PREDICTING NUTRIENT LOADS IN TWO EUROPEAN CATCHMENTS

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ABSTRACT

The hydrological model SWAT was applied to two watersheds, the Ouse (North of UK) and the Vantaanjoki (South of Finland). The Ouse watershed is characterised by heavy husbandry and large application of organic nitrogen and phosphorus on pasture. The Vantaanjoki watershed is dominated by forest and barley. The model performance was evaluated comparing the measured and predicted time series for flow, total nitrogen and total phosphorus at the watershed outlets. The model performed well in predicting water and nutrient losses. The model showed a good sensitivity in predicted nutrient losses for both the agricultural and forested catchments. The model was then used to estimate the contribution of agriculture to the total load of measured nutrient at the outlet of the two river basins. It was highlighted that for a same catchment diffuse contribution to total nutrient load can be highly variable both in time and space.

Key words: nutrient load, SWAT model

INTRODUCTION

The new EU Water Framework Directive (EC, 2000) commits Member States to take specific technical and scientific measures necessary for the practical implementation of general principles and definitions. Member States are required to implement all necessary measures to prevent deterioration of the status of surface water bodies, and to protect and enhance surface water bodies status in view of the achievement of good status by December 2015. At the same time, the program of measures has to ensure compliance with emission limits and controls as set out in other Community legislation, such as the Nitrates Directive (EC, 1991). In particular, Member States have to conduct a status review by 2004 that should include: analysis and characteristics of river basin district, register of areas requiring protection, reviewing and assessing significant pressures and impacts from anthropogenic activities, and economic analysis of water use (Murray et al., 2002). The identification of significant anthropogenic pressure should include point and diffuse sources, and address pollution sources from agricultural, industrial and urban activities. There is thus an urgent need at the European level, to develop and validate management tools that help Member States in complying with the Water Framework Directive, in both assessing the actual environmental status of European waters, and also in evaluating the environmental and economical sustainability of the program of measures. An extended validation of existing tools is also of primary interest to IGO's such as HELCOM and OSPARCOM to help them in their initiative of reducing nutrient loads to the North Sea by 50%. Initiative at the European level are being taken to develop harmonised methodologies for quantifying and reporting nutrient losses from diffuse source (EUROHARP, 2003). This paper presents the evaluation of the efficiency of the SWAT model (Arnold et al., 1999) in predicting diffuse pollutant losses on two watersheds located in the UK, and Finland. A source apportionment between the contribution of agricultural and urban activities is also shown.

MATERIALS AND METHODS

Finnish catchment

The Vantaanjoki watershed covers an area of 1682 km^2 and drains into the Gulf of Finland. The catchment lies on a Precambrian bedrock and includes mostly clay soils (70.1% of the area) and Moraine (24.5 %). The watershed can be classified as lowland. The mean elevation is around 75 m and the outlet elevation is 3 m (Figure 1). The southern and middle parts of the watershed are flatter and occupied by agricultural land on clay soils. Agricultural land represents about 26% of the whole watershed, forest occupies more than 59 % of the whole area. The area covered by water is about 3% of the watershed, while urban areas and wetlands represent 5 and 7 % of the catchment (Figure 1). The climate is continental with the mean maximum annual temperature varying from –3.37 in January to 21.4 in July. The mean annual precipitation is 657 mm and the mean annual potential evapotranspiration is 429 mm.

