshold values of 5% in the case of Clarianna and 20% in the case of Dripsey and Oona catchments while the soil thresholds values were 3%

in the case of Clarianna and 10% in the case of Dripsey and Oona catchments. The reason for using a smaller threshold for the land use and soil in the Clarianna catchment is that a lumped catchment (no division into sub-catchments) configuration was used and hence as many HRUs, which can obtained within this lumped catchment, as possible are allowed for in order to account for the spatial heterogeneity.

As Table 3.1 shows that three HRUs in the Clarianna catchment. Each of these has the same soil type but with different land use types. Two of the three sub-catchments in the Dripsey catchment were further divided into two HRUs while the third one was represented by a single HRU. In the Oona catchment, only 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. The values of the sub-catchment average slope steepness, main channel length and slope are summarised for the Dripsey and Oona catchments in Tables 3.2 and 3.3. Also the land use type, soil type and area of the HRUs in two catchments were added to the same tables.

Table 3.1 Summary of HRUs in Clarianna catchment.

HRU No.	1	2	3
Area of HRU (ha)	160	1925	210
Land use type	Non-irrigated arable land	Pasture	Annual crops associated with permanent crops
Soil type	Soil31 (*)		

*: Grey Brown Podzolics (80%), Gleys (10%), Brown Earths (5%), Basin Peats (5%).

Table 3.2 Summary of sub-catchments and HRUs in Dripsey catchment.

Sub-catchment No.	1		2		3
Sub-catchment area (ha)	1281		148		58
Sub-catchment Average slope steepness (m/m)	0.05		0.05		0.05
Sub-catchment main channel length (km)	10.3		2.2		1.4
Sub-catchment main channel slope (m/m)	0.01		0.02		0.05
HRU No.	1	2	3	4	5
Area of HRU (ha)	751	530	58	90	58
Land use type	Pasture		Pasture		Pasture
Soil type	Soil6 (**)	Soil15 (***)	Soil1 (*)	Soil6 (**)	Soil1 (*)

*: Soilprop1: Peaty Podzols (75%), Lithosols (15%), Blanket Peats (10%)
**: Soilprop6: Brown Podzolics (60%), Gleys (15%), Podzolics (5%)
***: Soilprop15: Brown Podzolics (60%), Acid Brown Earths (20%), Gleys (20%)

Table 3.3 Summary of sub-catchments and HRUs in Oona.

Sub-catchment No.	1	2		3	4	5			6		7		8
Sub-catchment area (ha)	1441	1088		618	975	2066			1329		1018		1072
Sub-catchment average slope (m/m)	0.08	0.08		0.08	0.08	0.08			0.08		0.08		0.08
Sub-catchment main channel length (km)	9.0	6.4		7.0	7.6	11.2			8.0		8.4		8.0
Sub-catchment main channel slope (m/m)	0.01	0.01		0.02	0.01	0.01			0.02		0.01		0.01
HRU No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Land use type	Pasture		Agriculture with natural vegetation		Pasture							Complex cultivation	Pasture
Soil type	Soil27 (***)	Soil27 (***)	Soil27 (***)	Soil27 (***)	Soil27 (***)	Soil27 (***)	Soil29 (****)	Soil12 (**)	Soil1 (*)	Soil27 (***)	Soil12 (**)	Soil12 (**)	Soil27 (***)
Area of HRU (ha)	1441	821	266	618	975	980	539	546	175	1155	701	317	1072

*: Soilprop1: Peaty Podzols (75%), Lithosols (15%), Blanket Peats (10%)
**: Soilprop12: Acid Brown Earths (70%), Gleys (25%), Podzolics (5%)
***: Soilprop27: Gleys (85%), Interdrumlin Peats and Peaty Gleys (15%)
****: Soilprop29: Acid Brown Earths (75%), Interdrumlin Peats and Peaty Gleys (25%)

3.3.2 Fitting the HSPF model

HSPF has a user-friendly Windows interface called WinHSPF (Duda et al., 2001) which was used to build and edit the User's Control Input (UCI), the major input file to the model. Before building the UCI file with WinHSPF, two preparatory steps in the BASINS package (USEPA, 2001) were required. First, the catchment and sub-catchment boundaries and the stream network were obtained from the DEM in a similar manner as for SWAT model. Then for each sub-catchment the actual land use types were converted into the corresponding HSPF types using a user defined table in a similar way to the creation of the HRUs in SWAT. After finishing the preparatory steps, BASINS was used to create some input files which are essential to building the UCI file. The purpose of these files produced in BASINS is to convert information from the GIS data into a form readable by the external program WinHSPF that interacts with BASINS to build the UCI file.

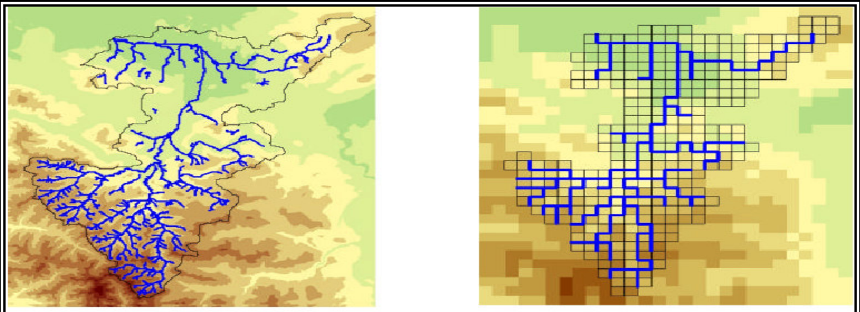
The same procedure used in SWAT to divide the study catchments into sub-catchments was also applied in the BASINS. Therefore the same shape and characteristics for the sub-catchments and stream networks were obtained. Table 3.4 shows the existing types in the CORINE map and the equivalent HSPF land use types for the Clarianna, Dripsey and Oona catchments. The required input times series data to the model was weather data including rainfall, solar radiation, temperature, dew point temperature, wind speed, cloud cover, evaporation and potential evapotranspiration. Furthermore chemical input data was used to model the application of fertiliser.

Table 3.4 Summary of HSPF land use types in Clarianna, Dripsey, and Oona.

CORINE land use type	HSPF land use type	Area occupied by HSPF land use type (ha)		
		Clarianna	**Dripsey**	**Oona**
Pasture land	Pasture land	1715	1159	8157
Complex cultivation	Range land	345	202	1125
Land principally occupied by agriculture	Range land			
Non-irrigated arable land	Agriculture land	178	81	25
Peat bogs	Wet land	-	-	128
Broad-leaved forests	Forest land	-	13	58
Mixed forests	Forest land	-	-	
Mineral extraction sites	Urban land	-	31	84
Discontinuous urban	Urban land	-	-	
Sport and leisure facilities	Urban land	28	-	-
Inland marshes	Wet land	28	-	-
Water bodies	Water	-	-	7

3.3.3 Fitting the SHETRAN/GOPC model

An example for a typical shape of a catchment and streams network along with their representation in the SHETRAN model are shown in Figure 3.4.a and 3.4.b respectively. For all the study catchments, the orthogonal grid characterising each catchment has been created using the shape of the catchment obtained from the delineation process. The characteristics of the grids and the stream networks links, which have been used to run SHETRAN model on the study catchments, are presented in Table 3.5.



(a) Actual shape (b) Model representation

Figure 3.4 Grid and streams network representation to a catchment in the SHETRAN model (Adapted from WRSRL, 2000).

Table 3.5 Characteristics of grids and stream network links in Clarianna, Dripsey, and Oona.

Catchment	**Cell size (m x m)**	**No. of columns**	**No. of rows**	**No. of computational elements**	**No. of links**
Clarianna	200×200	51	23	571	160
Dripsey	200×200	19	39	366	55
Oona	200×200	60	68	2116	468

Table 3.6 Summary of SHETRAN land use types in Clarianna, Dripsey, and Oona.

CORINE land use types	**SHETRAN land use types**	**No. of cells occupied by each landuse**		
		Clarianna	**Dripsey**	**Oona**
Pasture land	Grass land	430	283	1880
Complex cultivation pattern	Arable land	132	72	217
Land principally occupied by agriculture	Arable land			
Non-irrigated arable land	Arable land			
Broad-leaved forests	Deciduous forest land	-	3	10
Mixed forests	Deciduous forest land	-	-	-
Mineral extraction sites	Urban land	-	8	9
Discontinuous urban fabric	Urban land	-	-	-
Sport and leisure facilities	Urban land	9	-	-

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. Table 3.6 summarises the distribution of the land types in the grids that represent the study catchments. The distribution of soil types in each of the grid which has been used to run SHETRAN in each of the study catchments is summarised in Table 3.7.

Table 3.7 Summary of soil types in the Clarianna, Dripsey, and Oona catchments used in the SHETRAN model.

Catchment	Soil type	No. of cells in model with indicated soil type
Clarianna	Grey Brown Podzolics (80%), Gleys (10%), Brown Earths (5%), Basin Peats (5%)	571
Dripsey	Peaty Podzols (75%), Lithosols (15%), Blanket Peats (10%)	54
	Brown Podzolics (60%), Gleys (15%), Podzolics (5%)	187
	Brown Podzolics (60%), Acid Brown Earths (20%), Gleys (20%)	125
Oona	Peaty Podzols (75%), Lithosols (15%), Blanket Peats (10%)	118
	Acid Brown Earths (70%), Gleys (25%), Podzolics (5%)	119
	Gleys (85%), Interdrumlin Peats and Peaty Gleys (15%)	1732
	Acid Brown Earths (75%), Interdrumlin Peats and Peaty Gleys (25%)	147

Since the GOPC is a postprocessor for SHETRAN, it uses the exact same catchment configuration as in SHETRAN. In addition all parameters and the time series of the chemical application required by the GOPC are read from a general input file.

3.4 Approach used for SWAT, HSPF and SHETRAN/GOPC model calibrations

Reviewing previous work on calibration of the three models used in this study show that manual calibration has been used in the vast majority of applications and very limited automatically calibration attempts were made. Moreover when attempted, the efficiencies of the models performances obtained with automatic calibration were still within the range of the manually calibrated models despite the considerable effort that has to be made in automatic calibration. To avoid the complexity and computational demands that might arise when using automatic calibration, and which would not allow these models be used in many practical situations, a simple manual strategy is employed to calibrate parameters of the three models used in the present work. Here we followed these steps recommended by Gupta et al. (2003) for the manual calibration of the three models parameters in the three study catchments. Moreover the sensitivity of the calibrated models to time steps different from those used in the calibration was also examined in the case of the HSPF model where that is possible.

Due to the difficulties in calibrating the large number of flow and phosphorus variables simultaneously, the three models were first calibrated to produce reasonable simulations for the flow and after achieving satisfactory flow (i.e. little further improvement in R^2 and mean square error) calibration the parameters of the best flow calibration were used without any further change during the phosphorus calibration. Furthermore due to the difficulties in manually calibrating more than one phosphorus variable at the same time, the three models were only calibrated to produce the best estimates for total phosphorus loads. However, the performance of the three models in simulating the dissolved reactive phosphorus loads was also investigated using the parameters obtained after the total phosphorus loads calibration. Moreover the total and dissolved reactive phosphorus concentrations were calculated and compared with the actual values in order to assess the models performances in estimating phosphorus concentrations.

A summary of the number of effective parameters in the three models and the methods in which they have been used in the water and phosphorus components for each model is given in Tables 3.8 and 3.9 respectively. Definition of the effective parameters used in phosphorus modelling can be found in Appendix A. Since the present study ignores the in-stream transport of non-point source pollution, the methods used in modelling in-stream sediment and phosphorus variables are omitted from these tables.

Table 3.8 Methods and parameters in the water components of SWAT, HSPF, and SHETRAN/GOPC.

<table>
<tr><th rowspan="2">Process</th><th colspan="2">SWAT</th><th colspan="2">HSPF</th><th colspan="2">SHETRAN</th><th>GOPC</th></tr>
<tr><th>Method</th><th>No. of parameters</th><th>Method</th><th>No. of parameters</th><th>Method</th><th>No. of parameters</th><td rowspan="10">A phosphorus model - uses flow and sediment simulations of other hydrological models (e.g. SHETRAN)</td></tr>
<tr><td>Interception</td><td>Water balance</td><td>1</td><td>Water balance</td><td>No parameters</td><td>Modified Rutter et al. (1975)</td><td>5</td></tr>
<tr><td>Potential evapotranspiration</td><td>Penman-Monteith/ Priestley-Taylor/ Hargreaves</td><td>No parameters</td><td>User defined</td><td>No parameters</td><td>User defined/ Penman</td><td>No parameters</td></tr>
<tr><td>Actual evaporation</td><td>Ritchie (1972)</td><td>2</td><td>Water balance of storages satisfying the demand</td><td>4</td><td>Penman-Monteith/ Feddes</td><td>2</td></tr>
<tr><td>Runoff</td><td>SCS</td><td rowspan="2">5</td><td rowspan="3">Conceptual approach based on linear probability density function</td><td rowspan="3">8</td><td>Approx. of St. Venant eqn.</td><td>1</td></tr>
<tr><td>Infiltration</td><td>Water balance</td><td rowspan="4">Variably-saturated sub-surface model</td><td rowspan="4">8</td></tr>
<tr><td>Interflow/ Return flow</td><td>Kinematic storage model</td><td>2</td></tr>
<tr><td>Baseflow</td><td>Linear reservoir model</td><td rowspan="2">5</td><td>Linear reservoir model</td><td>2</td></tr>
<tr><td>Percolation to groundwater</td><td>Water balance</td><td>Empirical relation</td><td>1</td></tr>
<tr><td>River/stream channelFlow routing</td><td>Variable storage/ Muskingum</td><td>3</td><td>Water balance</td><td>Not required</td><td>Approx. of St. Venant eqn.</td><td>1</td></tr>
</table>

Table 3.9 Methods and parameters in the phosphorus component of SWAT, HSPF, and SHETRAN/GOPC.

Process	SWAT		HSPF		SHETRAN	GOPC	
	Method	Parameters	Method	Parameters		Method	Parameters
Soil phosphorus processes	Mass balance	6	First order kinetics model	5	Model simulates flow and sediment only	Mass balance	7
Loss of dissolved phosphorus	Empirical relation	1	Complete mix model	No parameters		Empirical relation	1
Loss of phosphorus attached to sediment	Empirical relation	1	Complete mix model	No parameters		Empirical relation	1
Leaching	Empirical relation	1	Complete mix model	No parameters		Advection	1
Overland phosphorus routing	Linear reservoir model	No parameters	Not simulated by this model	No parameters		Mass balance	2
Loss of phosphorus with return flow	Not simulated by this model	No parameters	Complete mix model	No parameters		Advection	No parameters
Loss of dissolved phosphorus with	User defined concentration	1	Complete mix model	No parameters		User defined concentration	1

3.5 Data used in flow and phosphorus calibration

For each of the three models, the simulation of discharge, total phosphorus, and dissolved reactive phosphorus 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 catchments. This was the data provided by the project LS-2.2.1 teams (Kiely et al., 2005). As shown in Table 3.10, rainfall and other meteorological data are available for the whole period at a time step of 5, 15 and 30 minutes in the Oona, Clarianna, and Dripsey catchments respectively. The discharge data is available at the outlet of the three catchments in time steps shown in Table 3.10.

Table 3.10 Summary of the available data in the three catchments (see report of project LS2.2.1 for details of data).

Catchment		**Clarianna**	**Dripsey**	**Oona**
Meteorological data	**Method**	Observed	Observed	Observed
	Time step	15 minutes	30 minutes	5 minutes
Flow discharge	**Method**	Observed	Observed	Observed
	Time step	1 hour	15 minutes	1 hour
Soil phosphorus application regime	**Method**	Estimated	Estimated	Estimated
	Frequency	Annual amount	Annual amount	Annual amount
Total phosphorus and dissolved reactive phosphorus data	**Method**	Observed	Observed	Observed
	Time step	Event avg. concs. [Calculated from flow proportional composite samples]	Event avg. concs. Concentrations [Calculated from flow proportional composite samples]	Daily loads [Calculated from flow proportional composite samples]

Due to the insignificant contribution of point source pollution in the three catchments (discussed earlier) this source of phosphorus has been ignored here. Therefore the only source of additional phosphorus is fertiliser application. Detailed information about the actual soil phosphorus applications amounts and timing was not available.

Thus the total annual fertiliser application of phosphorus has been estimated as indicated Table 3.10. In Clarianna and Dripsey catchments, the total annual fertiliser application load were taken as 15 kg P ha^{-1} phosphorus which complies with the Teagasc recommendation (Teagasc, 1998 while in the Oona catchment this amount has been estimated using the existing summary of phosphorus inputs and outputs in Northern Ireland for the year 2000 (personal contact with Phil Jordan of University of Ulster group in LS-2.2.1.). It has been assumed that these phosphorus inputs and outputs were uniformly distributed over the total agricultural area of 106000 ha in Northern Ireland. This figure of the total agriculture area has been obtained from the Statistical Yearbook of Ireland, 2003 published by the Central Statistical Office in the Republic of Ireland (CSO, 2003). To allow for a daily distribution to the total annual amount, two different timing scenarios of phosphorus applications have been assumed in each of the three catchments. The first scenario assumes that the total annual amount is equally divided among the months of the year while in the second scenario the same amount is equally divided among the first six months (January to June) of the year (the main growing period and also when some slurry storage capacities are reached).

For the phosphorus calibration, the available observed data for total phosphorus and dissolved reactive phosphorus in the rivers at the outlets of the three catchments was used (Table 3.10). These data are available as concentrations in the Clarianna and Dripsey catchments, for both summer and winter flow regimes. Daily average concentrations were obtained by taking average of the available concentrations in each day. Hence phosphorus load of each day was found by multiplying the average daily concentration by the average daily discharge. Note that the resulting phosphorus load estimates may not be very accurate if the actual average of the daily concentrations is much different from the calculated one as explained above. In the Oona catchment, average daily loads of total and dissolved reactive phosphorus are available at a station located at a point draining an upland area of 88 km^2 out of the total catchment area of 96 km^2. Thus the available observed data for both parameters was scaled up by the ratio (96/88) in order to use it in calibrating the three models. The corresponding phosphorus concentrations were obtained by dividing the average phosphorus loads by the average daily discharges.

The phosphorus outputs from the SWAT, HSPF, and GOPC models are average loads of the mineral phosphorus delivered with the runoff water and the attached or particulate inorganic and organic phosphorus delivered with the eroded sediment. The sum of the two fractions of phosphorus represents an estimate of total phosphorus while the first fraction (mineral phosphorus) alone will be assumed to estimate dissolved reactive phosphorus. The estimated phosphorus loads have been divided by the estimated discharge from the models (SHETRAN in the case of GOPC) at the outlet location to obtain the daily mean phosphorus concentrations.

Table 3.11 The number of flow and phosphorus calibration runs and approximate run times in calibration.

Catchment	Model	Number of runs in flow calibration	Number of runs in phosphorus calibration	Approximate time devoted (weeks)
Clarianna	**SWAT**	7	5	2
	HSPF	6	7	2
	SHETRAN/ GOPC	21	10	3
Dripsey	**SWAT**	17	9	4
	HSPF	8	7	2
	SHETRAN/ GOPC	11	10	3
Oona	**SWAT**	15	14	4
	HSPF	19	7	4
	SHETRAN/ GOPC	5	10	5

3.6 Flow and phosphorus calibration in the study catchments

The manual calibration involves trial of several sets of parameters, a procedure which requires a considerable amount of time. The number of trial runs and approximate time devoted for the calibration of flow and phosphorus in the study catchments are summarised in Table 3.11. From the table it can be seen that the Clarianna has required the least calibration time while the Oona took the longest. Furthermore it can be noticed that the number of SHETRAN runs in the Oona catchment was the lowest despite the considerable time required by the other models. This is because of the extreme difficulty in running the SHETRAN model for the whole simulation period because of the large size of the catchment, long duration of the simulation period and the sensitivity of the model calculations to the elevation of the land surface and stream links. Although these elevations have been obtained from the DEM of the catchment, they still required further adjustment in order to obtain physically realistic flow directions. If those elevations are not adjusted a sink where flows from the four directions run into it would be created and as a result the model run stops. The recommendation of special elevation adjustment has been obtained through personal contact from the SHETRAN developers in the University of Newcastle upon Tyne. The other catchments did not require this step as the DEMs (provided by the Irish EPA) were already hydrologically consistent.

To demonstrate the manual calibration procedure which has been followed in the calibration of flow and phosphorus, the case of the GOPC phosphorus calibration in the Dripsey catchment is presented. Graphs of the best (run 8) and the worst (run 1) calibration results are shown in Figure 3.5 along with the observed data which shown as points. Furthermore in order to demonstrate the difference in magnitude between the two runs a log scale has been used.

