COMPARISON OF PHYSICALLY BASED CATCHMENT MODELS FOR ESTIMATING PHOSPHORUS LOSSES

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ABSTRACT

As part of a large EPA-funded research project, coordinated by TEAGASC, the Centre for Water Resources Research at UCD reviewed the available distributed physically based catchment models with a potential for use in estimating phosphorous losses for use in implementing the Water Framework Directive. Three models (HSPF, SWAT, and SHETRAN), representative of different levels of approach and complexity, were chosen and were implemented for a number of Irish catchments. This paper describes the main features of the three models and also reports on the preparation of the data required by them with special emphasis on the GIS technology which represents a powerful tool for data manipulation.

Keywords: Physically-based distributed approach; GIS; HSPF model; SWAT model; SHETRAN model

INTRODUCTION

Phosphorous is important in fresh water ecosystems since it is always the nutrient in shortest supply controlling the rate of eutrophication (Srinivasan et al., 1996). The main sources of phosphorous from agriculture land are plants, animal wastes, and soils (Nash and Halliwell, 2000). Among these the soil phosphorous represents the origin of the nonpoint sources phosphorous pollution and therefor it becomes the focus in modelling the phosphorous loss. Phosphorous in the soil can be found in dissolved, colloidal, or particulate forms with the particulate form being dominant. Generally most of the soil types contain considerable amounts of phosphorous material retained at the top layers which is susceptible to be transported with the runoff water as nonpoint source pollution. Two forms are usually found in the runoff water, the dissolve soluble phosphorous and the phosphorous removed with sediments particularly the lighter and finer-sized particles such as clays and organic matter. Another important transport process of phosphorous is the leaching of the soil soluble phosphorous downward into the existing tile drainage system or directly to the shallow groundwater where the subsurface transport can subsequently carry the available phosphorous back into surface water.

Water bodies receive pollutants from point source discharges and/or nonpoint sources. As point source pollution can be easily quantified and many efforts have been exerted to reduce their significance as source of pollution, the concern has now been focused on modelling the nonpoint source pollution as it represents a major source of pollution to the receiving water. The amount of certain pollutants in the receiving water body is highly related to the conditions and the characteristics of the nearby catchment. Therefore it is quite plausible to have nonpoint source pollution models with structures composed of several components describing the processes that occur in pollution transport through land surface and water. Since the nonpoint source pollution modelling is linked to various processes in the catchment, it is always required to supply large data and parameters as inputs to the model. The simulated output by the model is usually very sensitive to the spatial resolution of the input data (Fitzhugh and Mackay, 2000). Furthermore, the inputs have a time variation that should be considered in the model. Such type of modelling approach is referred to as physically-based distributed (PBD) approach and the models called physically-based distributed models.

The PBD approach can be looked at as a descriptive modelling approach, or in other words, modelling with the objective of achieving a better understanding of the physical and chemical processes involved in the nonpoint source pollution. The equations used in the PBD models are generally theoretically based micro-level non-linear relations representing the physical and chemical laws which control the nonpoint source pollution. However, empirical equations obtained from experimental studies are also used to describe some of the processes that are difficult to be captured by theoretical relations. It is possible to point out two types of PBD models according to the time scale of the resulted outputs, namely continuous and event oriented models (Novotny, 1986). The latter type simulates the response of a catchment to a major rainfall or snowfall event. On the other hand the continuous type of modelling sequentially simulates all processes incorporated in the model. The operation time interval of the continuous model ranges from a day to a fraction of an hour. The system water and pollutant mass balances are always preserved in the continuous model.