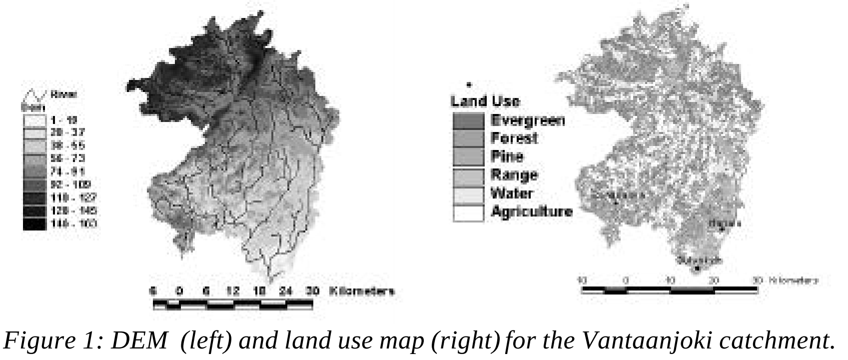

Figure 1: DEM (left) and land use map (right) for the Vantaanjoki catchment.

British catchment

The river Ouse is situated in northern England and drains to the east into the Humber estuary. The river drains a total area of about 3500 km^2. The elevation varies from 714 m at the highest point in the watershed to 2.5 m at the outlet. The DEM for the Ouse watershed is illustrated in Figure 2. Clay is the major soil present on the watershed (55% of the total area). The upper part of the basin is used for rough grazing while the lower and flatter part is mainly cultivated for cereal production. The majority of land use is agricultural dominated by of range, pasture and winter wheat (Figure 2). The mean annual precipitation is around 923 mm, with a strong gradient varying from 1800mm per year in the western part of the watershed to 700 mm per year in the eastern part. The average annual potential evapotranspiration is about 530 mm.

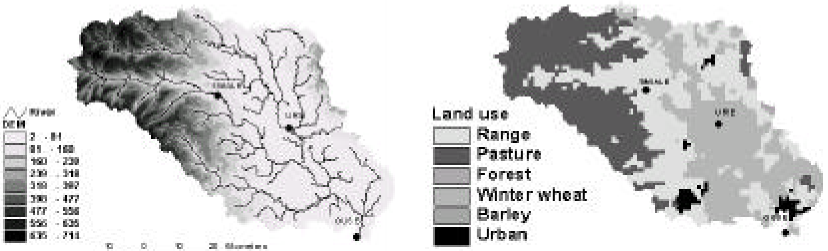

Figure 2: DEM (left) and land use map (right) for the Ouse watershed.

SWAT MODEL

The Soil and Water Assessment Tool (Arnold et al., 1999) is a time continuous and spatially distributed model, developed to simulate the impact of management decisions on water, sediment and agricultural chemical yields in river basins in relation to soil, land use and management practices. The model represents the large-scale spatial variability of soil, land use and management practices by discretizing the watershed into a number of sub-units using a two step approach. First, a topographic discretization is done by dividing the watershed into sub-units based on a threshold number of cells draining out of a specific sub-basin. This step serves as the basis determining the routing structure of water and pollutants through the watershed. During the second step, each sub-watershed is divided into one or several homogeneous hydrological response units (HRU) obtained by overlying the soil and land use maps. HRUs have no exact geographical location, they are only associated to a sub-basin. The HRU within a sub-basin have non-spatial link to each other. The response of each HRU in terms of water, sediment, and nutrient transformations and losses is determined. The losses are then aggregated at the sub-basin level and routed to the associated reach and to the watershed outlet through the channel network.

The hydrologic model is based on the water balance equation in the soil profile where the processes simulated include precipitation, infiltration, surface runoff, evapotranspiration, lateral flow and percolation. SWAT partitions groundwater into two aquifer systems: a shallow unconfined aquifer which contributes to the return flow and a deep and confined aquifer that, beside pumping, is disconnected from the system. Surface runoff volume is predicted for daily rainfall by using the SCS curve number equation (USDA, 1972). The peak runoff rate is computed using the modified rational formula. Excess precipitation that remains after runoff infiltrates into the soil profile. SWAT applies a multilayer storage routing technique to partition drainable soil water content for each layer into components of lateral subsurface flow and percolation into the layer below. A kinematic storage routing technique is used to calculate lateral subsurface flow. For the present study, the Priestley and Taylor (1972) approach was selected to determine the potential evapotranspiration (PET). The daily value of the leaf area index is used to partition the PET into potential soil evaporation and potential plant transpiration (Ritchie, 1972). Sediment yield is estimated for each HRU with the Modified Universal Soil Loss Equation (Williams, 1975) using the surface runoff, peak flow rate and the soil erodibility, crop management, erosion control practice and slope length and steepness factors.