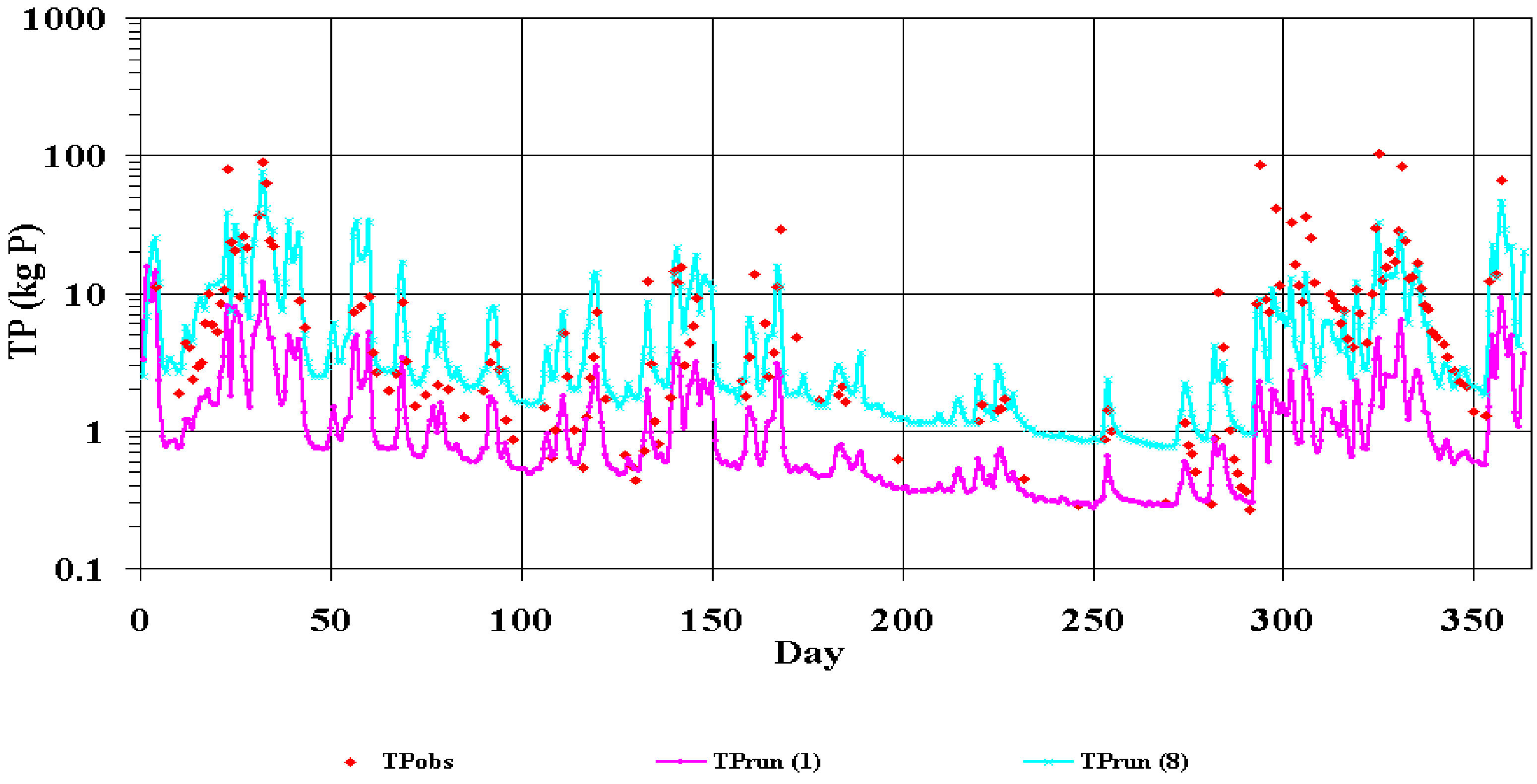


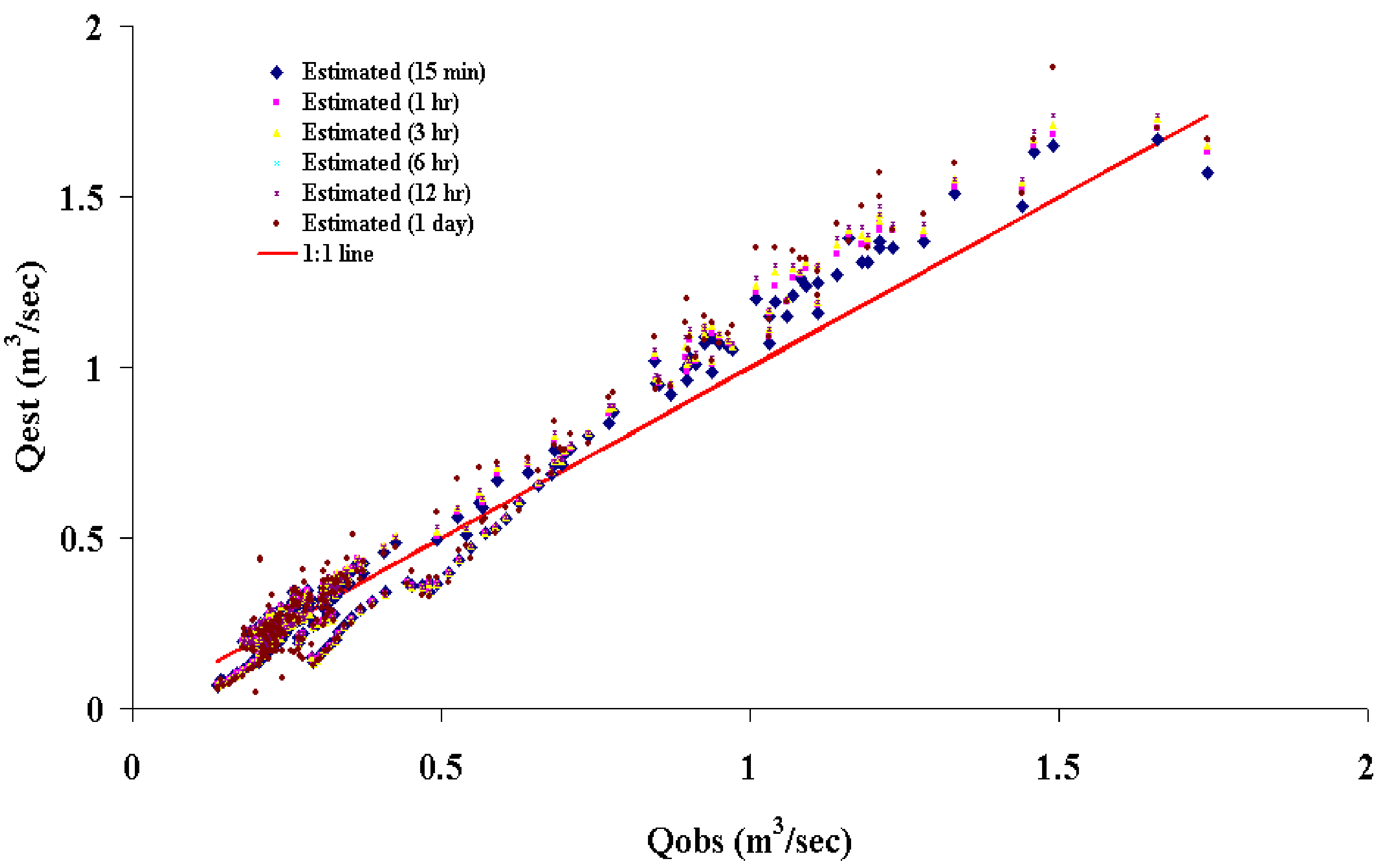
Figure 3.5 The best (run 8) and the worst (run 1) total phosphorus load per day results for the period 1/1/2002 -31/12/2002 for phosphorus calibration in the Dripsey catchment.

3.7 Effect of time step variations on HSPF performance in the three study catchments

In order to investigate the sensitivity of the HSPF model to different time steps, the calibrated model in each catchment has been run using different time steps (1, 3, 6, 12, and 24 hours). These time steps (for each catchment) were all higher than the time step used in the calibration runs (15 minutes). The discharges and total phosphorus loads results of the simulations are presented (Figures 3.6 to 3.11) and discussed. For both variables, the figures show the simulated values (using different time steps) as scattered points. Moreover in all figures the line of equality (1:1) is added to represent the situation when the simulated values are exactly equal to the observed values and it can be used to show how close the simulated values of a certain run fit the observed, i.e. the run that produces the most clustering of points around that line is regarded the best model run. Presentation of results in this form highlights the variation in the model estimation with respect to increase in the time step. To allow for the proper presentation of the highly varied results of phosphorus, results of total phosphorus loads were plotted on a log scale.

It is noticeable from Figure 3.6 that for discharge values above 0.5 m^3 s^{-1} the simulated values in the Clarianna catchment tend to increase as the time step increases and among the runs, the best results were of the 15 minutes time step run, as it showed the best fit between the model output and observations.

The effect of time step variations is clear on the total phosphorus load simulation (Figure 3.7) as the results increasingly deviate from the equality line as the time step increases. Running the model with a 24 hour time step gives total phosphorus loads much higher than the observed and the other results from different time steps. There is no significant difference between total phosphorus load results from 15 minute and 1 hour time steps simulations.



<u>Figure 3.6 Simulated mean daily flows (HSPF) with different time steps in the Clarianna catchment.</u>

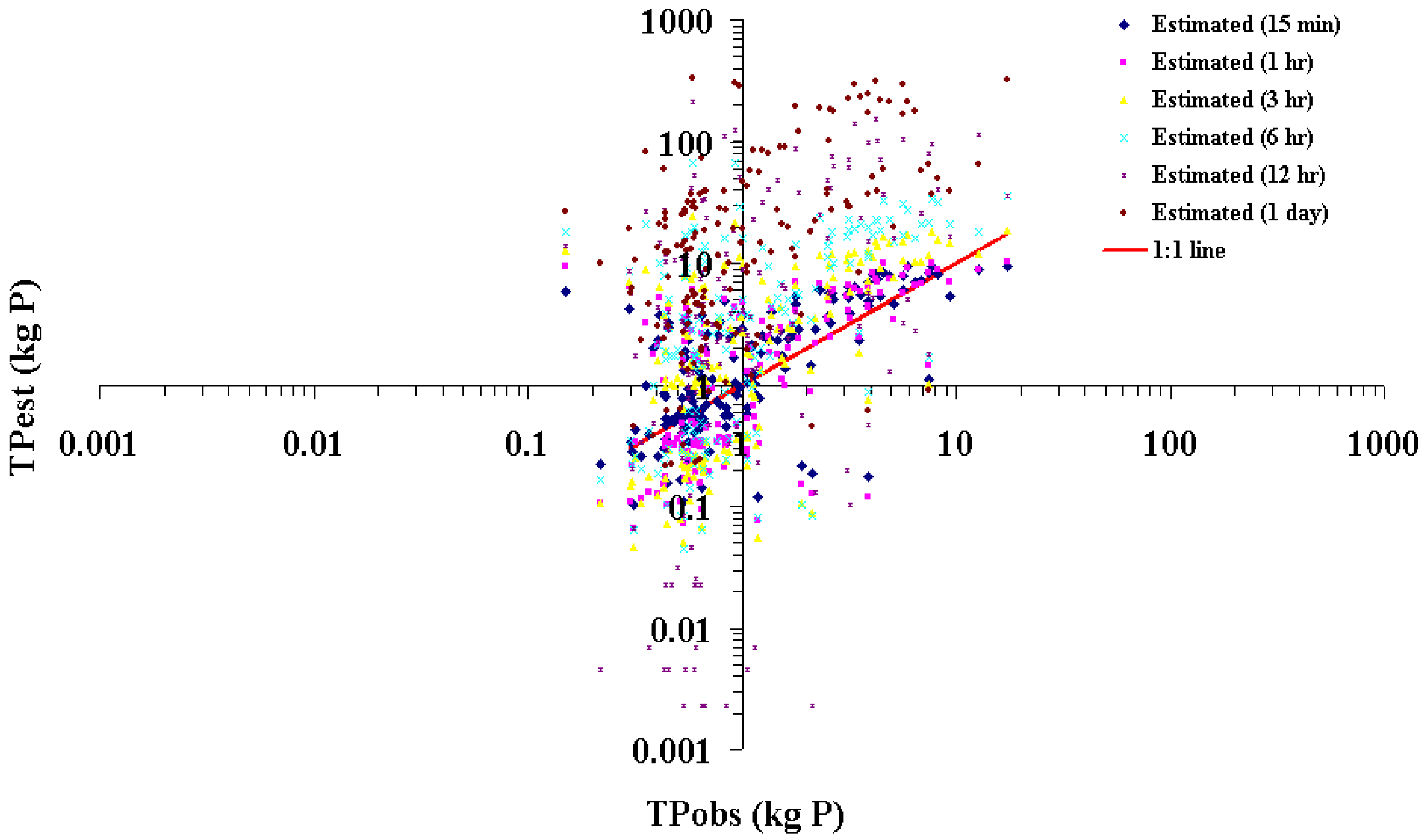


Figure 3.7 Simulated mean daily total phosphorus loads (HSPF) with different time steps in the Clarianna catchment.

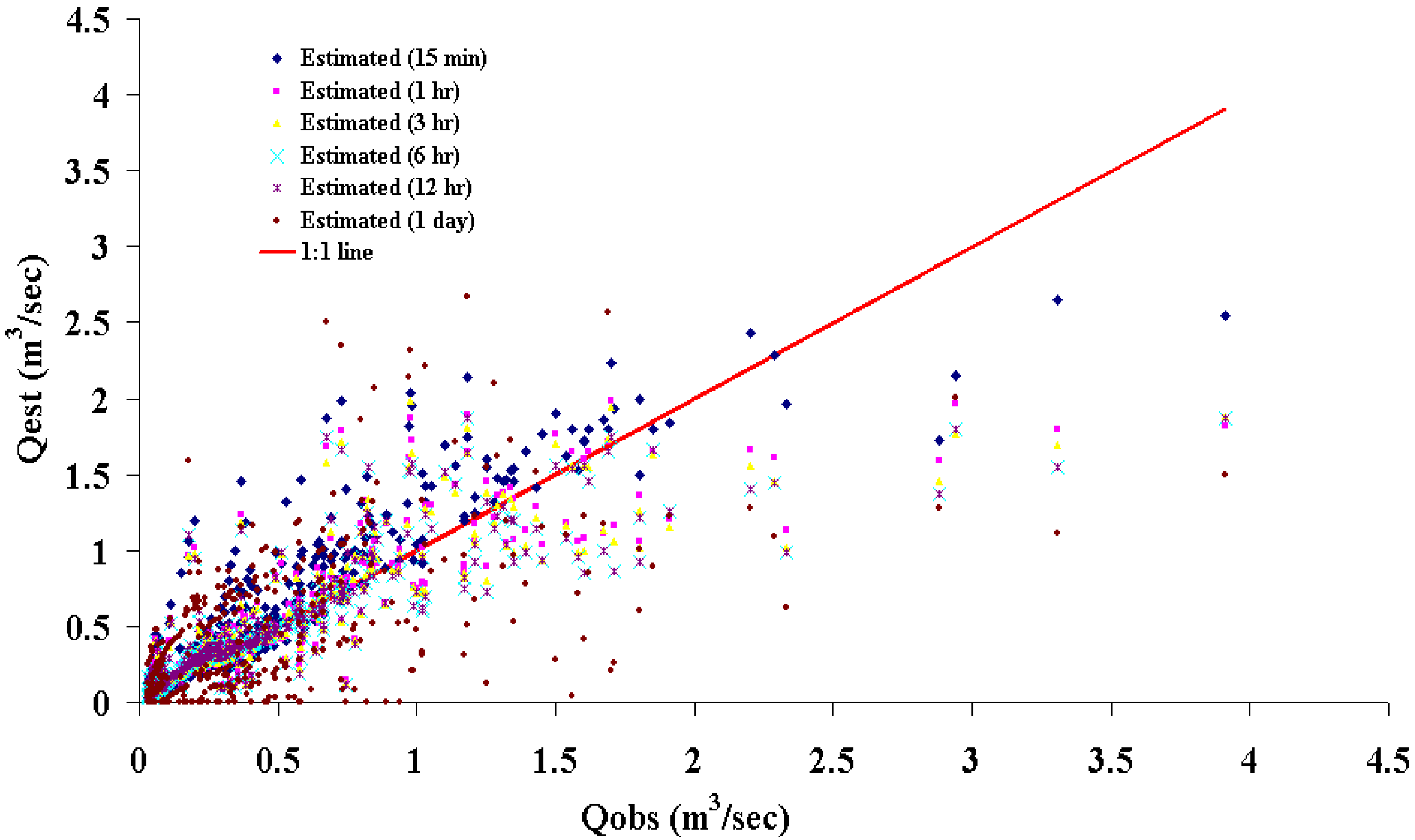


Figure 3.8 Simulated mean daily flows (HSPF) with different time steps in the Dripsey catchment.

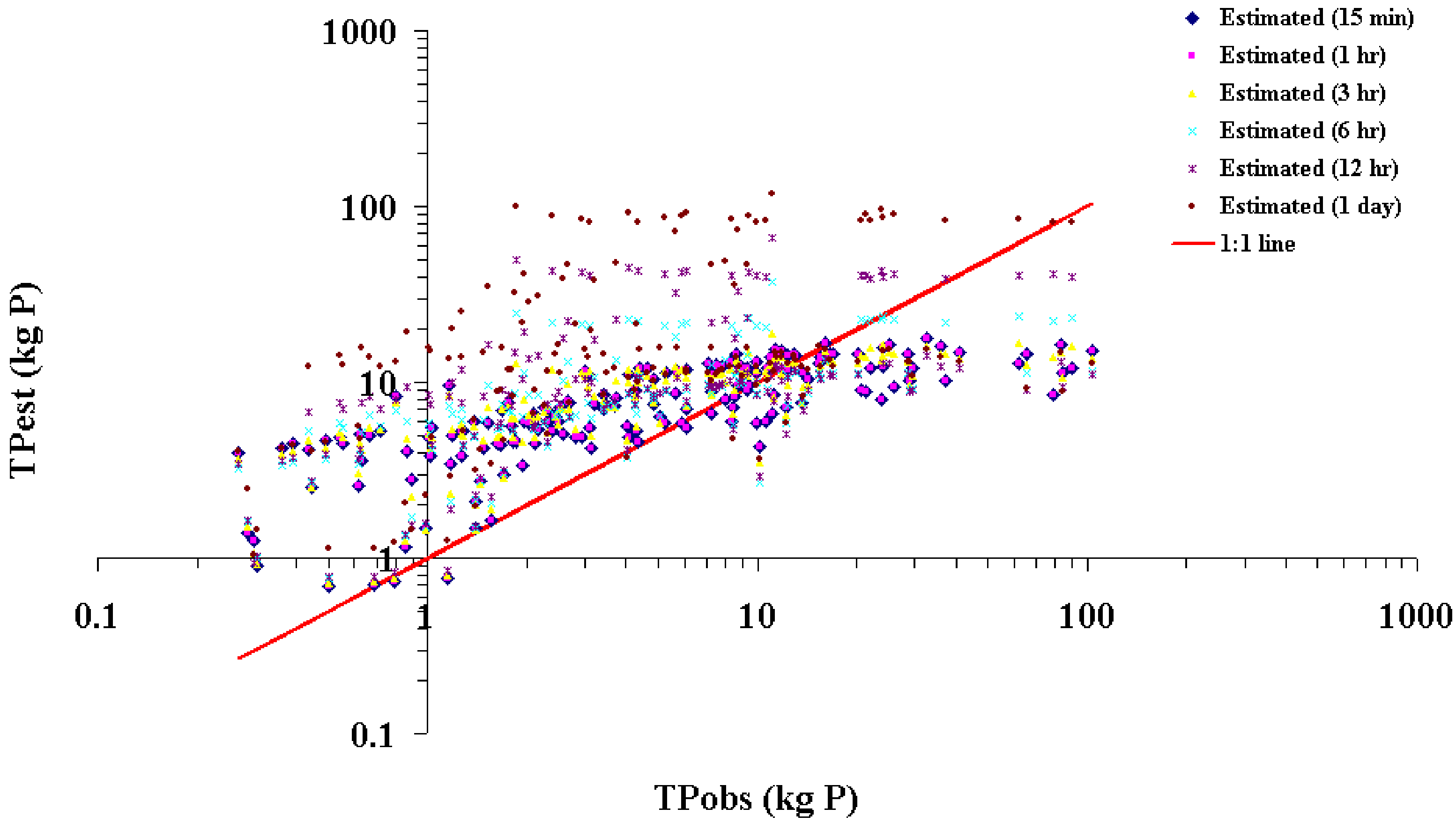


Figure 3.9 Simulated mean daily total phosphorus loads (HSPF) with different time steps in the Dripsey catchment.

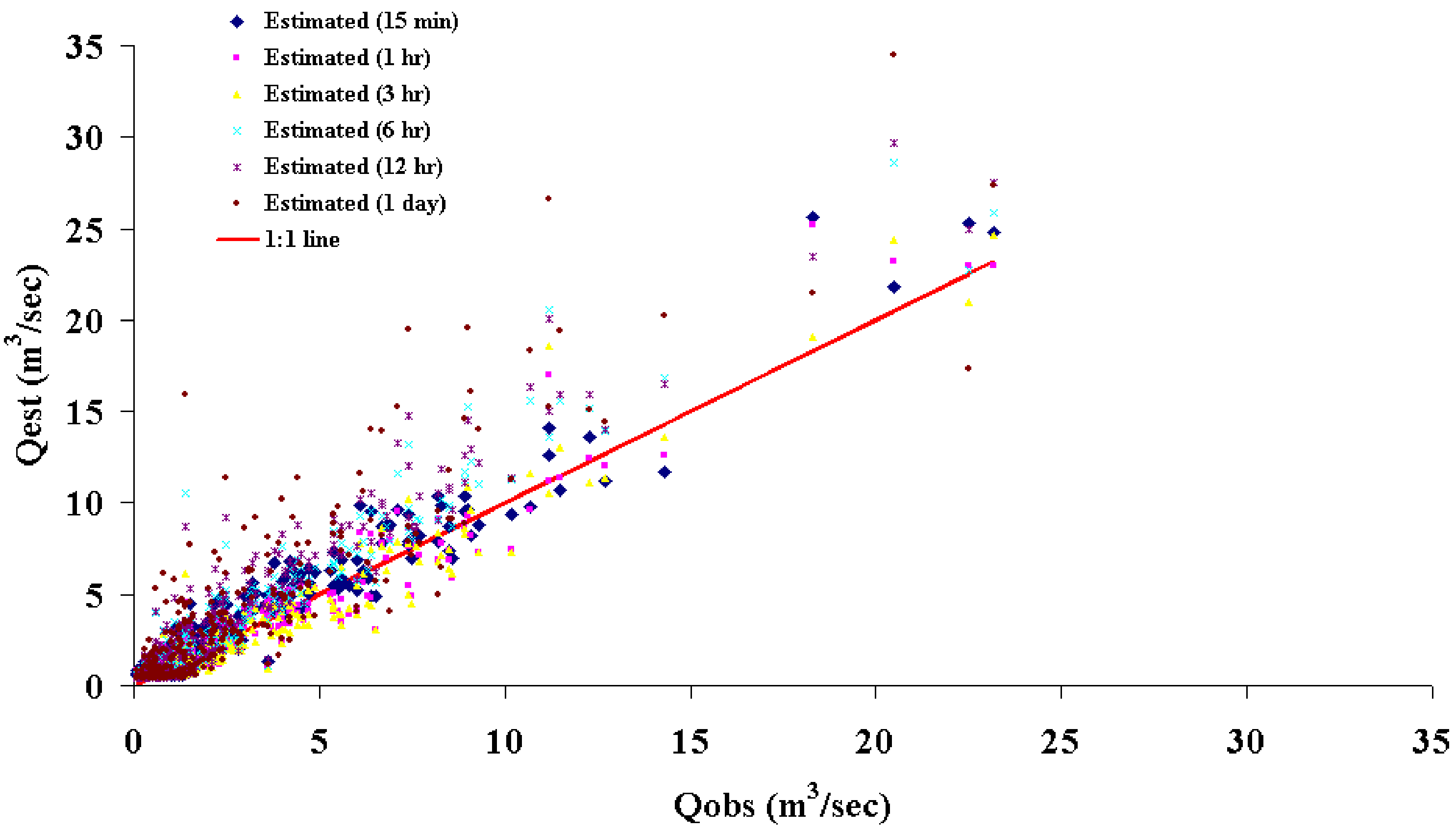


Figure 3.10 Simulated mean daily flows (HSPF) with different time steps in the Oona catchment.