The parameters required by the event and the continuous models can be used as an additional feature to differentiate between the PBD models. Thus the model can be either based on the lumped or distributed parameter and this in turn controls the spatial discretisation of the catchment. In the case of the lumped parameters model type, whole or large portion of the catchment can be treated as one homogenous unit which produces a uniform response to the external inputs. On the other hand the application of the distributed parameters models requires establishing a grid network over the catchment. The inputs (rainfall, evaporation, etc.) and flow and pollutant control parameters (Slope, crop, Manning coefficient, hydraulic conductivity, etc.) are specified for each grid, thereby accounting for their spatial distributions. The grid network representation would also allow the estimation of the variables of interest at each point in the catchment whereas these variables can be obtained at certain locations in the lumped models. It is obvious that there is variety of models rendering themselves to be possible alternatives for the nonpoint source pollution studies and also it is worth mentioning that there is no absolute good model that can be used for all cases. Therefore it is always necessary to review some of the potential models that can be used for certain problem before deciding on the models which are to be used.

The work in this paper is part of a project which has been set as initial step towards implementing the European Water Framework Directive (EWFD). The project was funded by the Environmental Protection Agency (EPA) in Ireland and coordinate by the TEGASC (Institute of Agriculture) in Ireland to quantify the amount of phosphorus removed from the agriculture catchment to the main water bodies using the PBD approach. Three well-known PBD models (HSPF, SWAT, and SHETRAN) were chosen to be implemented in a number of Irish catchments where agriculture is the dominant practice. Tow of the models (HSPF and SWAT) have been extensively used in the United States of America where conditions are different. The third model (SHETRAN) is somehow international and it was implemented in areas where the prevailing conditions are similar to the Irish catchments. The principal objective of the modelling work is to examine the capabilities of the three models to quantify the phosphorus loss from the study catchments. To achieve this objective the models will be fitted on three Irish catchments with different characteristics, namely the Clarianna (23 km^2), the Dripsey (98 km^2), and the Oona (96 km^2). This paper contains a brief description to the three models. Moreover the role which the GIS technology can play in performing the task of data preparation will be explained since it represents an important step in applying the models on the Irish conditions.

THE HSPF MODEL

The Hydrological Simulation Program - FORTRAN (HSPF model) is "a comprehensive package for simulation of watershed hydrological and associated water quality processes on pervious and impervious land surface, in the soil profile, and in streams and well-mixed impoundments" (Donigian et al., 1984). The model has been developed on the foundation of the Standford Watershed Model (SWM) (Crawford and Linsely, 1966) developed in the sixties. Since its emergence the mode has been used in various applications in the modelling aspects of water quantities and qualities studies.

There are three main modules in HSPF to deal with the simulation of the hydrological and chemical processes in the pervious land, the impervious land, and the reach namely PERLND, IMPLND, and RECHRES respectively. The PERLND module treats the land piece and the underlain soil profile as a number of connected storage zones, each of which either receives inputs, or spills output, or both. The IMPLND module is much simpler than the PERLND due to the absence of the water and chemical modelling underneath the soil surface since no water is considered to move beyond the soil surface. Finally the RESCRES module in HSPF is developed to route both the water and chemicals entering the reach from the land segment to the downstream point. Furthermore the HSPF model does not ignore the sediment modelling, it simulates the possible transport processes of the sediment at the land hill slope and the reach levels. The model assumes that the readily sediment material for transportation consists of three different types, sand, silt, and clay, each with a specific percentage depending on the nature of the parent soil material. Several options are available for the model user to estimate the sediment load from the land segment to the reach and the final load at the outlet location.

Various chemical parameters can be modelled in the HSPF including the phosphorus. It is assumed in the model that the phosphorus is undergoing different chemical processes in the pervious land segment (this is not the case for the impervious land). These processes include the mineralisation/immobilisation, adsorption/desorption, and plant uptakes. The model offers two methods to simulate the rate of adsorption and desorption of the phosphorus material in the soil, the first order kinetics and the single value Freundlich isotherm. The mineralisation/immobilisation processes are handled in the model using first order kinetics only. Three methods are available in the model to estimate the amount of the phosphorus taken up by the plants so that the user's definition of the phosphorus requirements can be satisfied. These methods include the simple first kinetics, yield-based algorithm, and the Michalis-Menten or saturation kinetics method. Phosphorus removed from the land either in dissolved form or associated with the sediment are delivered with the runoff water to the main river channel where chemical stream processes occur all the way through until the outlet point is reached.