SWAT simulates the movement and transformation of nitrogen and phosphorus in the watershed. Basic processes simulated are mineralisation, denitrification, volatilisation, plant uptake for N and mineralization, immobilisation and plant uptake for P. Mineralisation of N considers a fresh organic N pool, associated with crop residue and microbial biomass, and the stable organic N pool, associated with the soil humus. Mineralisation from the fresh organic N pool is estimated as described by Seligman et al. (1981). Organic N associated with humus is divided into active and stable pools using an equilibrium equation. Only the active pool of organic N is subjected to mineralisation. Similarly, the mineralisation of organic P associated with humus is estimated for each soil layer. Additional details about the N and P cycle simulated by SWAT can be found in Arnold et al. (1999). Plants uptake of nitrogen and phosphorus is one of the main loss pathway and is estimated using a supply and demand approach. The nitrogen demand is computed on a daily basis based on the optimal N and P crop concentration for each growth stage. Nitrogen and phosphorus are taken from the root zone and are only limited by the available N and P present in the root zone. . Nitrogen and phosphorus can be lost from the watershed in particulate or dissolved forms.

RESULTS AND DISCUSSION

Model Parameterisation

For the Vantaanjoki watershed, the available data included a digital raster elevation map on a 25x25 m grid. The data was processed using the SWAT interface, and the basin was discretized in 70 topographical sub-basins. A soil map and land-use map were also available as raster grids on a 25x25m resolution. For each sub-basin a threshold of 10% for soil and land-use was used, resulting in 376 HRUs. The agricultural land was assumed to be occupied by barley and the crop database of SWAT was used to parameterise the crop-input file. Four rain gauges providing daily precipitation were used. Two stations were available for daily maximum/minimum and average air temperature.

For the Ouse catchment, a 50x50m raster digital elevation map was available. Raster maps of soil texture and land use were available on a 25x25m grid resolution. The watershed was divided into 25 topographical sub-basins, and the dominant soil and land-use were determined resulting in one HRU per sub-basin. Six rainfall stations provided daily rainfall measurements for the 1986-1999 period. One station was available for the daily measurements of maximum/minimum and average air temperature.

Model calibration

The calibration consisted in modifying the curve number to adjust the surface runoff and the parameters controlling the shallow aquifer balance to better represent the base-flow without introducing any long term trend in the groundwater storage. The quality of the predictions were evaluated using the coefficient of efficiency defined as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} \left(I_{\mathrm{mod}} - I_{obs} \right)^2}{\sum_{i=1}^{n} \left(I_{obs} - \bar{I}_{obs} \right)^2} \qquad (1)$$

where n represents the number of observation in the time series, I_{obs} is the observed value of the variable, I_{mod} is the predicted value of the variable, and $\hat{I}_{obs}$ represents the mean measured value of the variable.

Model results

For the Vantaanjoki catchment, the period 1986-1988 was used for calibration while the period 1989-1999 was used for validation. The analysis of the results consisted in computing the efficiency on a daily basis for water flow at three gauging stations. The results for the daily flow and monthly total nitrogen and phosphorus load are presented in Figure 3. The coefficients of efficiency for the daily flow simulations were 0.57. The model reproduced very well the seasonality of water losses that are dominated from March to May by snow-melt. The SWAT model did not succeed in predicting very accurately the low flow of the summer period. The model performance was however satisfactory in reproducing the water flow behaviour, even though forest is the dominant land use (70% of the whole watershed). The coefficients of efficiency were 0.34 and 0.62 for the total nitrogen losses, and total phosphorus losses, respectively. The model had a tendency to over-predict sediment losses during April, the month during which the highest snow melt takes place. This might be explained by that the dominant processes of sediment detachment and transport during a rainfall event and snow melt are different. The model performed well also in predicting nutrient losses for both phosphorus and nitrogen, that are coming mainly from agricultural areas, and point sources.