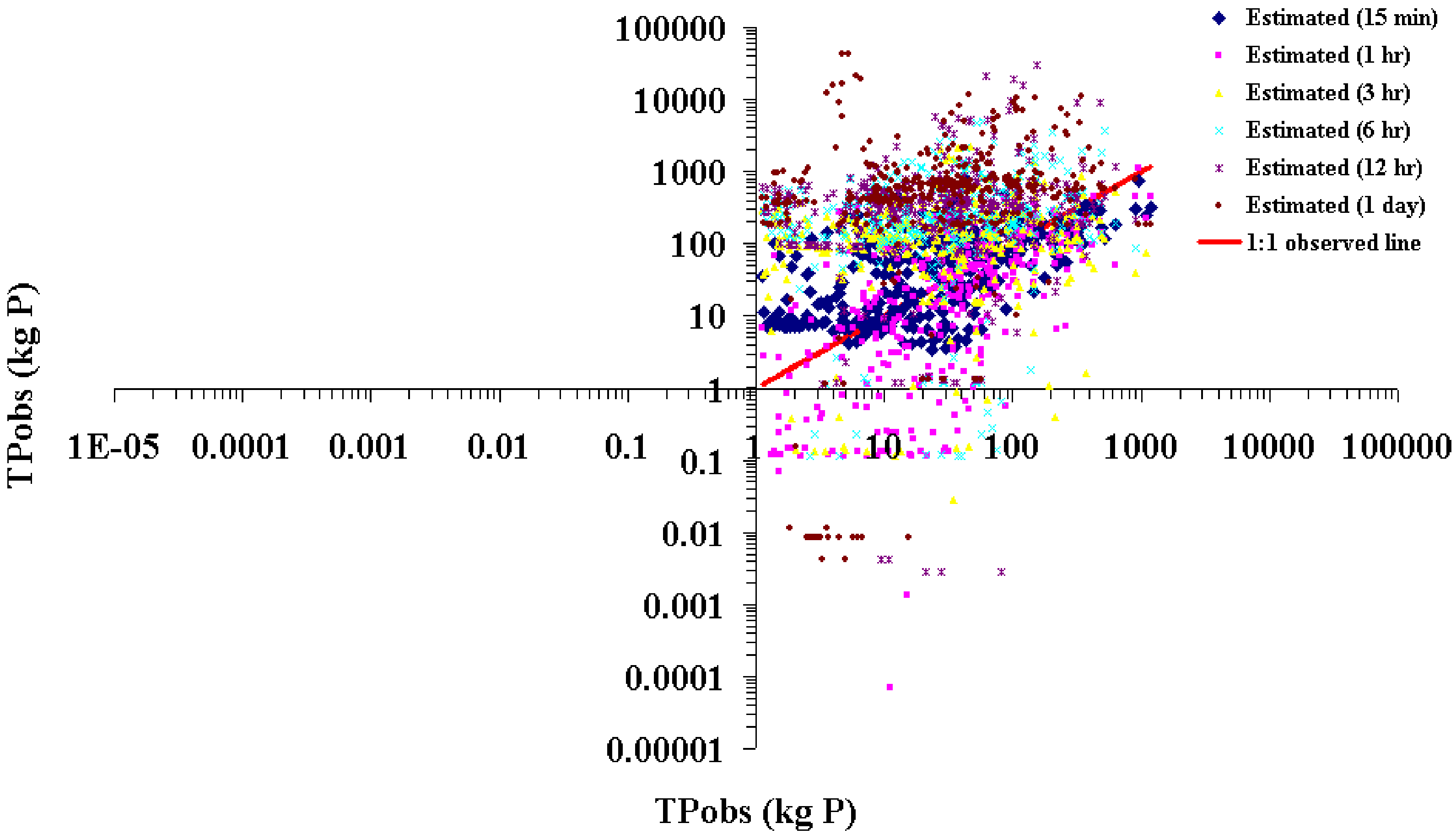


Figure 3.11 Simulated mean daily total phosphorus loads (HSPF) with different time steps in the Oona catchment.

Unlike the Clarianna catchment, the simulated flow values in the Dripsey catchment generally decreased with increase in time step as flow exceeded 0.5 $m^3 s^{-1}$ (Figure 3.8). This increases the underestimation of the observed values as the time step increases. However the variation in the underestimation is significant while the overestimation is marginal and thus using the model with smaller time step would be better. As shown in Figure 3.9 the total phosphorus load simulations with 30 minutes and 1 hour were not much different. The results of the 3, 6 and 24 hours cases (Figure 3.9) show similar behaviour with values higher than those obtained from the lower time step for the total phosphorus load. Generally the results of the 15 minutes case are the closest to the line of equality.

Figure 3.10 shows that the flow simulation results from the 15 minutes case is the best in the Oona catchment. The general trend is that simulated discharge values increase as the time step increase although this has been violated in few instants where the opposite becomes true. As with the flow, the total phosphorus loads simulation using the 15 minutes time step are better than the results for larger time steps (Figure 3.11).

3.8 Summary

In this Chapter a thorough discussion of the issues relevant to fitting of the three models used in the present study was given. Furthermore the approach to calibrating these models was explained. For the only model (HSPF) that the variation in the time step of simulation is possible a discussion of the effects of using different time steps on the model performance was added. In the next Chapter comparison of the best results obtained from the calibration of the three models in the three catchments will be presented. In addition comparison of the verification results in the Oona catchment will be also added in the same Chapter.

4 COMPARISON BETWEEN THE PERFORMANCES OF THREE MODELS

4.1 Introduction

The main objective in applying the three models to the study catchments is to evaluate and compare their performances. Therefore to enable an easy comparison only the best calibrated results of the flow and the phosphorus simulation from the three models will be compared in each of the study catchments. Moreover in the Oona catchment, an independent set of observed data has been used to validate the three models' performance. The first period covers three months before the calibration period while the second period represents a month after the calibration period. The criteria, which have been used in the comparison of the performance of the models, are described below.

4.2 Criteria for model comparison

The first criterion in the assessment is a graphical representation which gives a clear and forceful overview of model performance. The rainfall hyetograph has been added at the top of all figures which show the observed and the estimated (by each model) flow hydrographs. Likewise in all figures showing the graphs of load and concentration of the total phosphorus and the dissolved reactive phosphorus, the observed flow (Qobs) and the estimated flow by the three models (Qest) hydrographs are displayed at the top while graphs of the observed total phosphorus (TPobs) or dissolved reactive phosphorus (DRPobs) and the estimated total phosphorus (TPest) or dissolved reactive phosphorus (DRPest) by each model are at the bottom. This arrangement should help in determining the effect of the flow simulation on the phosphorus one. Moreover a log scale has been used in all graphs to allow investigating the low values.

In addition to the visual assessment of the models various descriptive statistics defined below are also used. The values of these statistics for the flow and phosphorus cases have been calculated by analysing the time series of both the observed and the estimated values by each model. The results are summarised in a tabular format. For the observed and each model estimated time series of the flow and phosphorus variables, two groups of statistics have been calculated, as explained below.

The first group allows a comparison between the observed and the estimated values on a one by one basis for each statistic. This group includes the sum, average, sum of squares of differences between each value and its average, and standard deviation. In terms of evaluating the performance with the statistics in this group the good model should always have values as close as possible to the corresponding values obtained from the observed data. The first statistic in the group, the sum, provides a measure of the area under the simulated graph and this in turn assists in evaluating the water balance of the flow and the mass balance of the phosphorus variables. The other statistics in this group (average, standard deviation, sum of squares of differences between each value and its average, and standard deviation) give a measure of the shape of the distribution which describe the data (either flow or phosphorus). While the average represents a central value about which the other values are distributed, the sum of squares of differences between each value and its average, and standard deviation measure the degree by which the values deviate from the average value. It is obvious that the first group of the descriptive statistic provides a measure to the shape of the simulated graphs comparing to the actual one and this is important in assessing the model performances.

The second group of statistics is used to measure the strength of the relationship between the observed and the estimated values, such as Sum square of errors (residual variance), Mean square of errors, Coefficient of correlation, Nash-Sutcliffe coefficient, Standard error of predictions, Greatest positive error, Greatest negative error. From the definitions of the sum and mean squares of errors (SSE and MSSE), it can be seen that both quantities are not dimensionless. Therefore they are suitable for comparing the performance of different models on the same catchment and data set but not for different catchments. Nash and Sutcliffe (1970) introduced a criterion (R^2) which would enable the evaluation of the performance of models on different catchments as well as on a single catchment. Moreover the strength of the relationships between the observed and the estimated time series can be evaluated using the coefficient of correlation (CORR). Also, the greatest positive error (GPE) and greatest negative error (GNE) both measure the highest underestimation and overestimation of the observed values respectively by the model. Finally the standard error of prediction (SE) provides a measure of the accuracy of predictions made with a regression line which describes a linear relation between the observed and predicted values. The evaluation with the second group of the descriptive statistics varies depending on the type of the statistics under consideration. Higher values close to one for CORR and R^2 always mean a good estimation by the model while smaller and negative values implies the opposite. On the other hand a good model should always have relatively small value for SSE, MSSE, SE, GPE, and GNE statistics.

4.3 Comparison between the three models' performance in the Clarianna catchment

All the models have been calibrated to simulate flow, total phosphorus, and dissolved reactive phosphorus for the period from 1/12/2001 to 29/07/2002. The flow and phosphorus results from the models have been averaged over a day, if the model output is not already so (SWAT case) and hence the comparison between the performances of the models is based on daily values. The comparison of the results will cover the flow first and then the phosphorus.

4.3.1 Comparison of flow results

The visual comparison between hydrographs of observed and estimated discharge by the three models (Figure 4.1) reveals that HSPF has produced a hydrograph resembling the actual one except for some discrepancy during the falling limb. Most of the peaks in the observed hydrograph were well captured by HSPF. On the other hand hydrograph from SWAT is not as good as the one from HSPF and it shows a significant underestimation of one of the biggest observed peaks on day 70. The worst hydrograph shape was that from SHETRAN. The SHETRAN model failed to simulate one of the major peaks in the observed hydrograph although it did simulate the other one correctly. Also it does not match the flow recession after any of the peaks. The final point to notice in the figure is that SWAT and SHETRAN models have shown a feature not in the actual hydrograph.

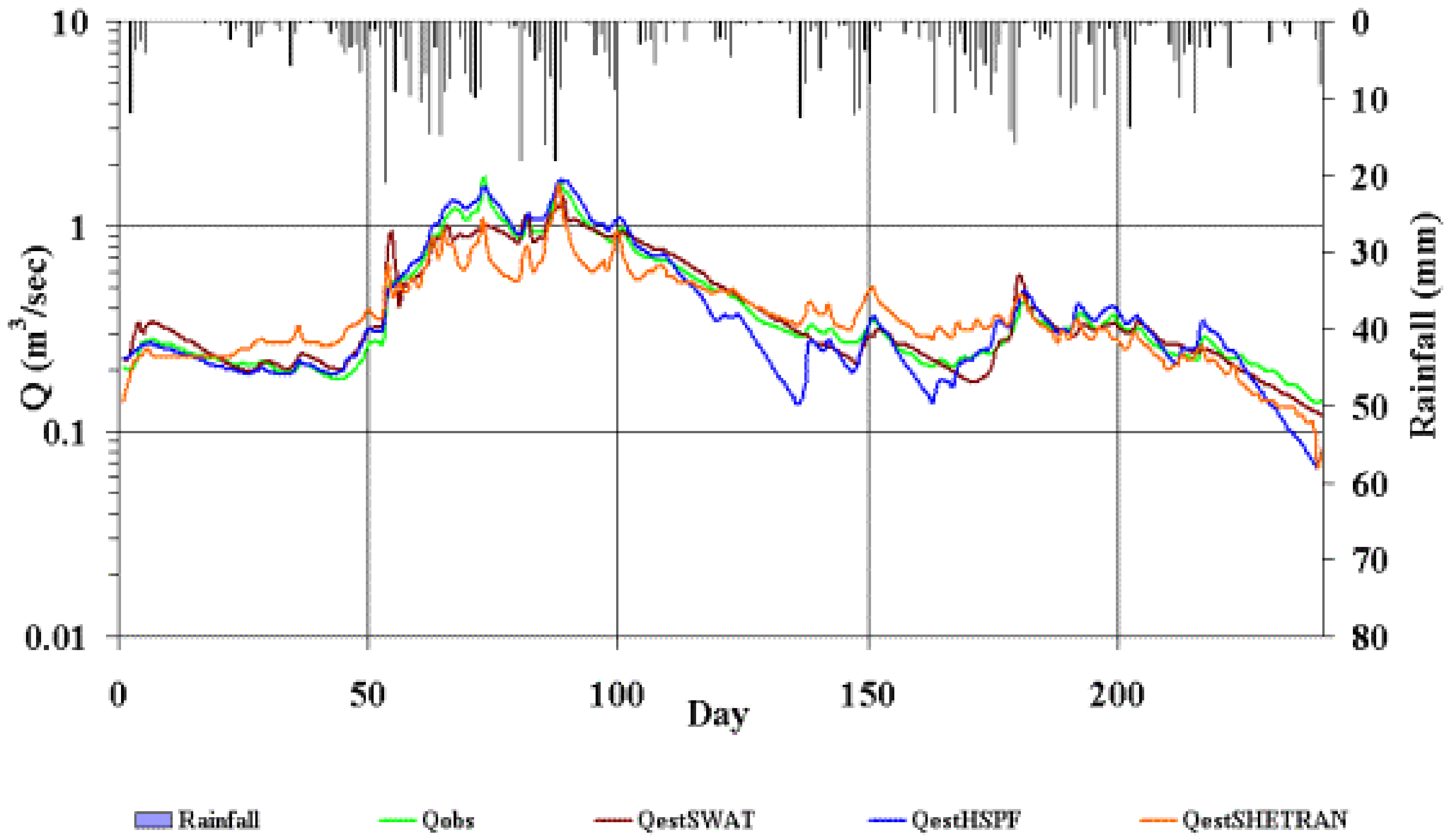


Figure 4.1 Flow results in Clarianna (1/12 - 29/07 2002).

This feature is the relatively high value simulated by all the models at the rising point of the hydrograph on day 53. This value coincides with a high rainfall and hence the models seem to work properly but with overestimation of the observed value assuming that the observed data represents the real situation correctly. This behaviour of the models could be attributed to high simulation of the soil moisture content which in turn resulted in more overland flow.

Table 4.1 Statistics of flow results in Clarianna

	Observed	Estimated		
		SWAT	HSPF	SHETRAN
No. of data	241	241	241	241
Sum	106.28	103.71	108.34	95.60
Avg.	0.44	0.43	0.45	0.40
Sum (value- avg.)^2	26.45	19.89	34.14	11.17
Stand. dev.	0.33	0.29	0.38	0.22
CORR		0.96	0.99	0.92
SSE		2.46	1.22	6.60
MSSE		0.01	0.01	0.03
R^2		0.91	0.95	0.75
SE		0.08	0.06	0.09
GPE		0.74	0.17	0.70
GNE		-0.40	-0.22	-0.16

The results of statistical analysis of the flow simulations from each model are presented in Table 4.1. The sums of the flow estimates from SWAT and HSPF models are very close to the sum of the observed values while in the case of SHETRAN the sum is significantly lower. The sum of squares of differences between each value and its average is higher in the case of HSPF than the observed and lower for the other two models. This means that the HSPF output has more variability than the observed flow series and that the other models have less. Similar results also occurred for the standard deviation. The best results for SSE, MSSE, CORR, R^2, and SE are observed in the case of the HSPF model and the shape of the flow hydrograph has confirmed this. Likewise the value of GPE for the HSPF model is better than the other two models while its value of GNE is the second best. The CORR, R^2 values for HSPF are 0.99 and 0.95 respectively. The values of SSE, MSSE, CORR, R^2, SE, GPE, and GNP for the case of SWAT are generally better than the case of SHETRAN and this also agrees with the observed shapes of the hydrographs from the two models.

4.3.2 Comparison of total phosphorus results

Figure 4.2 shows the results of total phosphorus simulation by SWAT, HSPF, and GOPC models. It is obvious that at the end of the simulation period there are high total phosphorus values which none of the three models have reproduced. By looking to the flow hydrographs at the top of the figure it can be noticed that during this period the flow is very low and therefore it is hard to believe that these total phosphorus values are caused by non-point source pollution delivered by runoff as soluble or particulate forms. However it has been confirmed by the people in this catchment that there was catchment 'maintenance dredging' in the river during that period, releasing silt into the water, which means the samples that have been taken were not representative of the natural total phosphorus level in the river. So, the comparison of total phosphorus will only be from the starting period to day 211.

Regarding the performance of the models in simulating the total phosphorus load values, SWAT model has performed quite well generally except for some high total phosphorus load values which were not reproduced by the model. Note that it gives good results for the total phosphorus peaks on days 55 and 90, but not for day 67 (Fig. 4.2). The reason for this can be attributed to the failure of SWAT to adequately simulate the flow peak corresponding to this total phosphorus value. The GOPC performance is second to SWAT and again the deficiency in simulating some of the total phosphorus load values is related to the corresponding deficiency in the flow simulation by SHETRAN model. It is quite surprising to notice that the HSPF performance was the third although it has the best performance in simulating the flow hydrograph. The main reason for this result could be the much simpler nature of the phosphorus component in the HSPF model compared to SWAT and GOPC.

The results for the total phosphorus concentrations (Figure 4.3) show the same trend for the three models except that SWAT and GOPC have simulated similar values of total phosphorus during the low flow periods. This behaviour from the two models is

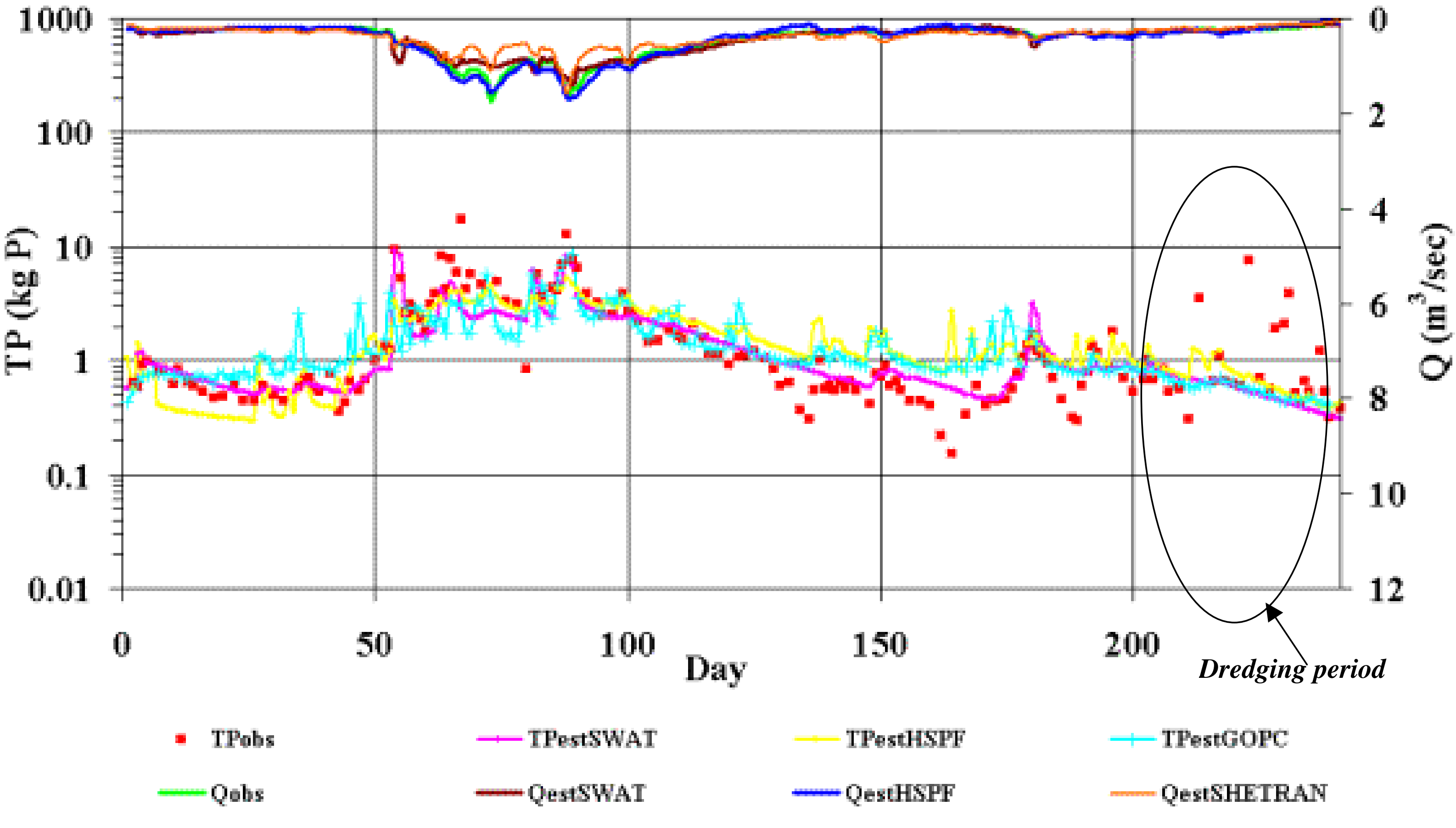


Figure 4.2 TP (loads) results in Clarianna (1/12 - 29/07 2002).