THE SWAT MODEL

SWAT (Soil and Water Assessment Tool) 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, (Neitsch et al., 2001). The model was obtained by merging the models SWRRB (Simulator for Water Resources in Rural Basins), (Williams et al., 1985), and ROTO (Routing Outputs To the Outlet), (Arnold et al., 1995). The goal of developing the SWRRB model is mainly the predication of the effect of management decisions on water and sediment yields with reasonable accuracy for ungauged rural basins throughout the United States (Arnold and Williams, 1987).

The hydrological phase in SWAT provides the required parameters for the phosphorous calculations. The most important parameter is the runoff volume computed by the modified SCS curve number method. In this method, the curve number varies non-linearly with the moisture content of the soil exhibiting a drop as the soil approaches the wilting point while there is an increase to near 100 as the soil approaches saturation. Another significant flow parameter to the phosphorous modelling is the lateral subsurface flow or interflow which represents a stream flow contribution originating below the soil surface but above the zone where rocks are saturated with water. The model applies the kinematic storage method to estimate this stream flow component. The last stream flow component, which has valuable use in the model prediction of both the sediment and phosphorous, is the water contributed by the shallow aquifer or the base flow. The model solves the water mass balance equation in the aquifer to estimate the base flow contribution. Finally the phosphorus associated with the sediment requires the calculation of the amount of sediment removed from the land surface and for this purpose the mode uses the Modified Universal Soil Loss Equation (MUSLE).

The soil profile is allowed in SWAT to be divided into several layers with variable hydraulic and chemical properties. For each layer the soil phosphorus pool is assumed to be comprised of fresh organic phosphorous, active and stable organic phosphorous, soluble phosphorous, active and stable inorganic phosphorous. The soil phosphorus processes which the model accounts for are decay of plant residue, decomposition of the fresh organic matter, mineralisation and immobilisation, adsorption desorption, and plant uptake. The amount of soluble phosphorus removed in runoff is predicted using solution phosphorus at the top 10 mm of soil, the runoff volume and a partition factor. Phosphorus transported with sediments is calculated by a loading function which estimates the daily organic phosphorus runoff loss based on the concentration of organic and active inorganic phosphorus in the top layer, the sediment yield, and enrichment factor. This factor represents the ratio of the phosphorus concentration on the detached sediment material to that in the parent soil.

THE SHETRAN MODEL

Among many other physically based spatially distributed (PBSD) models SHETRAN is characterised by its comprehensive nature and capabilities for modelling subsurface flow and transport (Ewen et al., 2000). The SHETRAN model and its later version which contains sediment component, SHESED system (Wicks and Bathurst, 1996), were inherited from the Systeme Hydrologique Europeen (SHE) model (Abott et al., 1986a, b).

This model is fully distributed in the spatial scale since the catchment area is represented by orthogonal grid network in the horizontal direction with a column of horizontal layers underlain each grid square in the vertical direction. Each cell of the horizontal grid is composed of the land surface and the soil column, an indication that the model is a three-dimensional model coupling the surface and subsurface to simulate the flow, sediment with multiple size, and solute transport in the river basin.

The water movement in the basin is represented with an integrated surface and subsurface systems incorporating the major elements of the land phase of the hydrological cycle (interception, evapotranspiration, snowmelt, overland and channel flow, unsaturated and saturated flow). The amount of the rainfall intercepted by the vegetation canopies is predicted with storage model which considers the effect of the evaporation. Any excess water to the interception storage will deliver through the vegetation trunk to the soil surface where the infiltration process takes place. Subsurface water processes are simulated in the model to result in the distribution of soil moisture content and tension in the unsaturated zone, and recharge to the saturated zone. Surface water flow is generated by either infiltration excess or saturation excess mechanism, and is routed into the channel as sheet overland flow.