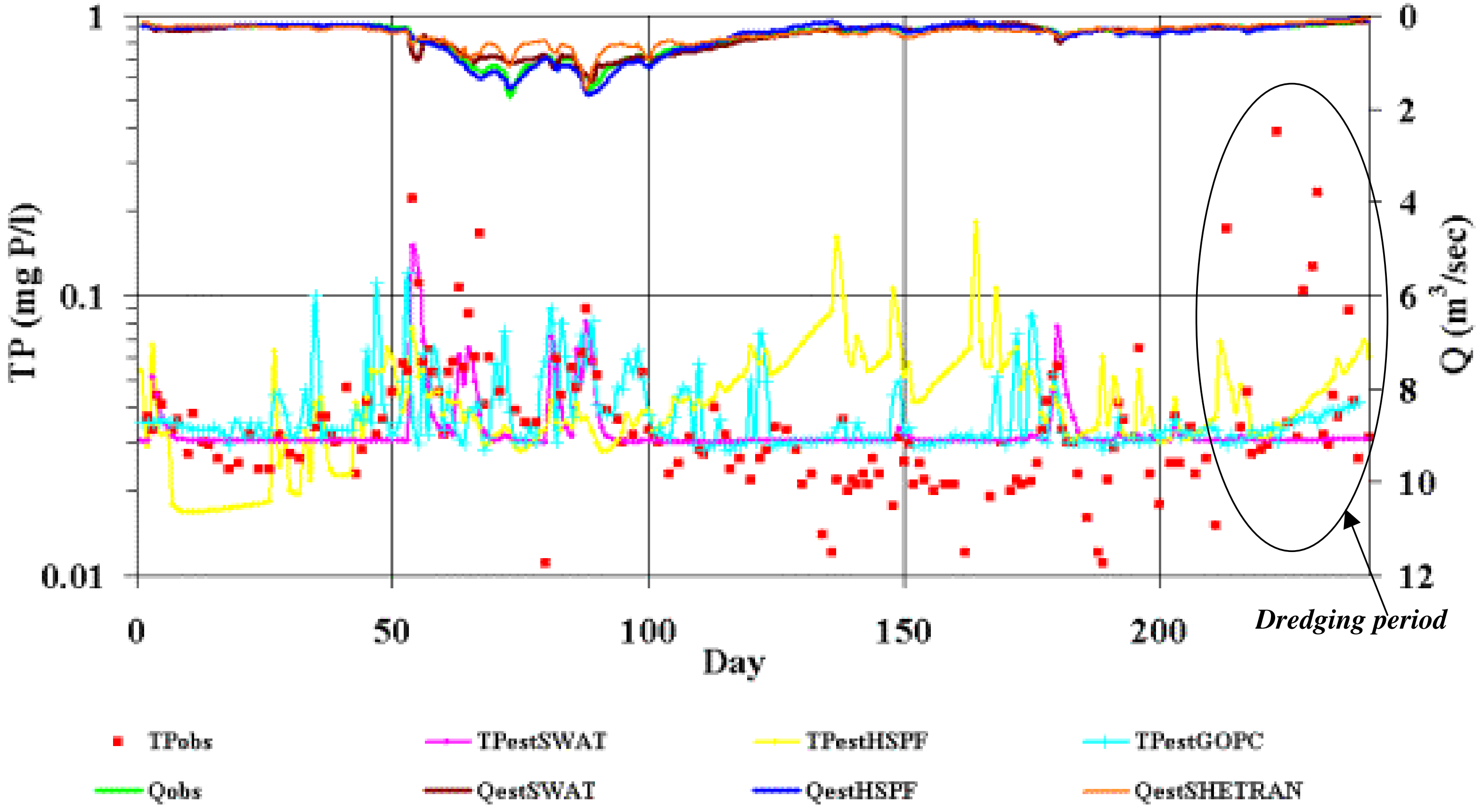


Figure 4.3 TP (concentrations) results in Clarianna (1/12 - 29/07 2002).

understandable since both models use similar soil phosphorus equations and should produce similar results provided that their flow results are also same and that is the case during these periods. HSPF has generally produced higher total phosphorus concentrations during the low flows period and this has been already reflected in the total phosphorus load results from this model.

Table 4.2 Statistics of TP (loads) in Clarianna.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	143	143	143	143
Sum	260.35	221.19	244.31	233.08
Avg.	1.82	1.55	1.71	1.63
Sum (value- avg.)^2	836.12	330.77	177.81	224.28
Stand. dev.	2.43	1.53	1.12	1.26
CORR		0.79	0.78	0.65
SSE		341.53	411.24	501.82
MSSE		2.39	2.88	3.51
R^2		0.59	0.51	0.40
SE		0.93	0.70	0.96
GPE		14.53	13.43	14.28
GNE		-3.17	-2.52	-2.70

The statistical analysis results for the total phosphorus loads is summarised in Table 4.2. The sum of the observed total phosphorus loads was underestimated by the three models with the value from HSPF being the biggest among the three models. The average of the total phosphorus load from HSPF is comparable to the observed value while the average from SWAT and GOPC which is significantly lower than the observed. All the three models have lower values for the sum of the difference between each value and the average of the time series than the one obtained from the observed time series and similarly for the standard deviation. Values of CORR, R^2, SSE, and MSSE for SWAT are the best among the three models while SE, GPE, and GNE statistics for HSPF are the best among the three models. The SE, GPE, and GNE statistics for GOPC are not different from SWAT values. The rest of the statistics

(CORR, SSE, MSSE, and R^2) for GOPC are the worst among the three models. The best results of CORR and R^2 (from SWAT model) have values of 0.79 and 0.59 respectively.

Table 4.3 Statistics of TP (concentrations) results in Clarianna.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	143	143	143	143
Sum	5.22	5.07	6.26	5.59
Avg.	0.04	0.04	0.04	0.04
Sum (value- avg.)^2	0.09	0.03	0.07	0.03
Stand. dev.	0.03	0.02	0.02	0.02
CORR		0.76	-0.08	0.12
SSE		0.04	0.18	0.11
MSSE		0.0003	0.00	0.0008
R^2		0.55	-1.01	-0.24
SE		0.01	0.02	0.02
GPE		0.13	0.15	0.19
GNE		-0.03	-0.17	-0.08

Table 4.3 summarises the statistical analysis for total phosphorus concentrations. Generally the values of the statistics, which have dimensions, are small due to the smaller values of the concentration itself. Comparing to the observed total phosphorus concentration, the sum, average, and sum of the difference between each value and its average of the time series for the three models are following the same pattern as in the case of the load. The SSE, MSSE, SE, GPE, and GNE statistics for the three models are generally not different and they have small values. The best CORR and R^2 are from SWAT and they have values of 0.76 and 0.55 respectively. However unfortunately the HSPF and GOPC have a negative value for R^2 which implies a poor estimation of the concentrations by these models.

4.3.3 Comparison of dissolved reactive phosphorus results

As shown in Figure 4.4 the graphs of dissolved reactive phosphorus loads from the three models indicate that SWAT was the best while GOPC was the worst at simulating dissolved reactive phosphorus. However, it is also noticeable that in some periods GOPC has performed similarly to SWAT (the best model) and this emphasises the competitiveness of GOPC in modelling phosphorus loss from the catchment. Moreover the inadequate simulation by SWAT and SHETRAN of the flow peak has clearly reflected on the dissolved reactive phosphorus simulation by SWAT and GOPC as it is noticeable that both models did not capture the highest dissolved reactive phosphorus values. Note that the three models have always generated values of dissolved reactive phosphorus higher than the observed during the recession and low flows period. The reason for this could be that the focus in calibration was on total phosphorus loads only and the dissolved phosphorus loads was estimated using the parameters obtained from the total phosphorus calibration.

The dissolved reactive phosphorus concentrations from SWAT, HSPF and GOPC (Figure 4.5) are all higher than the observed except for few values (some corresponding to a flow peak and the other occurring during a low flow period). The HSPF model overestimates most of the dissolved reactive phosphorus concentrations during the recession and low flows periods and this result agrees with the total phosphorus result from this model which also overpredict concentrations. The final thing to notice from the graphs is that both HSPF and GOPC show a response in dissolved reactive phosphorus concentration to any rise in the flow during the low flow period whereas SWAT has always a constant dissolved reactive phosphorus during the same period.

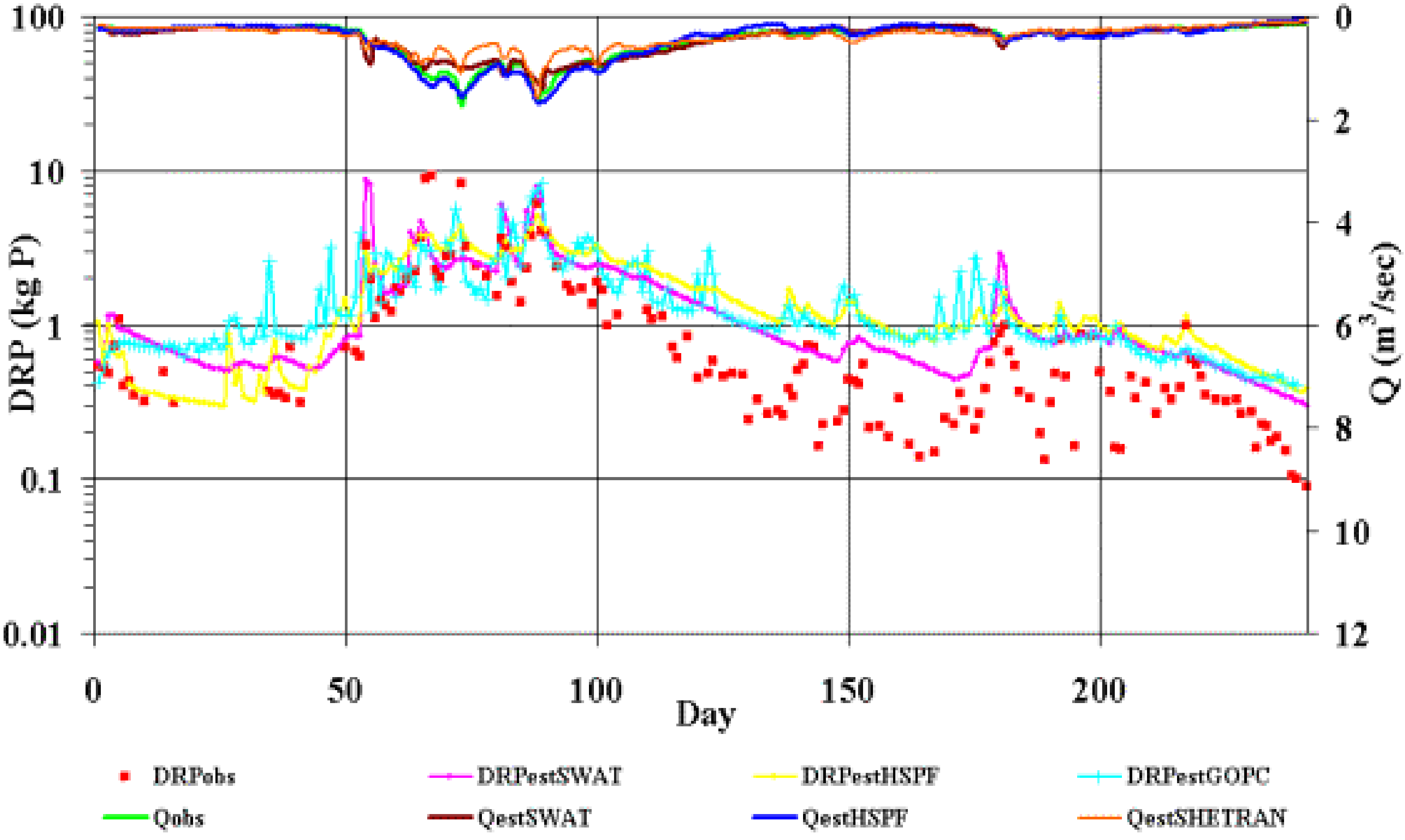


Figure 4.4 DRP (loads) results in Clarianna (1/12 - 29/07 2002).

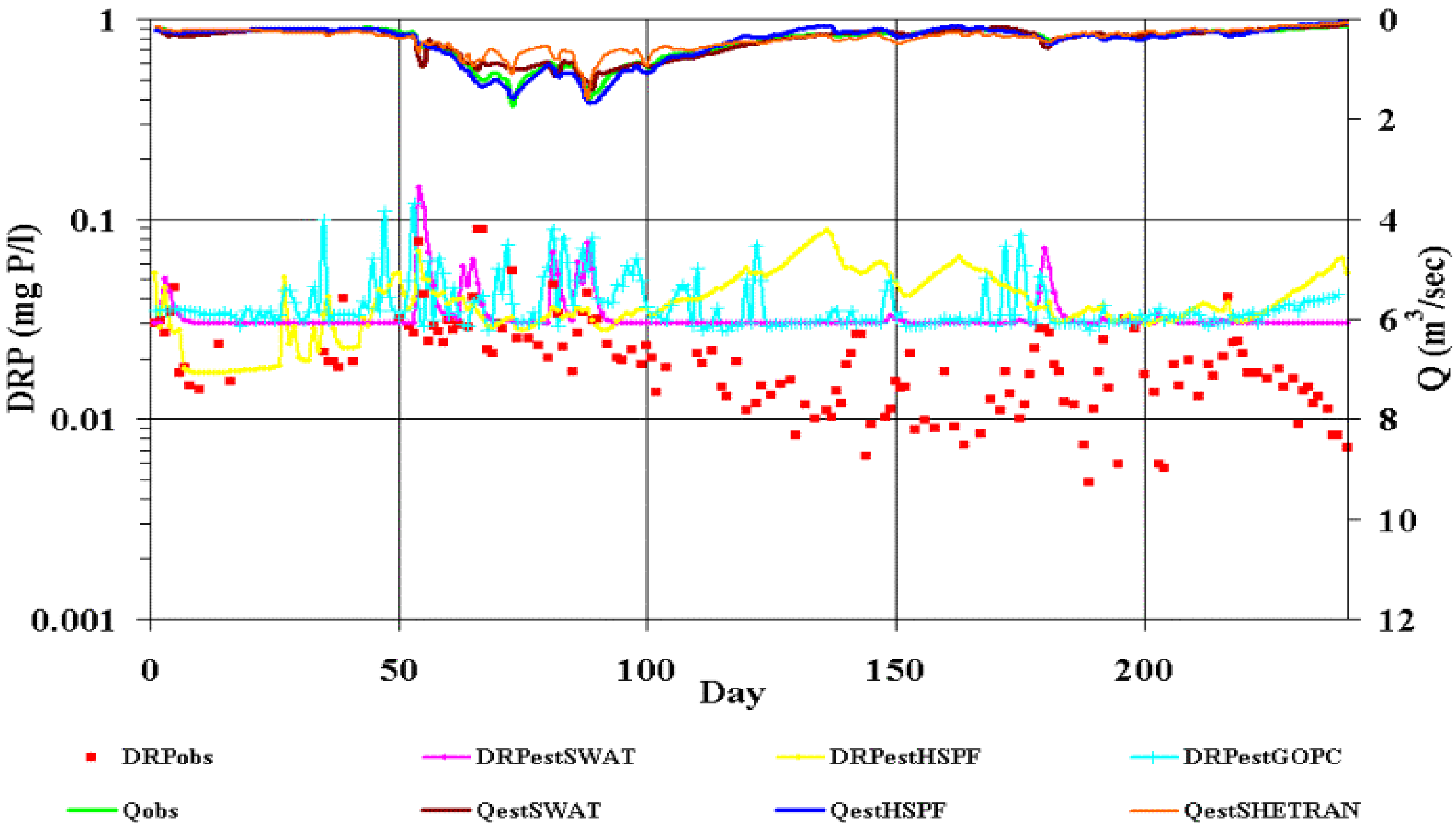


Figure 4.5 DRP (concentrations) results in Clarianna (1/12 - 29/07 2002).

Table 4.4 Statistics of DRP (loads) results in Clarianna.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	152	152	152	152
Sum	160.70	223.78	237.92	233.97
Avg.	1.06	1.47	1.57	1.54
Sum (value- avg.)^2	332.75	334.53	177.21	256.82
Stand. dev.	1.48	1.49	1.08	1.30
CORR		0.69	0.80	0.65
SSE		233.51	158.82	245.43
MSSE		1.54	1.04	1.61
R^2		0.30	0.52	0.26
SE		1.08	0.65	1.00
GPE		6.55	5.58	6.27
GNE		-6.10	-1.78	-4.35

Looking at the summary of the statistical analysis of the dissolved reactive phosphorus load results in Table 4.4 one can see that the three models have severely overestimated the sum and average of the observed values. The best results for CORR and R^2 have values of 0.80 and 0.52 respectively and obtained from the HSPF model. The statistical analysis of the dissolved reactive phosphorus concentrations (Table 4.5) does not differ very much from the statistical analysis of the dissolved reactive phosphorus loads in terms of assessment of the models except for very bad performance of HSPF. Although there is a high CORR value of 0.54 occurred in the case of SWAT model there is also an obvious thing to notice in that the R^2 statistic is negative for all models. This negative R^2 is coherent with the wide differences between the observed and the high simulated dissolved reactive phosphorus in the three models.

Table 4.5 Statistics of DRP (concentrations) results in Clarianna.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	152	152	152	152
Sum	3.19	5.29	237.92	5.82
Avg.	0.02	0.03	1.57	0.04
Sum (value- avg.)^2	0.03	0.03	177.21	0.03
Stand. dev.	0.01	0.01	1.08	0.01
CORR		0.542	0.80	0.171
SSE		0.055	158.82	0.095
MSSE		0.0004	1.04	0.001
R^2		-1.139	0.52	-2.707
SE		0.012	0.65	0.015
GPE		0.052	5.58	0.050
GNE		-0.073	-1.78	-0.093

4.4 Comparison between the three models' performances in the Dripsey catchment

The comparison between the performances of three models is based on the daily average values of the observed and the estimated time series of the flow and phosphorus variables in the year 2002. Note that the Dripsey catchment has more flow peaks and is quicker to respond to precipitation than the Clarianna. The following sections discuss the comparison between the results from the three models for discharge, total phosphorus, and dissolved reactive phosphorus respectively.

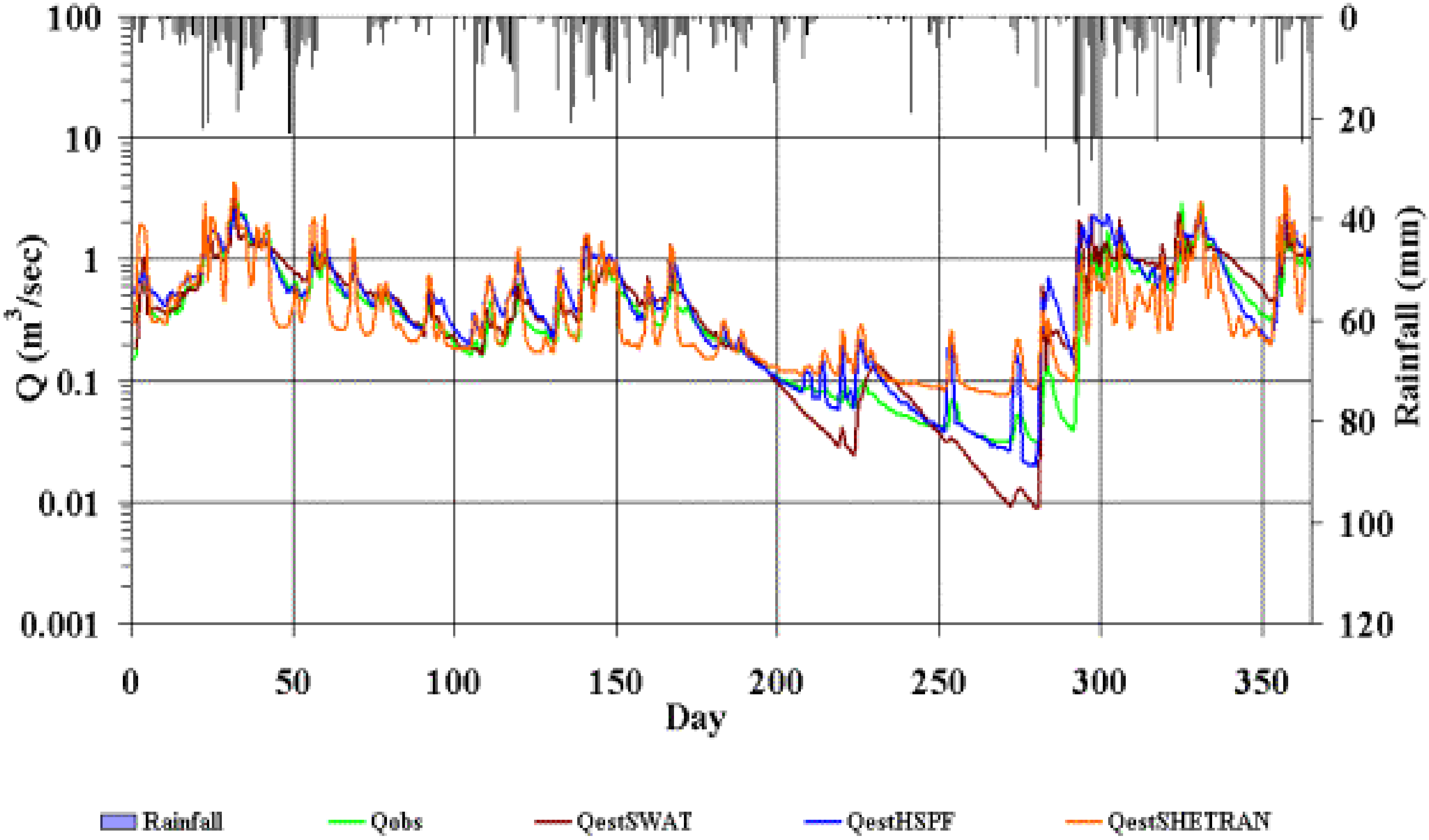


Figure 4.6 Flow results in Dripsey (1/1 - 31/12 2002).

4.4.1 Comparison of flow results

It is clear from Figure 4.6 that in Dripsey catchment the HSPF flow simulation is generally superior to the corresponding simulation by SWAT and SHETRAN models. Even though this model has shown an overestimation to the measured flow values at around 300 days in the simulation period. For the other two models, SWAT is second best while SHETRAN is the third. The noticeable weakness in the SWAT simulation is the underestimation of the flow values in the period between 200 and 250 days. On the other hand SHETRAN fails to adequately model the flow peaks and flow recessions. Most of its estimated peaks are either very much higher or lower than the actual ones and also the estimated flow recession following any peak is not as flat as the actual recession in the observed flow hydrograph.

Table 4.6 Statistics of flow results in Dripsey.

	Observed	Estimated		
		SWAT	**HSPF**	**GOPC**
No. of data	365	365	365	365
Sum	182.95	201.55	222.25	178.89
Avg.	0.50	0.55	0.61	0.49
Sum (value- avg.)^2	105.50	96.07	113.95	126.90
Stand. dev.	0.54	0.51	0.56	0.59
CORR		0.86	0.89	0.84
SSE		29.05	27.55	37.56
MSSE		0.08	0.08	0.10
R^2		0.72	0.74	0.64
SE		0.26	0.25	0.32
GPE		1.79	1.48	0.98
GNE		-1.87	-1.36	-2.21

In terms of statistical analysis of the results as presented in Table 4.6, SHETRAN has a sum slightly lower than the measured flow while the same statistics for SWAT and HSPF are relatively higher. The averages from HSPF and SHETRAN are close to the observed. HSPF has a slightly higher average while SHETRAN is slightly lower. For the standard deviation and the sum of the difference between each value and its average, the comparable values to those for the observed flow were obtained from HSPF. Likewise the CORR, R^2, SSE, MSSE, GNE are all best for HSPF compared to the other two models. The values of CORR and R^2 for this model are 0.89 and 0.74 respectively. However, note that SHETRAN is the best for GPE.

4.4.2 Comparison of total phosphorus results

Figure 4.7 shows that SWAT simulates well the total phosphorus load in the Dripsey catchment. As the figure shows, most of the total phosphorus load values have been captured in the SWAT simulation, particularly the high values. However, there is an obvious underestimation of the values during the period between 200 to 300 days and this corresponds to a deficiency in the flow simulation. The GOPC simulation for the total phosphorus loads is also good except for the remarkable underestimation to the peak values at around 300 days. 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. Despite being the best in flow estimation, HSPF has underestimated most of the high total phosphorus loads while overestimating some of the other values. This means that a good flow estimation by itself is not sufficient to produce a good total phosphorus estimation.

The total phosphorus concentrations results (Figure 4.8) indicate that SWAT model is generally the best in simulating the concentrations but with a noticeable underestimation of some of the peak values. The GOPC does not generate most of the peak values and this can be ascribed to the SHETRAN flow simulation since the total phosphorus loads were reasonably simulated (as discussed later) whereas the estimated flow peaks are generally higher than the observed and thus the corresponding concentration will be smaller (total phosphorus concentration = total phosphorus load/flow). Up to day 300 of the simulation period the HSPF model has generated lower values of total phosphorus concentration close to those obtained from SWAT model while its peak values were not as good as those from SWAT. During the rest of the simulation period all the total phosphorus concentrations from HSPF model were lower than the observed. The total phosphorus loads were overestimated by the model (Figure 4.7), however, the flows were overestimated and the resulting concentrations are lower than the observed.

The statistical analysis of the total phosphorus loads results in Table 4.7 reveal that all statistics in the first group (sum, average, standard deviation, and sum of the difference between each value and its average) for the three models are relatively lower than the observed. Apart from the sum of the difference between each value and its average and the standard deviation the values of the other statistics in the first group for HSPF model are the highest among the three models. SWAT has the highest standard deviation and the second highest sum and sum of the difference between each value and its average while GOPC has the second highest sum and average. The best result for CORR, R^2 was 0.74 and 0.51 respectively and it has been attained by GOPC model. Likewise the GOPC was the best in terms of SSE, and MSSE while HSPF model was the best in SE, GPE, and GNE. The results of SWAT for CORR, R^2, SSE, and MSSE are in the second rank while its results for SE, GPE, and GNE are worst.

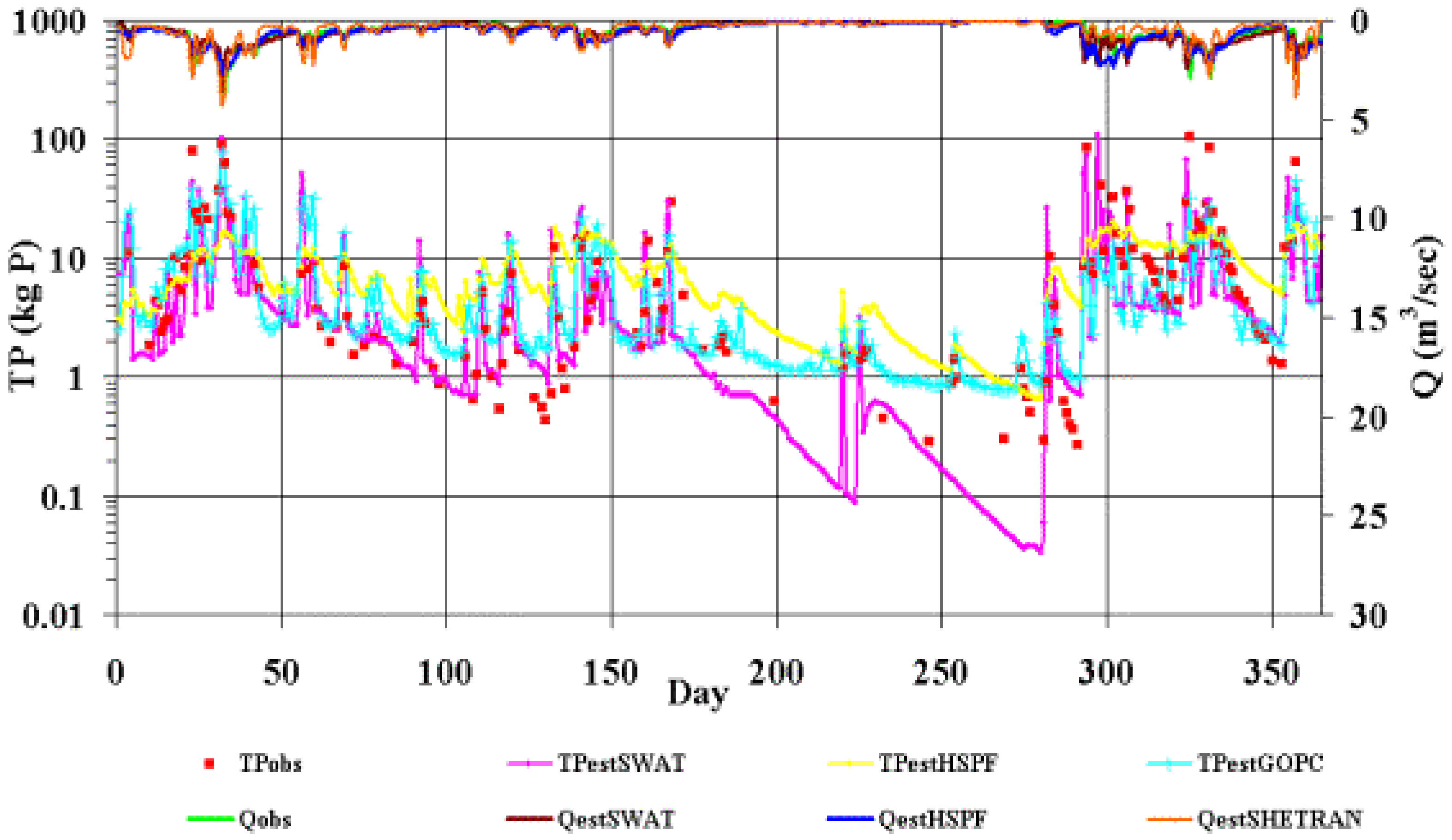


Figure 4.7 TP (loads) results in Dripsey (1/1 - 31/12 2002).

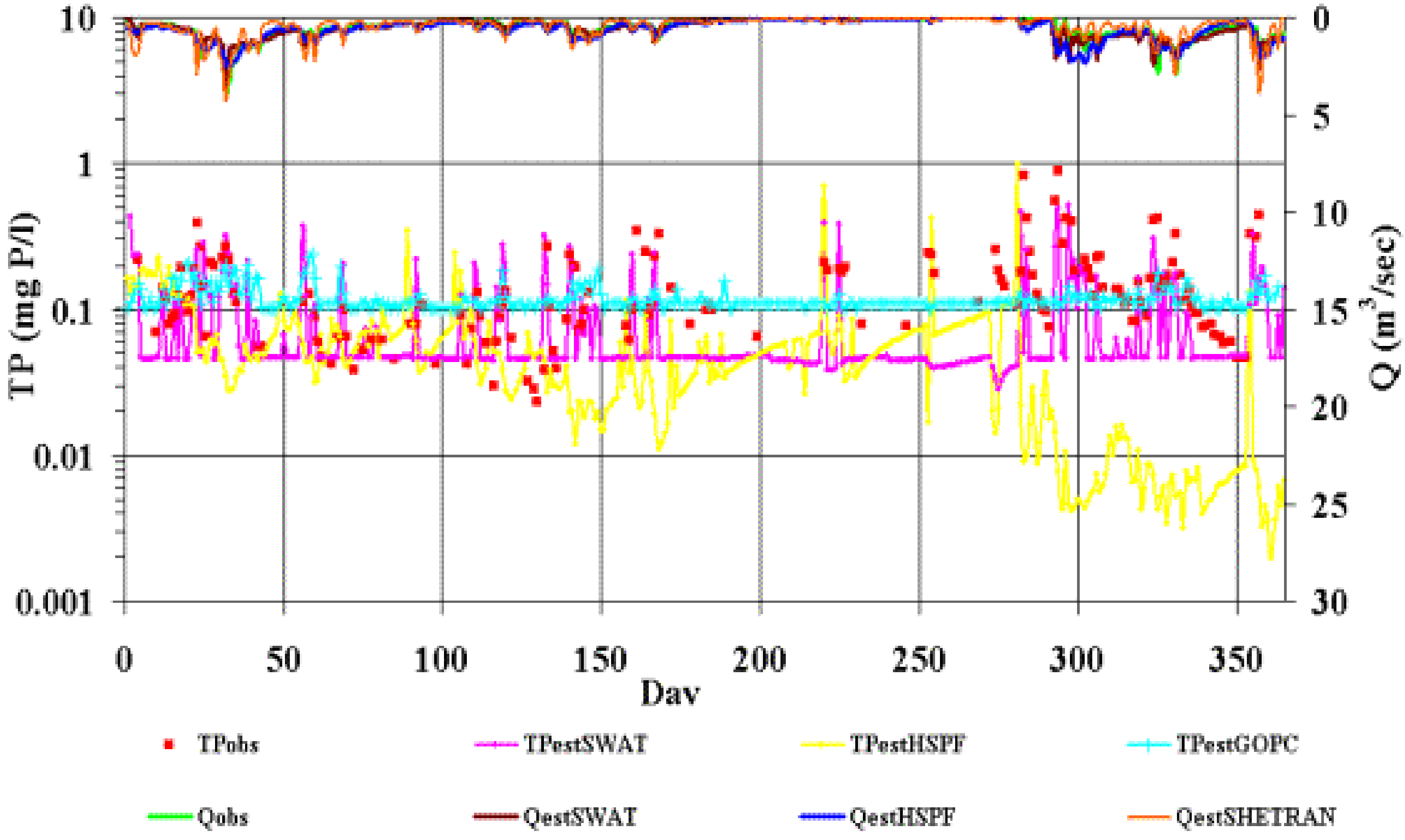


Figure 4.8 TP (concentrations) results in Dripsey (1/1 - 31/12 2002).

Table 4.7 Statistics pf TP (loads) results in Dripsey.

	Observed	Estimated		
		SWAT	**HSPF**	**GOPC**
No. of data	166	166	166	166
Sum	1719.17	1370.82	1530.14	1388.70
Avg.	10.36	8.26	9.22	8.37
Sum (value- avg.)^2	48611.17	32609.08	3715.74	17162.68
Stand. dev.	17.16	14.06	4.75	10.20
CORR		0.69	0.55	0.74
SSE		27323.19	37844.91	23714.63
MSSE		164.60	227.98	142.86
R^2		0.44	0.22	0.51
SE		10.26	3.99	6.89
GPE		14.53	12.90	14.28
GNE		-3.17	-1.63	-2.70

The first group of statistics for total phosphorus concentrations as presented in Table 4.8 follow the same pattern as in the case of the loads. In the second group of statistics, the only significant value for the CORR, which is 0.42, was in the case of SWAT model. On the other hand the R^2 values for the three models were all negative indicating a very poor performance. The other statistics in this group have all similar values apart from two cases which are the SSE for HSPF is relatively higher than the other two models and the GNE for GOPC is relatively lower than the other two models.

Table 4.8 Statistics of TP (concentrations) results in Dripsey.

	Observed	Estimated		
		SWAT	**HSPF**	**GOPC**
No. of data	166	166	166	166
Sum	25.09	16.15	9.02	20.50
Avg.	0.15	0.10	0.05	0.12
Sum (value- avg.)^2	2.52	1.34	1.70	0.10
Stand. dev.	0.12	0.09	0.10	0.02
CORR		0.42	-0.07	0.07
SSE		2.79	6.07	2.67
MSSE		0.02	0.04	0.02
R^2		-0.11	-1.41	-0.06
SE		0.08	0.10	0.02
GPE		0.77	0.88	0.79
GNE		-0.87	-0.87	-0.11

4.4.3 Comparison of dissolved reactive phosphorus results

As shown in Figure 4.9 the behaviour of SWAT model in simulating the peak values of the dissolved reactive phosphorus loads seems to be very different from the simulation of the peak values of the total phosphorus loads. The model has failed to capture most of the high values whereas the GOPC has performed better in this regard. In contrast to its inability to simulate the dissolved reactive phosphorus peak loads SWAT has exhibited good estimates for most of the low dissolved reactive phosphorus loads, which the other two models failed to do. The performance of the HSPF in simulating the dissolved reactive phosphorus loads is affected by its underestimation and the overestimation of the peak and the low values respectively.

Analogous to the estimated loads, the dissolved reactive phosphorus concentrations from SWAT are also not a good match with the observed values as Figure 4.10 shows. Also despite the fact that the GOPC has generated dissolved reactive phosphorus concentrations higher than those from SWAT, the points in the graph of this model do not correspond with the observed points. The shape of the dissolved reactive phosphorus concentrations graph for HSPF displays a prominent feature i.e. a significant drop after a period of stable dissolved reactive phosphorus values during a low flow period followed by a sudden rise. This may be due to numerical problems related to the calculation of the concentration from the dissolved reactive phosphorus loads and the flow discharge.

The figures for the sum of the dissolved reactive phosphorus loads from the three models in Table 4.9 show that SWAT has underestimated the actual sum while HSPF and GOPC have overestimated the actual sum. The closest values for the actual average and standard deviation were obtained from GOPC. The best CORR value (0.77) occurred in the case of SWAT while the best R^2 value (0.46) occurred in the case of GOPC. Also SWAT has achieved the best values for SE and GNE, while GOPC has achieved the best values for SSE, and MSSE, and HSPF has achieved the best values of GPE. The statistical analysis of the dissolved reactive phosphorus concentrations in Table 4.10 agrees with what has been found from the graphs. The GOPC and HSPF models have overestimated the sum of the actual values of dissolved reactive phosphorus concentrations. Also the average of the values from both models are higher than the average of the observed dissolved reactive phosphorus concentrations. Furthermore, HSPF is the only model among the three that has values for the standard deviation and sum of the difference between each value and the average very close to the values of the same statistics for the observed dissolved reactive phosphorus concentrations. The highest CORR was only 0.19 and it has been attained by SWAT model. On the other hand none of the models could get R^2 values greater than zero indicating that all three models performed poorly. The GOPC has only outperformed the other models in the SSE and MSSE. The best results for GPE and GNE were attained by HSPF and SWAT respectively.

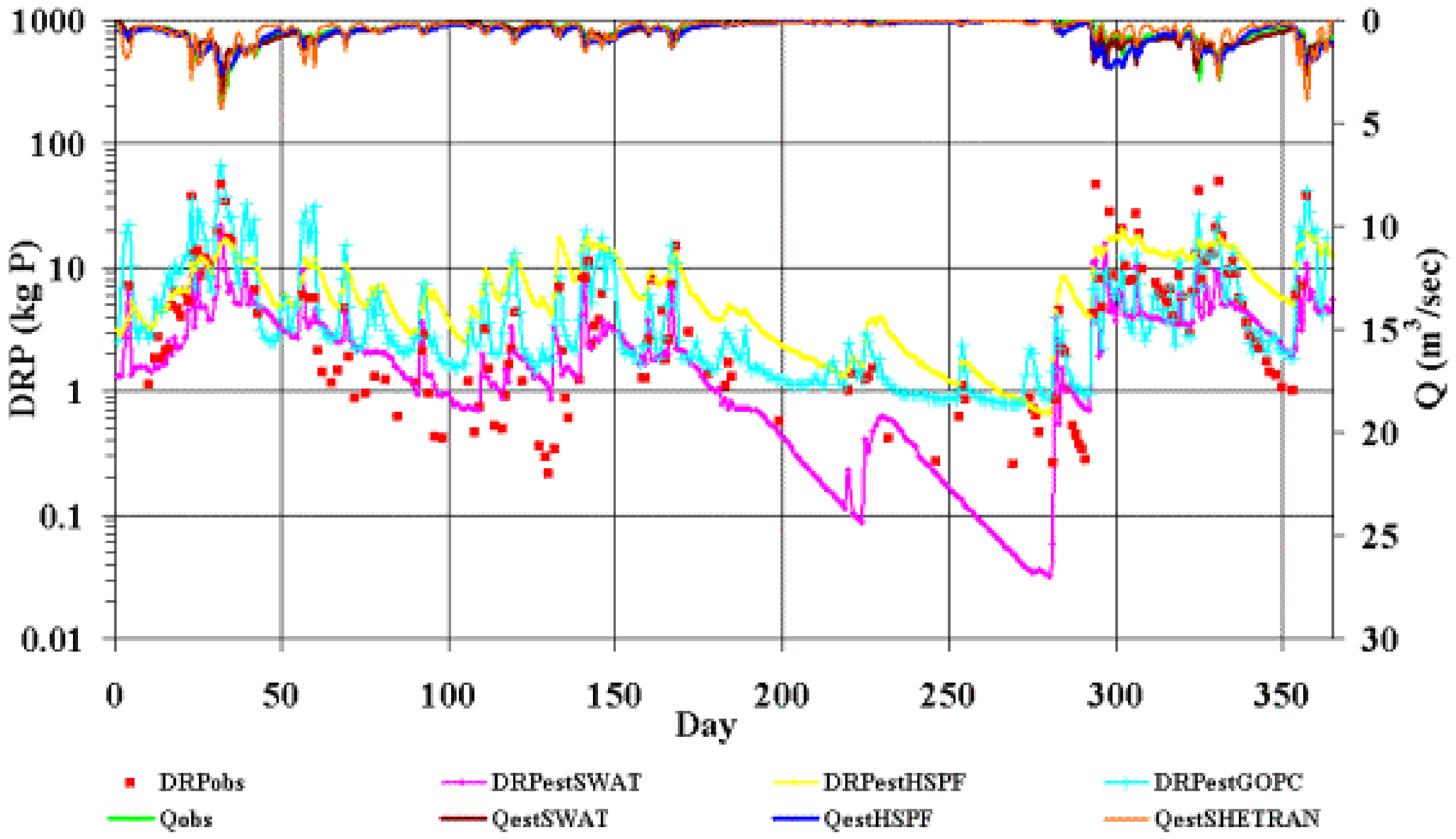


Figure 4.9 DRP (loads) results in Dripsey (1/1 - 31/12 2002).