The sediment component of the model provides an estimate to soil erosion by raindrop impact, leaf drip impact and overland flow, and transported by overland flow and channel flow. However, the solute transport component of the model can not be used to estimate the phosphorus loads since it is only appropriate for modelling the radioactive material in the soil. An independent Grid Oriented Phosphorus component (GOPC) (Nasr et al., 2003) has been developed for the purpose of modelling the phosphorus from a catchment where the SHETRAN is applied to estimate the flow and the sediment inputs to the component.

THE ROLE OF GIS IN APPLYING HSPF, SWAT, AND SHETRAN TO IRISH CATCHMENTS

Due to the spatial nature of the basic input data required by the three models (HSPF, SWAT, and SHETRAN) there is a significant role that the GIS technology can play. Two of the models, HSPF and SWAT, have been integrated in the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system which has been built using the ArcView macro language (Avenue). All the spatial input data required by the two models can be gathered together in the BASINS environment where they can be processed to create the necessary files to run the models on a certain catchment. The third model, SHETRAN, can use the same spatial input data to generate the grid network and the required parameters of the grid for the catchment. Therefore it is quite plausible to say that the GIS BASINS system can be used solely to produce all the required files to run the three models on the catchment.

Digital Elevation model (DEM) of the catchment is required by the three models to define the catchment outer boundary and also to delineate the stream networks within the catchment. The disaggregation of the catchment into smaller units is a direct procedure in SHETRAN model where the catchment is divided into number of cells to form the orthogonal grid overlaying the catchment area. The size of the cell is a user's choice and it always depends on the accuracy required by the model. The stream networks of the catchment should be superimposed over the catchment so that each stream link is located at the edge of the grid cell and this might need some manual editing to the stream networks resulting from the GIS. The land use and the soil maps of the catchment should be in a raster format with a grid size similar to the one of the catchment in order to define the land use and the soil associated with each element in the grid.

Using the resulting stream networks from the DEM delineation the subcatchments in HSPF and SWAT models can be defined such that each subcatchment is draining the area upstream of a certain location in the stream networks. However the case is different with HSPF and SWAT models when defining the smallest modelling unit as the land use and the soil maps are needed to accomplish this task. In SWAT the smallest spatial unit is the Hydrologic Response Unit (HRU) which is characterised by a uniform response to all the external inputs. The HRU within each subcatchment is obtained by overlaying the land use map first and then the soil map over the subcatchment and the user should define threshold value for the area where land use types with area equal or below this threshold are excluded. Likewise a threshold area value is defined for the soil type to include soils with areas above the threshold. In order to divide the subcatchments into subunits, the land use map of the catchment should be classified into the recognised types by the HSPF model. Moreover the subunits can be disintegrated further into two types of different hydrological characteristics, pervious or impervious lands. For each of the subunits in the HSPF model, the soil map is used to identify their soil types

The GIS data for the three catchments have been prepared as one of the project objectives. These data were made available to our part in the Centre for Water Resources Research (CWRR), University College Dublin (UCD), Ireland. Among other available geographically related data the DEM and the soil maps have been used as input to the models. In addition, a land use map available in the CWRR has been used.

CONCLUSIONS

A short description is given of three well-known PBD models (HSPF, SWAT, and SHETRAN) which have been used in a project funded by the EPA in Ireland and corrdinated by TEGASC. The principal objective of this project is to quantify the amount of phosphorus removed from the soil of three agriculture catchments in Ireland (the Clarianna, the Dripsey, and the Oona catchments). The preparation of the data required in running the models was also reported in this paper with more focus on the role of the GIS technology that can play to achieve this task. The results from applying the three models on the Clarianna catchment were presented in another paper elsewhere in this volume (Nasr et al., 2003).

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