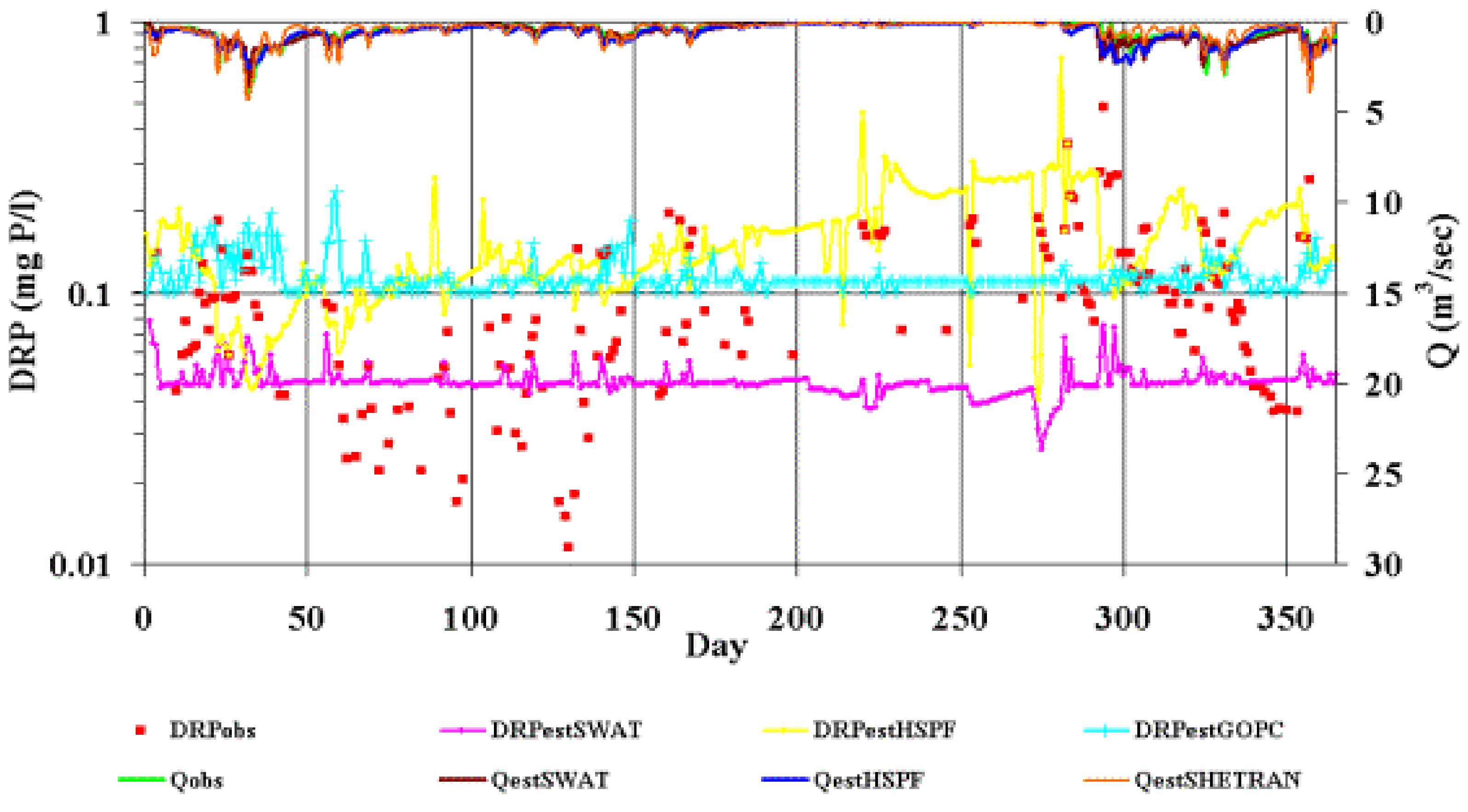


Figure 4.10 DRP (concentrations) results in Dripsey (1/1 - 31/12 2002).

Table 4.9 Statistics of DRP (loads) results in Dripsey.

	Observed	Estimated		
		SWAT	**HSPF**	**GOPC**
No. of data	166	166	166	166
Sum	1054.48	531.39	1504.61	1301.89
Avg.	6.35	3.20	9.06	7.84
Sum (value- avg.)^2	13904.17	1397.95	3841.11	14104.31
Stand. dev.	9.18	2.91	4.82	9.25
CORR		0.77	0.62	0.74
SSE		10191.94	9855.70	7547.50
MSSE		61.40	59.37	45.47
R^2		0.27	0.29	0.46
SE		1.88	3.78	6.20
GPE		41.43	32.48	37.27
GNE		-6.59	-13.26	-25.61

4.5 Comparison between the three models' performances in the Oona catchment

The comparison in the Oona catchment is based on results from the three models for simulation of flow, total phosphorus, and dissolved reactive phosphorus in the year 2002. The following sections discuss the comparison in terms of discharge, total phosphorus, and dissolved reactive phosphorus respectively.

<u>Table 4.10 Statistics of DRP (concentrations) results in Dripsey.</u>

	Observed	Estimated		
		SWAT	**HSPF**	**GOPC**
No. of data	166	166	166	166
Sum	16.64	7.95	24.94	19.67
Avg.	0.10	0.05	0.15	0.12
Sum (value- avg.)^2	0.76	0.01	1.06	0.06
Stand. dev.	0.07	0.01	0.08	0.02
CORR		0.19	0.14	0.002
SSE		1.20	1.98	0.88
MSSE		0.01	0.01	0.01
R^2		-0.57	-1.59	-0.15
SE		0.01	0.08	0.02
GPE		0.41	0.36	0.38
GNE		-0.04	-0.63	-0.12

4.5.1 Comparison of flow results

It is clear from Figure 4.11 that the hydrographs of SWAT and HSPF are better simulations of the observed flow than that of SHETRAN for the Oona catchment. This is because both SWAT and HSPF simulated well the peak values while SHETRAN underestimated most of these peaks. In addition the SHETRAN model was bad at simulating most of the recessions. This model failed to cope with the flashy nature of the catchment. Furthermore it is worth noticing that all three models have simulations that deviated from the actual at different periods during the low flows. This stresses the difficulty in calibrating the flow of this catchment perfectly despite the many attempts that have been made during the calibration.

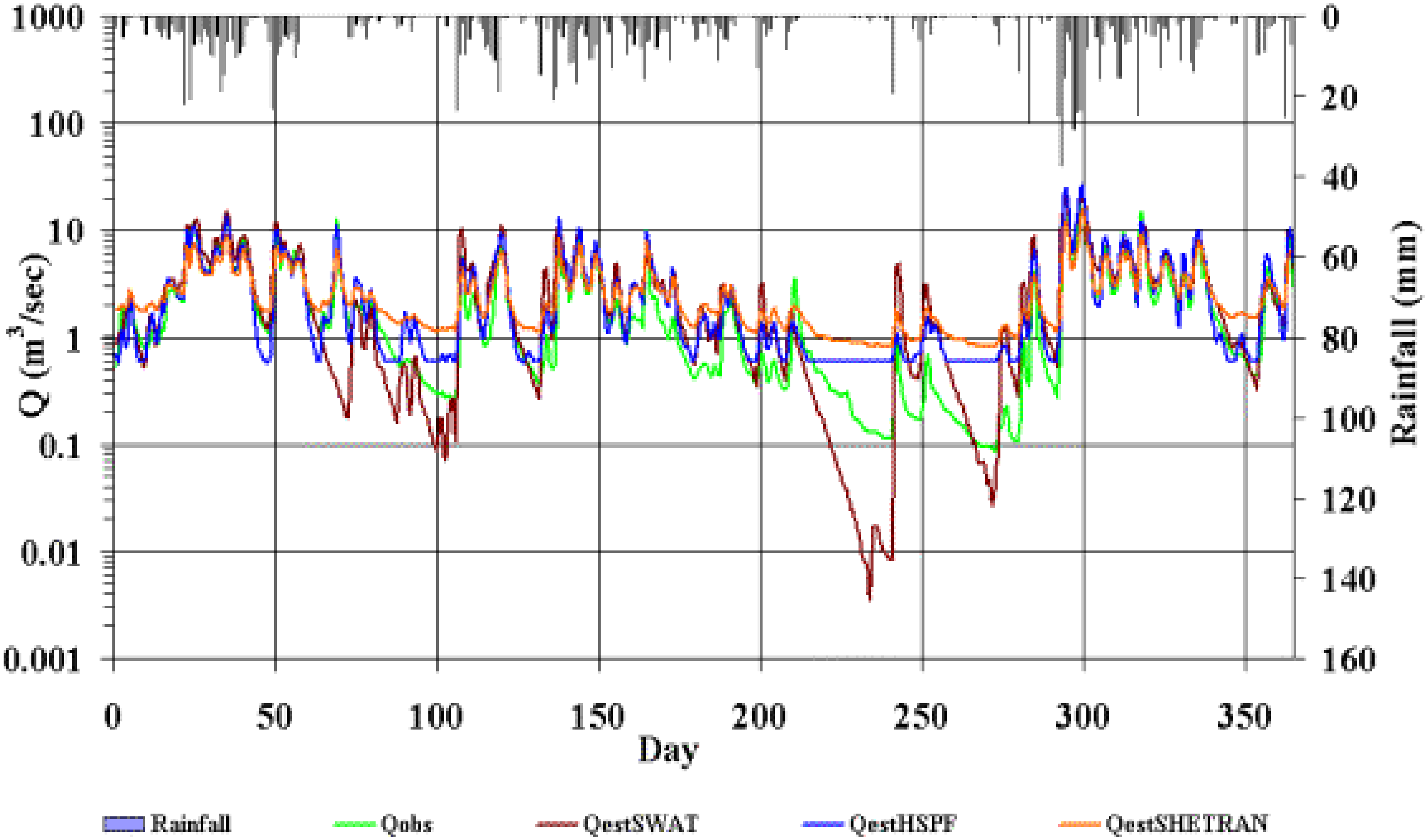


Figure 4.11 Flow results in Oona (1/1 - 31/12 2002).

Table 4.11 Statistics of flow results in Oona.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	365	365	365	365
Sum	870.10	1096.37	1051.40	984.68
Avg.	2.38	3.00	2.88	2.70
Sum (value- avg.)^2	3845.92	4555.32	4573.89	1511.22
Stand. dev.	3.25	3.54	3.54	2.04
CORR		0.90	0.97	0.96
SSE		1047.09	365.11	750.58
MSSE		2.87	1.00	2.06
R^2		0.73	0.91	0.80
SE		1.58	0.85	0.55
GPE		12.30	2.56	10.54
GNE		-6.87	-7.28	-2.09

By examining the statistical analysis results in Table 4.11, it can be seen that the sums and averages of Qest from the three models are greater than the sum of Qobs. Also due to the significant underestimation of the flow peaks by SHETRAN model, the standard deviation and the sum of squares of the difference between each value and its average are smaller than the corresponding Qobs values. The same statistics for SWAT and HSPF are higher than those for Qobs. As shown in the table, CORR of 0.97 and R^2 of 0.91 for HSPF illustrate the excellent performance of this model compared to the other two models which give lower values for both statistics. Moreover the HSPF is the best in terms of SSE, MSSE, and GPE but the worst in GNE showing a very minor difference to SWAT. SHETRAN is the best in SE and GNE while SWAT is the worst in all other statistics (CORR, R^2, SSE, MSSE, GPE).

4.5.2 Comparison of total phosphorus results

The good flow simulation by SWAT model has reflected on its performance in simulating the total phosphorus loads. Figure 4.12 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 captured. Also all of the underestimated flows shown in Figure 4.11 have corresponding deficiencies in the total phosphorus results. 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 excessively bad as the low total phosphorus values do not deviate much from the observed while the high total phosphorus values are not as good as the observed. The GOPC is obviously affected by the poor simulation of the flow peaks by SHETRAN since none of the simulated high total phosphorus loads (corresponding to the underestimated flow peaks) reaches a good level compared to the other two models. Conversely, the GOPC simulation of the low total phosphorus values is in good agreement with the observed a result similar to, and sometimes better than, the other two models.

Figure 4.13 shows that the graphs of total phosphorus concentrations from SWAT and HSPF contain prominent high spikes which are an order of magnitude higher than the observed values. The spikes occur concurrently with the flow peaks and thus they could be related to the flow simulation as well as the total phosphorus load simulation. After investigating the flow and total phosphorus loads it has been found that the spikes occur either due to overestimation in the total phosphorus loads or to underestimation of the flow values as the concentrations have been calculated by dividing the total phosphorus loads by the flow discharge. This emphasises the importance of a good flow modelling in the Oona catchment since any shortcoming in the flow peak simulation will magnify the error in the phosphorus simulation. As can be expected, the performance of GOPC in simulating the total phosphorus concentration is virtually similar to the simulation of the total phosphorus loads. The model results could not reach up to the high total phosphorus concentrations and the low values have been slightly underestimated.

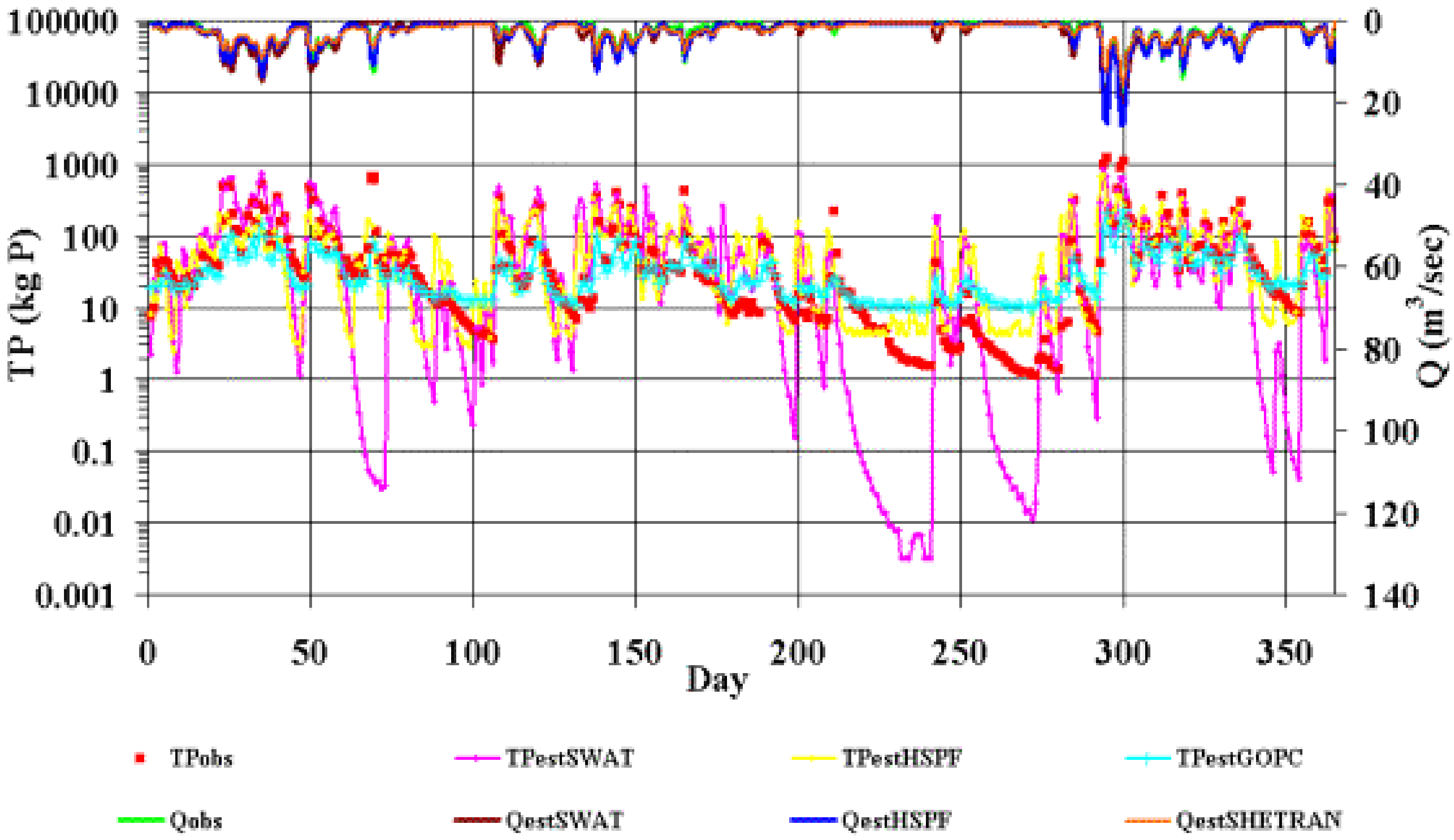


Figure 4.12 TP (loads) results in Oona (1/1 - 31/12 2002).

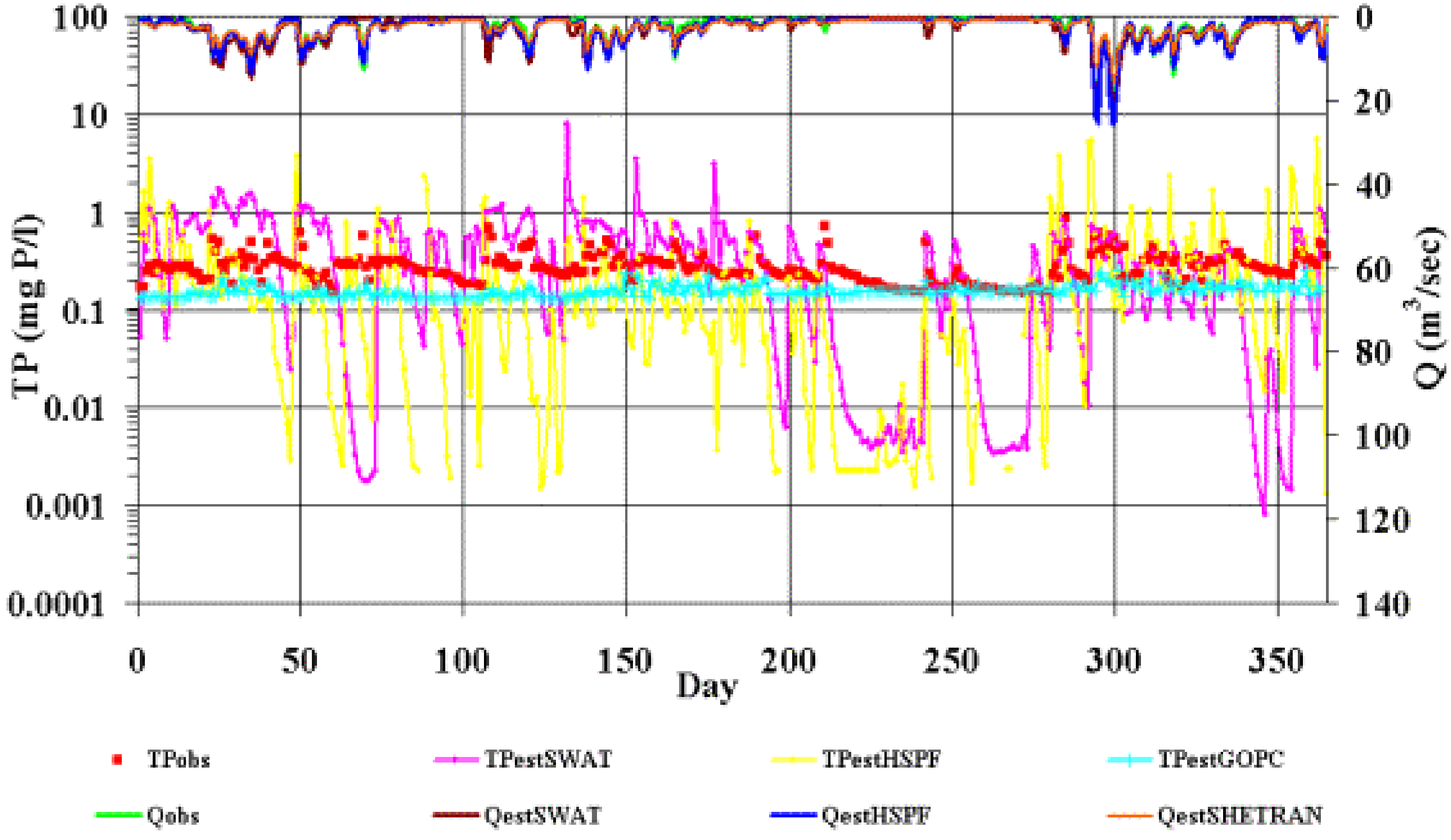


Figure 4.13 TP (concentrations) results in Oona (1/1 - 31/12 2002).

Table 4.12 Statistics of TP (loads) results in Oona.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	365	365	365	365
Sum	27495.75	33284.96	25717.06	12518.61
Avg.	75.33	91.19	70.46	34.30
Sum (value- avg.)^2	7190139.63	7186797.26	2776852.82	314930.74
Stand. dev.	140.55	140.51	87.34	29.41
CORR		0.79	0.60	0.87
SSE		3155210.46	4614483.22	5514414.23
MSSE		8644.41	12642.42	15107.98
R^2		0.56	0.36	0.23
SE		86.82	69.98	14.75
GPE		624.81	878.26	980.59
GNE		-441.84	-619.80	-18.06

Table 4.12 displays the results of the statistical analysis for the total phosphorus loads simulated by the three models. The sum and average of total phosphorus loads from SWAT are higher than the observed values whereas the same statistics from GOPC are much lower than the observed values. This is expected for the GOPC since the hydrological variables used from SHETRAN model underestimated the flow peaks and hence resulted in a lower delivery of phosphorus loads from the soil. This in turn has resulted in underestimation of the high total phosphorus loads and hence a sum lower than the observed. The only way to rectify this situation is to improve the performance of the SHETRAN model in this catchment by seeking a better calibration method than the manual calibration used in this study. SWAT has values of standard deviation and sum of squares of the difference between each value and its average almost equal to the observed values. HSPF has values lower than the observed for the sum, average, standard deviation, and sum of squares of the difference between each value and its average. The best CORR was 0.87 in the case of GOPC model while the best R^2 was 0.56 in the case of SWAT model. Also the former model was the best in terms of SE and GNE while the latter was superior in terms of SSE, MSSE, and GPE.

Table 4.13 Statistics of TP (concentrations) results in Oona.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	365	365	365	365
Sum	101.49	156.29	156.29	105.87
Avg.	0.28	0.43	0.43	0.29
Sum (value- avg.)^2	3.77	117.49	117.49	159.94
Stand. dev.	0.10	0.57	0.57	0.66
CORR		0.26	0.02	0.17
SSE		118.40	162.84	9.23
MSSE		0.32	0.45	0.03
R^2		-30.43	-42.22	-1.45
SE		0.55	0.66	0.02
GPE		0.57	0.65	0.71
GNE		-7.48	-5.19	-0.02

The effect of the spikes in the total phosphorus concentration simulations of SWAT and HSPF has become clear in their sums, averages, standard deviations, and sums of squares of the difference between each value and its average (Table 4.13) which are very high compared to the observed. The first two statistics for GOPC agree with the observed while the last two statistics are remarkably higher than observed. In the simulation of total phosphorus concentrations by the three models the best CORR was only 0.26 in the case of SWAT but the R^2 values are negative for all models. In terms of the other statistics, GOPC is the best in SSE, MSSE, SE, and GNE while SWAT is the best in GPE.

4.5.3 Comparison of dissolved reactive phosphorus results

Simulation of the high dissolved reactive phosphorus loads by SWAT is generally higher than the observed as shown in Figure 4.14. The equivalent high loads from HSPF are better than those from SWAT although some values still exceed the observed. The third model, GOPC, has produced peaks of dissolved reactive phosphorus loads that are constantly less than those obtained from SWAT and HSPF but its values are closer to the observed. All three models show simulation for the low dissolved reactive phosphorus loads that poorly match the observed. Figure 4.15 reveals that peaks of dissolved reactive phosphorus concentrations simulated by HSPF and SWAT are far greater than the observed values. The GOPC produced values that match the peaks and overestimate the low values. Looking at the results of total phosphorus and dissolved reactive phosphorus concentrations, it is plausible to say that the models simulations are essentially dependent on the flow results since the calculations of these concentrations significantly rely on the flow.

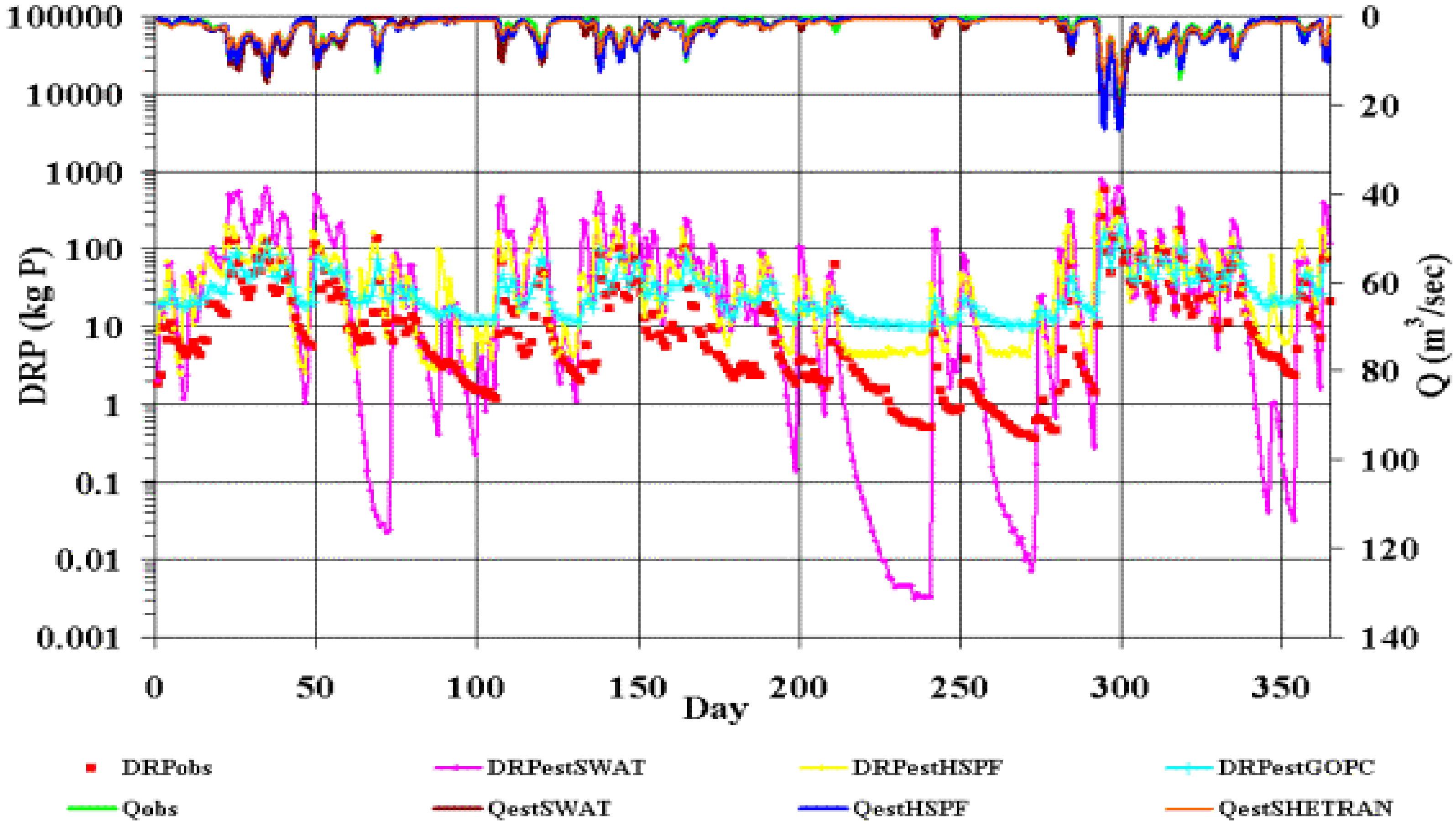


Figure 4.14 DRP (loads) results in Oona (1/1 - 31/12 2002).

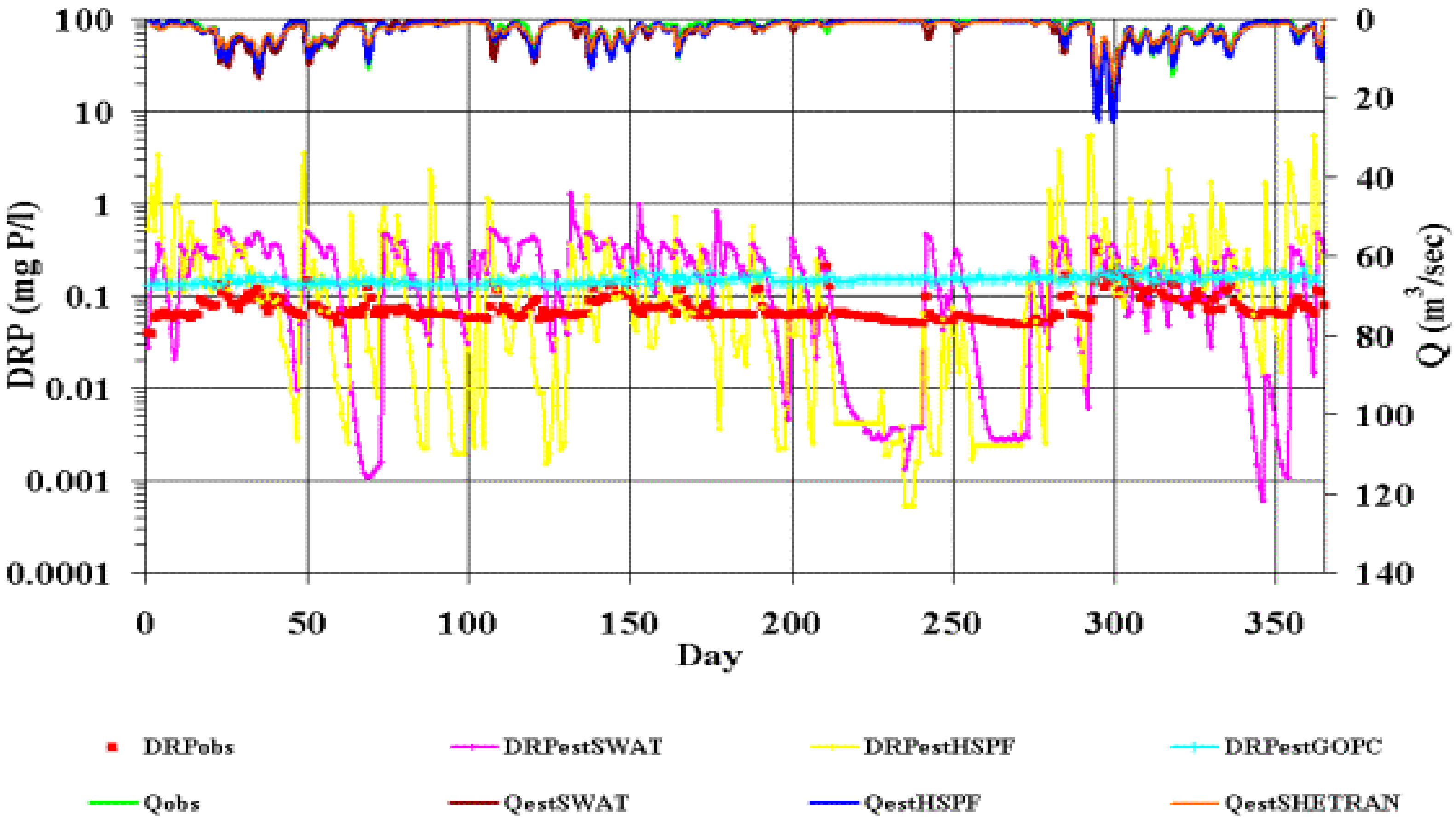


Figure 4.15 DRP (concentrations) results in Oona (1/1 - 31/12 2002).

Table 4.14 Statistics of DRP (loads) results in Oona.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	365	365	365	365
Sum	7959.36	29207.70	17458.04	11678.77
Avg.	21.81	80.02	47.83	32.00
Sum (value- avg.)^2	800682.64	5903269.60	1198745.10	234510.23
Stand. dev.	46.90	127.35	57.39	25.38
CORR		0.75	0.50	0.84
SSE		4695243.49	1264507.68	348386.08
MSSE		12863.68	3464.40	954.48
R^2		-4.86	-0.58	0.56
SE		84.86	49.73	13.94
GPE		132.98	406.75	422.51
GNE		-522.56	-491.81	-51.85

From Table 4.14 it can be noticed that all three models have overestimated the sum, average, standard deviation, and sum of squares of the difference between each value and its average of the observed dissolved reactive phosphorus loads. In terms of CORR and R^2, the GOPC was the best among the three with values of 0.84 and 0.56 respectively. The R^2 for the other two models are negative and that is due to the unrealistically high peaks simulated by the two models. With the exception of the GPE, the GOPC was the best in the three models according to the values of SSE, MSSE, and GNE. The best result for GPE was obtained from SWAT. The corresponding statistics for the dissolved reactive phosphorus concentration results in Table 4.15 has the same trend as the comparison results obtained from the statistical analysis of the dissolved reactive phosphorus loads. The three models have overestimated all statistics in the first group including sum, average, standard deviation, and sum of squares of the difference between each value and its average for the observed values. In the second group of statistics, the best CORR was 0.35 and it was obtained from SWAT in this case. All the models have showed negative values for the R^2 statistics. The GOPC is again the best in the values of SSE, MSSE, SE, and GNE while SWAT has the best GPE.

Table 4.15 Statistics of DRP (concentrations) results in Oona.

	Observed	Estimated		
		SWAT	HSPF	GOPC
No. of data	365	365	365	365
Sum	27.73	71.67	98.20	53.97
Avg.	0.08	0.20	0.27	0.15
Sum (value- avg.)^2	0.29	10.80	156.94	0.12
Stand. dev.	0.03	0.17	0.66	0.02
CORR		0.35	0.01	0.17
SSE		15.16	170.65	2.23
MSSE		0.04	0.47	0.01
R^2		-51.83	-593.80	-6.78
SE		0.16	0.66	0.02
GPE		0.12	0.16	0.13
GNE		-1.23	-5.41	-0.13

4.6 Validation of the three models the in Oona catchment

The purpose of model validation is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort (Donigian, 2002). As mentioned earlier, all data used in this work was obtained from the Clarianna, Dripsey, and Oona EPA project groups responsible of data collection. The initial data received were sufficient to perform the three models calibration. However, only the Oona group was able to provide more data for two different periods than the one used in the calibration. This additional data has been used in the three models validation in this catchment and because no additional data (particularly phosphorus) has been provided for the other two catchments no model validation has been made.

Ideally, validation set of data should cover a period of time following the calibration period. However, the two data periods made available by the Oona group have covered 3 months (1/10/2001 to 31/12/2001) prior to and 1 month (January 2003) after the calibration. Therefore to overcome difficulties regarding initial conditions, the initial values of the flow and phosphorus variables were obtained by running each model one year before the start time of the validation period (i.e. one year warming-up period) using the calibration data. Then independent runs of the three models (SWAT, HSPF, and SHETRAN/GOPC) were made for the two periods using the parameters corresponding to the best results from the calibration process in each model. Finally, the results of the validation were compared with the observed data of discharge, total phosphorus, and dissolved reactive phosphorus.

Table 4.16 Nash-Sutcliffe values of flow and phosphorus validation results in Oona.

	First validation period (1/10/2001 - 31/12/2001)			**Second validation period (1/1/2003 - 31/1/2003)**		
	SWAT	**HSPF**	**GOPC**	**SWAT**	**HSPF**	**GOPC**
Flow	0.61	0.90	0.69	0.77	0.78	0.80
Total phosphorus load	0.53	0.59	0.15	0.49	0.77	0.23
Total phosphorus concentration	-1.42	-1.41	-0.78	-2.93	-3.40	-3.16
Dissolve reactive phosphorus load	-1.34	-15.28	0.39	-5.56	-6.40	-0.65
Dissolve reactive phosphorus concentration	-11.51	-369.01	-10.08	-27.58	-26.59	-4.78

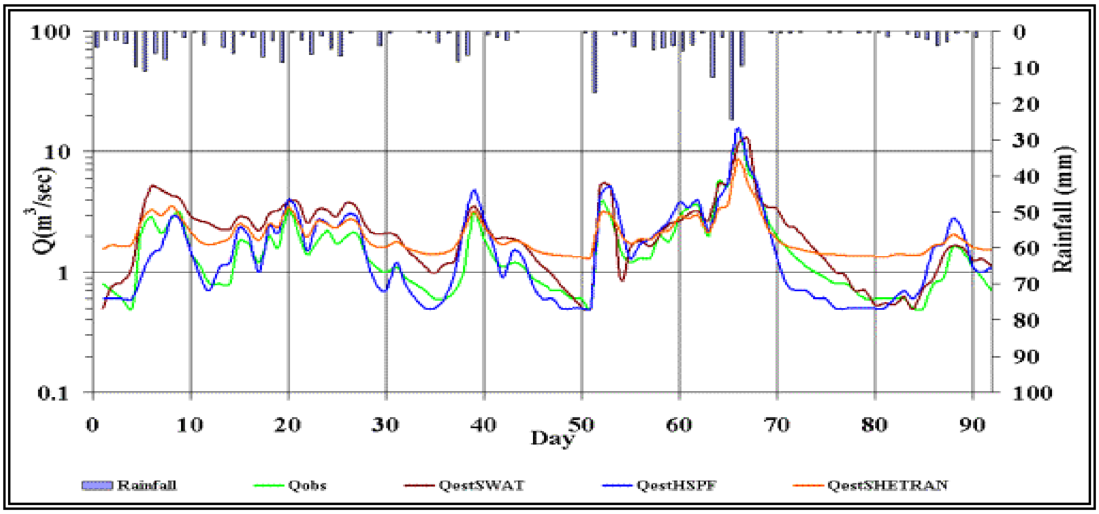


Figure 4.16 Flow results in Oona (1/10 - 31/12 2001).

4.6.1 First validation period (1/10/2001 – 31/12/2001)

Figure 4.16 shows that the HSPF simulated hydrograph was the best match to the observed hydrograph in the first validation period, particularly at the highest peak a feature which both SWAT and SHETRAN underestimated. However when examining the overall shape of the simulated hydrographs using the latter two models, it can be seen that the SWAT performance was generally better than SHETRAN in flow simulation. Statistical analysis of the first period results (Table 4.16) revealed that HSPF model has the best R^2 value of 0.90 while SHETRAN has the lowest of 0.69.
The total phosphorus load simulation by HSPF was remarkably better than the other two models in simulating the high values during the first period (Figure 4.17). The second best model in capturing the high values was SWAT while the GOPC was the best in simulating the low values. Statistical analysis of the total phosphorus loads results (Table 4.16) supports the remarks made on the graphs of these models. The R^2 values of HSPF, SWAT, and GOPC were 0.59, 0.53, and 0.15 respectively indicating the superiority of the HSPF model among the three models.

Simulation of total phosphorus concentrations by the three models was not as good as the simulation of the loads. As Figure 4.18 shows, the HSPF graph is the only one for which most of its peak values are close to the observed values. SWAT has always produced very low values which are far below the observed. The GOPC performance was very poor and it generated values always lower than the observed. The inferior performance of the three models in simulating the total phosphorus concentrations was reflected in negative values for their R^2 values reported in Table 4.16.

The good simulation by HSPF of the total phosphorus loads was accompanied by an overestimation of the dissolved reactive phosphorus loads (Figure 4.19). The closest shape to the observed graph of the same phosphorus variable was achieved by SWAT. The GOPC performance was better in simulating the dissolved reactive phosphorus loads than the total phosphorus. In addition the GOPC is the only model among the three which has adequate dissolved reactive phosphorus load results to produce a positive value of 0.39 for the R^2 (Table 4.16). As shown in Figure 4.20 the dissolved reactive phosphorus concentrations graphs of the three models do not have any attribute to distinguish preferences between them. The SWAT model is the best of the three. Some of the , R^2 statistics were negative (Table 4.16).

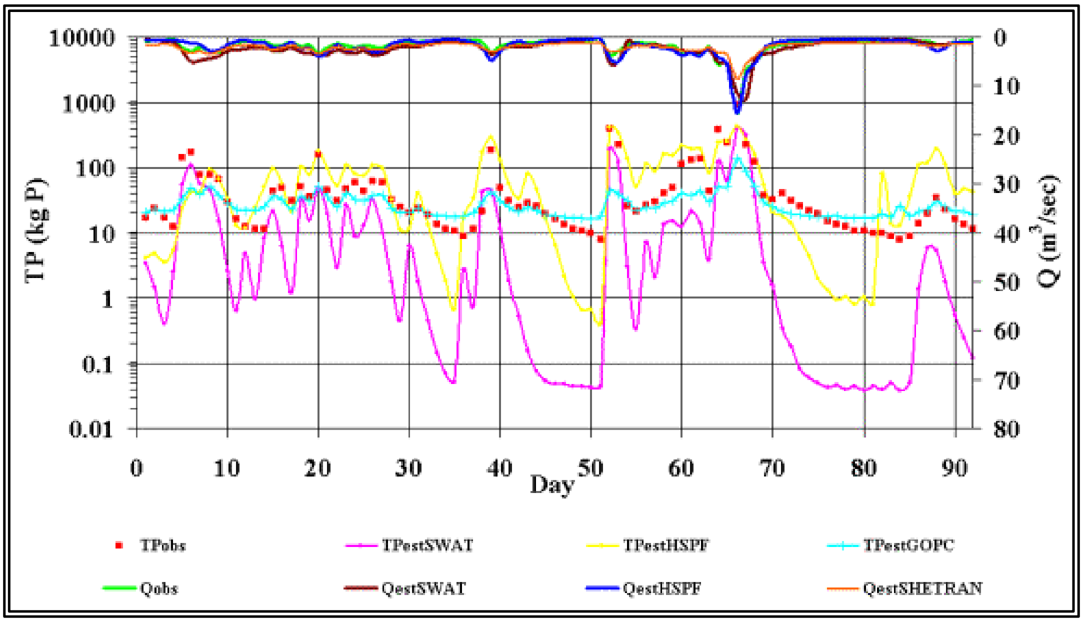


Figure 4.17 TP (loads) results in Oona (1/10 - 31/12 2001).

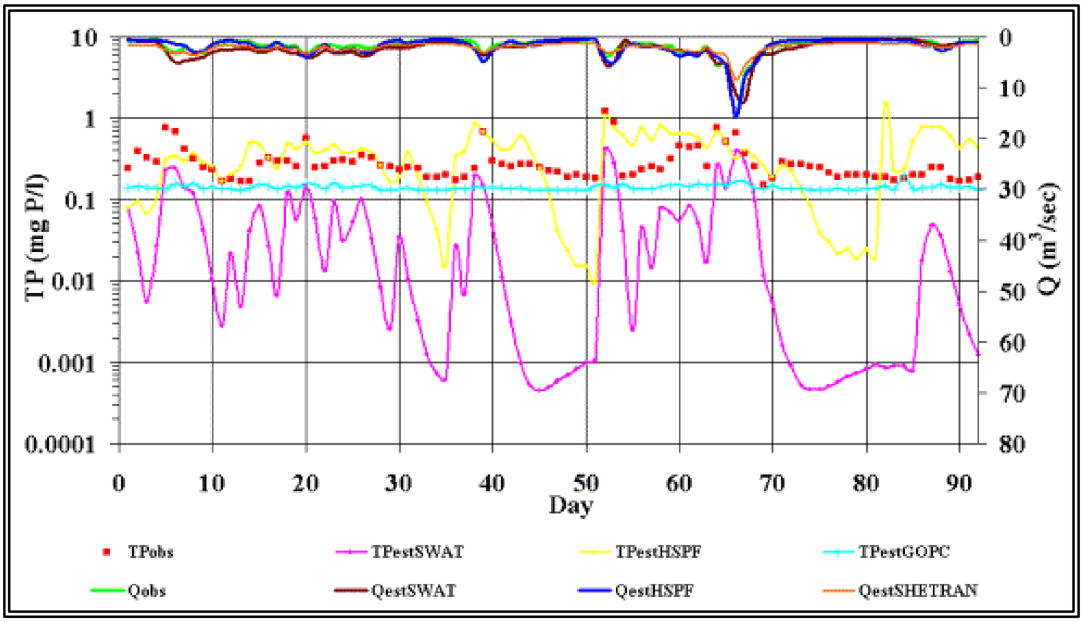


Figure 4.18 TP (concentrations) results in Oona (1/10 - 31/12 2001).

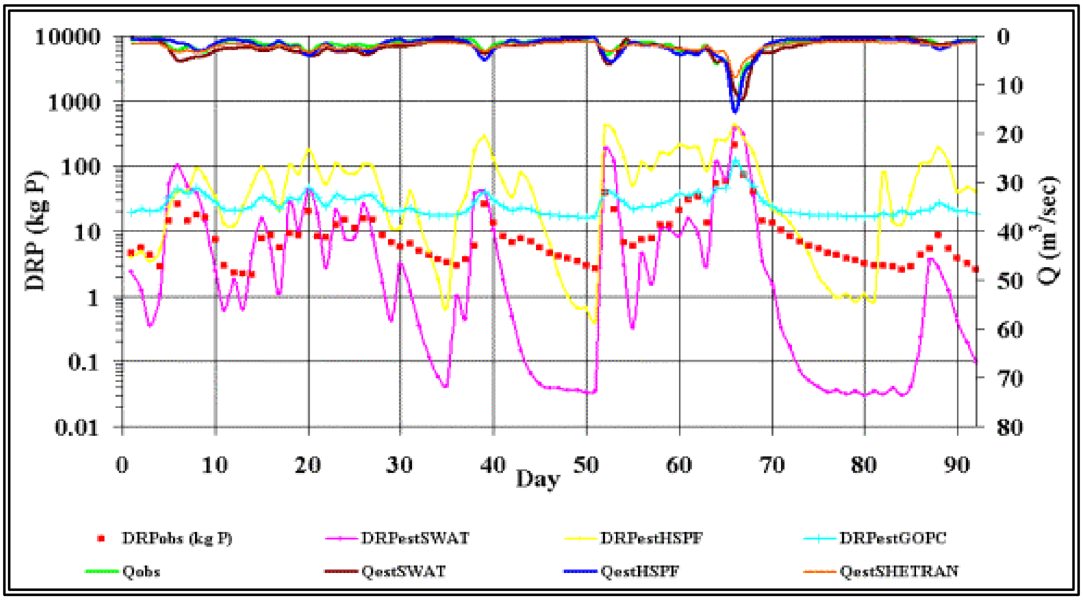


Figure 4.19 DRP (loads) results in Oona (1/10 - 31/12 2001).

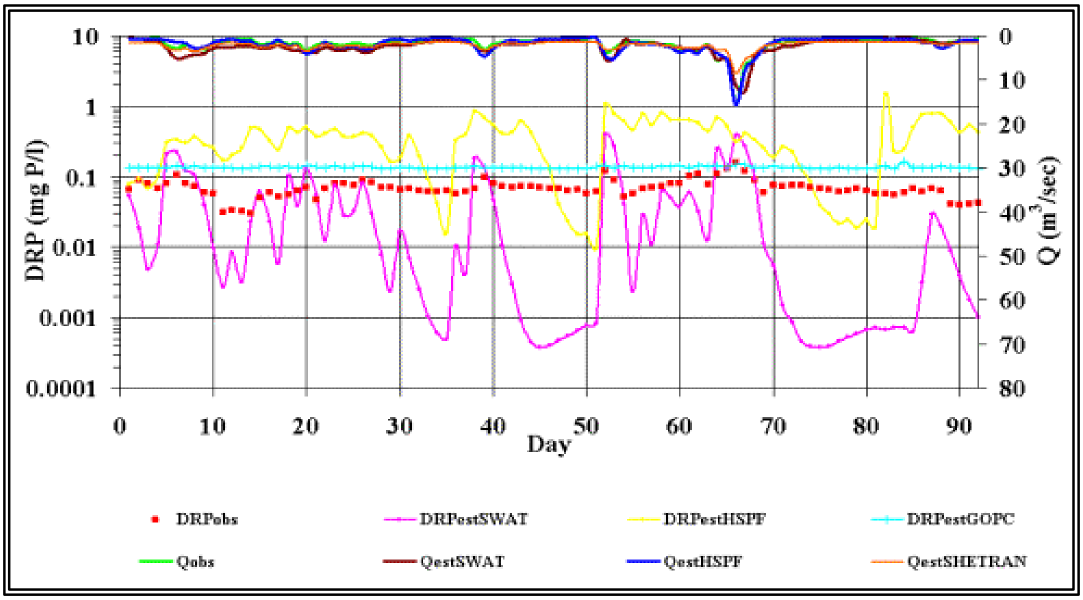


Figure 4.20 DRP (concentrations) results in Oona (1/10 - 31/12 2001).

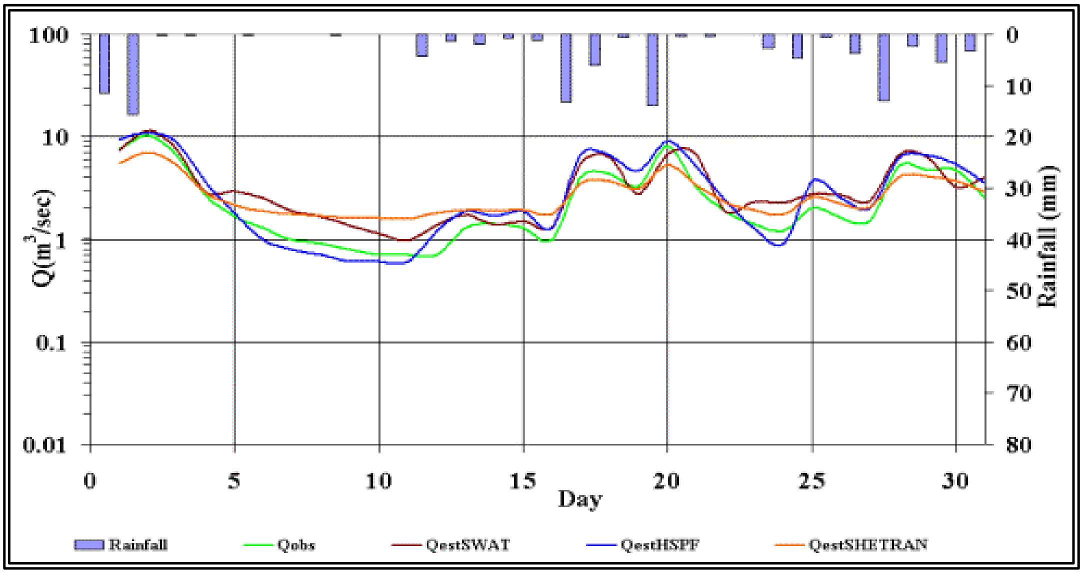


Figure 4.21 Flow results in Oona (1/1 - 31/1 2003).

4.6.2 Second validation period (1/1/2003 – 31/1/2003)

During the second period, the simulated hydrographs (Figure 4.21) indicated that for peaks all three models were poor. Yet the SHETRAN has achieved the best R^2 of 0.80 which is marginally higher than the HSPF and SWAT values by 2% and 3% respectively (Table 4.16).

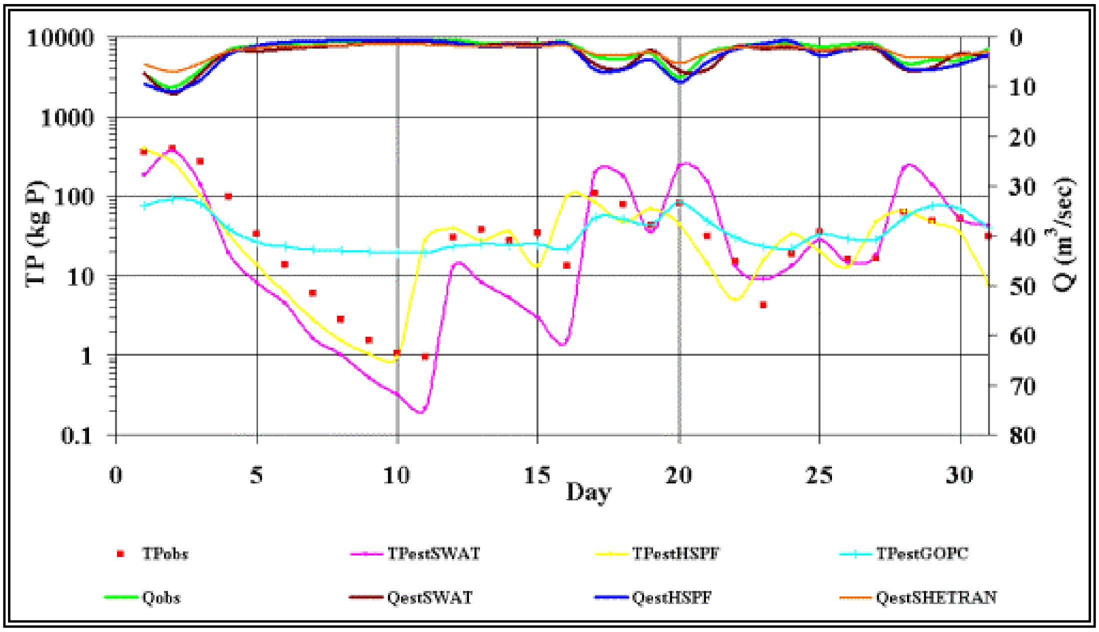


Figure 4.22 TP (loads) results in Oona (1/1 - 31/1 2003).

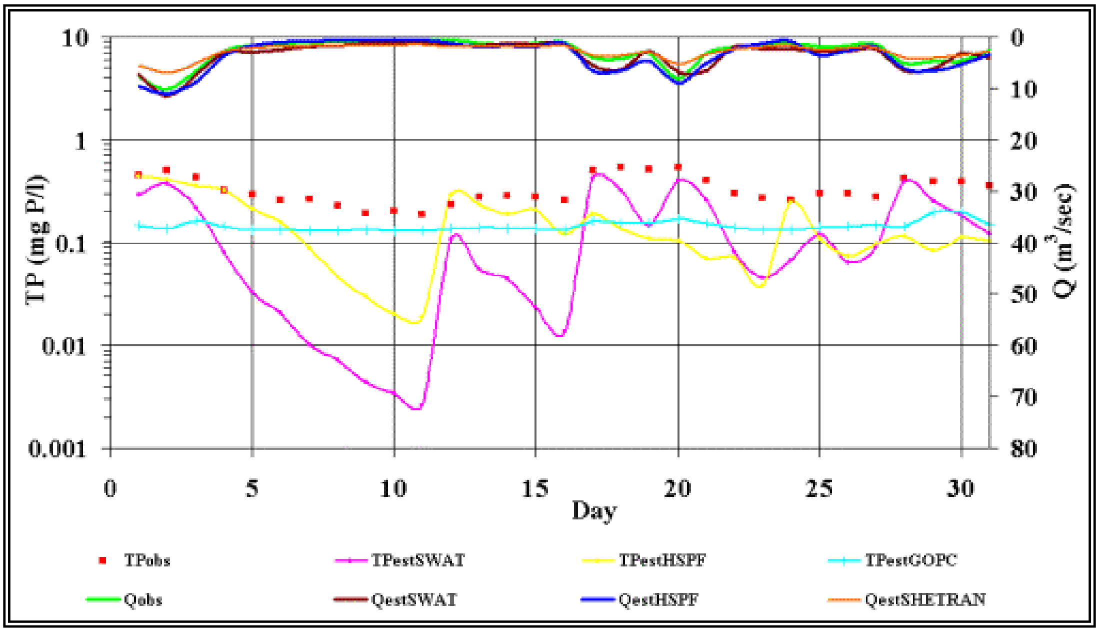


Figure 4.23 TP (concentrations) results in Oona (1/1 - 31/1 2003).

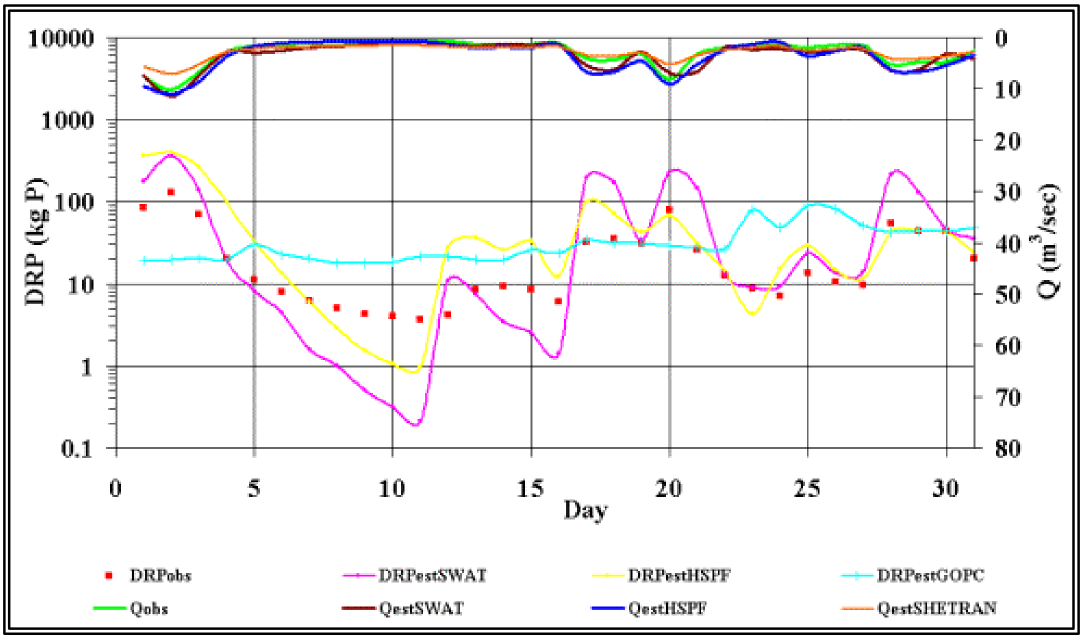


Figure 4.24 DRP (loads) results in Oona (1/1 - 31/1 2003).

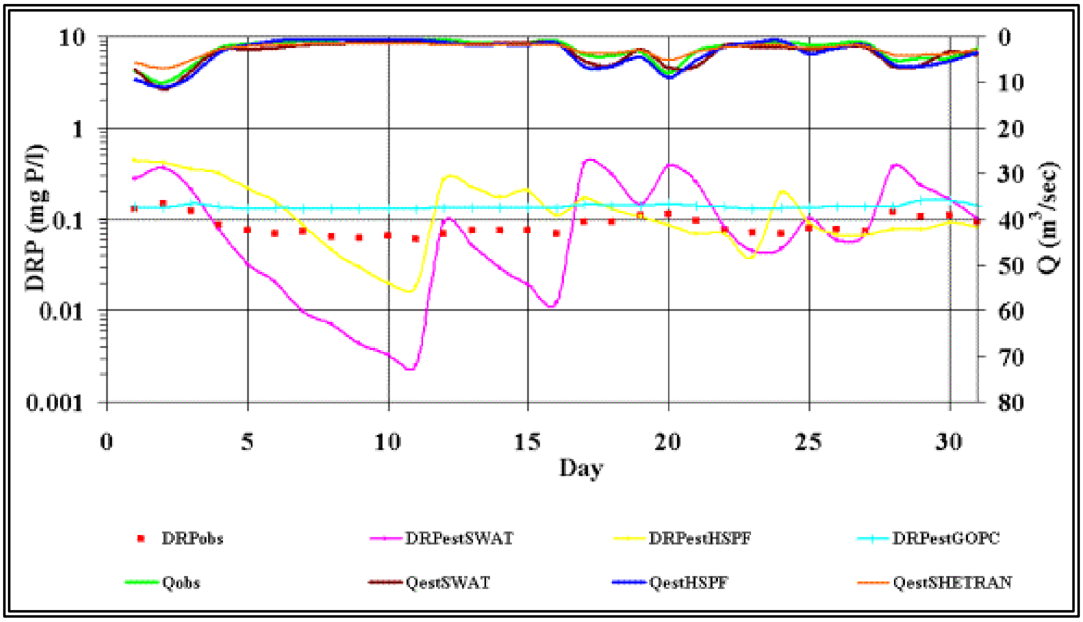


Figure 4.25 DRP (concentrations) results in Oona (1/1 - 31/1 2003).

Similar to the first period, HSPF has also performed better than SWAT and GOPC in simulating the total phosphorus loads during the second period (Figure 4.22). The R^2 value of HSPF obtained from the statistical analysis of the total phosphorus loads results was 0.77 which is substantially higher than the R^2 values of 0.49 and 0.23 for SWAT and GOPC respectively (Table 4.16). From Figure 4.23 it can be seen that the SWAT performance was generally the best at simulating some of the high total phosphorus concentrations. The HSPF performance was affected by the deficiency in simulating the high values. Same unchanged features in the GOPC graph during the first period can also be noticed in the second period. The negative R^2 values (Table 4.16) of the three models indicate the poor performance in simulating total phosphorus concentrations.

In contrast to the first period, the HSPF has the best graph to match the observed dissolved reactive phosphorus loads graph of the second period, Figure 4.24. The SWAT graph could also have been a good match to the observed if it did not show the remarkable overestimation of the peak values of the dissolved reactive phosphorus loads. The GOPC acceptable performance in the first period has been undermined in the second period and as a result the simulated dissolved reactive phosphorus loads graph has the poorest match to the observed. None of the three model results for dissolved reactive phosphorus was able to produce a positive R^2 value (Table 4.16). The results from the three models for the dissolved reactive phosphorus concentrations during the second period were much better than the results of the first period. Figure 4.25 shows that the SWAT and HSPF graphs are both better than the GOPC graph in matching the observed values inspite of the overestimation to the peak values by the two models. Negative R^2 values have been found after analysing the dissolved reactive phosphorus concentrations results (Table 4.16).

4.7 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 to assess the models' performance. Table 4.17 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.

Table 4.17 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.

	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
Total phosphorus load	SWAT	0.59	GOPC	0.51	SWAT	0.56	HSPF	0.59	HSPF	0.77
Total phosphorus concentration	SWAT	0.55	-	No useful	-	No useful	-	No useful	-	No useful
Dissolved reactive phosphorus load	HSPF	0.70	GOPC	0.46	GOPC	0.56	GOPC	0.39	-	No useful
Dissolved reactive phosphorus	-	No useful	-	No useful	-	No useful	-	No useful	-	No useful

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. Anderton et al. (2002) has attributed this shortcoming in the recession simulation by this model to three reasons. They suggested that the first reason could be the combination of parameter values used in the soil moisture and root zone evapotranspiration is inappropriate. Also they added that the scale of model application is insufficient to capture important micro-scale heterogeneity in process operation in the catchment. And finally, important processes governing runoff generation and soil moisture dynamics in the catchment are not incorporated within SHETRAN. 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, Im et al. (2003) found that SWAT was good during calibration whereas HSPF was good during the validation in simulating phosphorus loads, an outcome which is similar to the results of 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.

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 essence there are two limitations in the phosphorus model comparisons with measured data. First the lack of measured information about the actual application rates of phosphorus to the soil. This has necessitated some assumption of phosphorus application scenarios, based on Teagasc guidelines to farmers, which could introduce some uncertainty. The second relates to differences in the averaging process between the model and the data processing algorithms, both estimating mean daily loads.

In all cases the three models are better at simulating phosphorus loads than concentrations. Also the simulation of the 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 P concentrations obtained with parameters calibrated for loads suggests that the models should be independently calibrated for the concentrations if good estimates are required.

Therefore for future work in order to exploit the maximum capabilities of the models, a strategic calibration approach is recommended where all parameters are targeted at a once by constructing an appropriate multi-objective function including all the variables required by the end-user.

4.8 Conclusions

The conclusions, which can be made regarding 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 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.
- Dissolved Reactive Phosphorus: [bad] Simulation of the daily dissolved reactive phosphorus loads and concentrations by the three models in the study catchments were 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 water bodies, the load delivered to the water body is the more important parameter.

4.9 Limitations

- This study was based on data collected during an intensive monitoring period, done especially for the project. As always, if additional data were available then a wider range of climates and model behaviour could be tested.
- The assumptions made in defining the model variables representing dissolved reactive phosphorus (DRP) might not be adequate and may explain the model's difficulty in modelling this variable
- No information about the actual loads of phosphorus applied to the soil in the study catchments has been provided to the modeller. Assumptions of typical

phosphorus application scenarios had to be made and this increases the modelling uncertainties.

4.10 Recommendations

For the further improvements of the phosphorus loss simulation in the study catchments using SWAT, HSPF, and SHETRAN/GOPC models, some suggestions are 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 “hotspots” 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 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. So far a number of decision support tools (e.g. MULINO (Giupponi et al., 2004), AVGWL (Evans et al., 2002), MIKE Basin (Jha and Das Gupta, 2003)) have been proposed for use in WFD-related decision-making, but these tools are being further developed. However, none of these yet incorporate a comprehensive integration of modelling with leading-edge multi-criteria decision support tools.

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APPENDIX A

SWAT parameters

Parameter	Calibrated value
CMN	0.3
UBP	20
PPERCO	10
PHOSKD	500
PSP	0.5
RSDCO	0.05
RSDIN	1000.0
ERORGP	0.5
SOL_LABP	25.0
SOL_ORGP	275

CMN: Rate factor for humus mineralization of active organic nitrogen
UBP: Phosphorus uptake distribution parameter
PPERCO: Phosphorus percolation coefficient (10 m3/ Mg)
PHOSKD: Phosphorus soil partitioning coefficient (m3/ Mg)
PSP: Phosphorus sorption coefficient
RSDCO: Residue decomposition coefficient
RSDIN: Material in the residue pool for the top 100 mm of soil (kg/ha)
ERORGP: Organic phosphorus enrichment ratio
SOL_LABP: Initial concentration of the labial (soluble) phosphorus in the soil (mg P/kg soil)
SOL_ORGP: Initial concentration of the organic phosphorus in the soil (mg P/kg soil)

HSPF parameters

Parameter	Calibrated value
THPLP	1.07
THKDSP	1.07
THKADP	1.05
THKIMP	1.07
THKMIP	1.05
KDS	4
KAD	0
KIMP	0
KMIP	4
PLP	8
ORGP	2
P4AD	2
P4SU	0
PLTP	2
IP4SU	0.001

THPLP: temperature coefficient (theta) for plant uptake
THKDSP: temperature coefficient (theta) for phosphate desorbtion
THKADP: temperature coefficient (theta) for phosphate adsorption
THKIMP: temperature coefficient (theta) for phosphate immobilisation
THKMIP: temperature coefficient (theta) for organic P mineralisation
KDS: first-order reaction rate parameter for phosphate desorbtion
KAD: first-order reaction rate parameter for phosphate adsorption
KIMP: first-order reaction rate parameter for phosphate immobilisation
KMIP: first-order reaction rate parameter for organic P mineralisation
PLP: first-order plant phosphorus uptake reaction rate parameters
ORGP: initial organic P storage
P4AD: initial adsorbed phosphate storage
P4SU: initial solution phosphate storage
PLTP: initial P stored in plants
IP4SUP: initial storage of phosphate in the upper layer transitory (interflow) storage

GOPC parameters

Parameter	Calibrated value
F_l	0.521
K_d	2
$E_{p:sed}$	0.9
c_k	0.02
d_k	0.7

Fl: Phosphorus sorption coefficient

Kd: Soil phosphorus partitioning coefficient

Ep:sed: phosphorus enrichment ratio

C_k: first coefficient in the adsobrtion relation for each sediment class

d_k: second coefficient in the adsobrtion relation for each sediment class