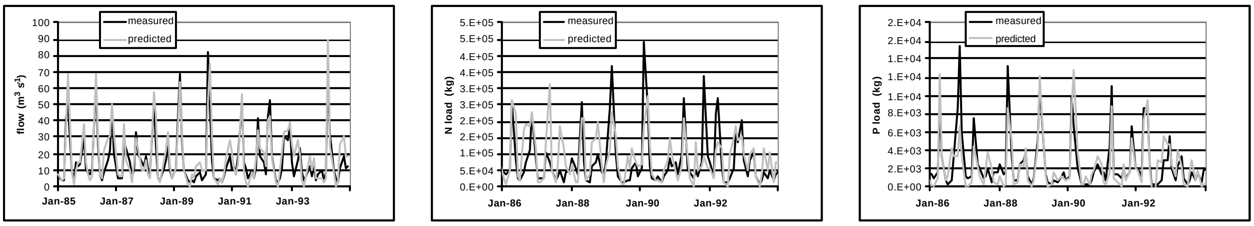

Figure 3: Measured and predicted daily water flow (left), monthly measured and predicted total nitrogen (middle), and phosphorus losses (right) for the Vantaanjoki basin.

For the Ouse catchment, the analysis of the results consisted in computing the efficiency on a daily basis for three water flow gages, and in computing the efficiency for the monthly prediction of nitrate losses. The calibration period extended from 1986 to 1987 and was performed on the Ure sub-basin. The validation was carried from1986 to 1990 for the whole catchment and the Swale sub-catchment. The efficiency was computed on a monthly basis for the nitrate losses because only limited management practices data were available for each land use type. The results for the daily prediction of water flow are presented in Figure 4a.

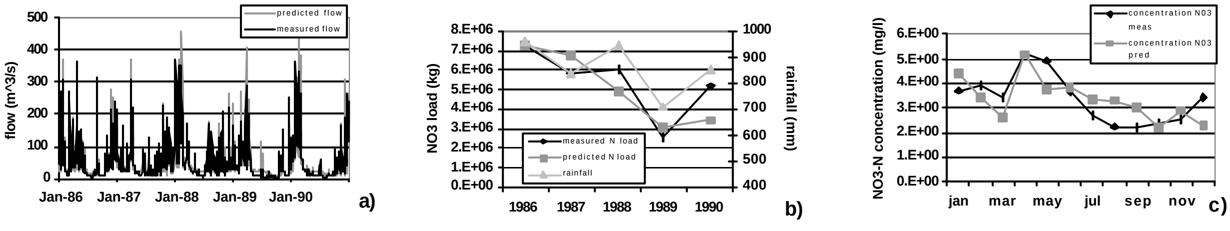

Figure 4: Predicted and measured daily water flow for the Ouse catchment for the general outlet (left), annual measured and predicted nitrate load (middle), and measured and predicted monthly nitrate concentration at the general outlet (right).

The coefficients of efficiency for the water flow prediction are 0.77, and 0.39 for the general and Swale outlets, respectively. The model did a good job in representing the spatial distribution of daily flow within the watershed. The model reproduced accurately the peak runoff, while it tended to under-predict the low flows during the summer months.

The model performance is satisfactory in estimating the monthly nitrate losses at the general outlet. The annual losses for nitrate are illustrated in Figure 4b. It can clearly be seen the positive correlation between the annual rainfall and nitrate load. The regression coefficients between the annual nitrate load and the annual rainfall are 0.87 for the measured series and 0.38 for the predicted series. The coefficient of efficiency for the nitrate load predictions on a monthly basis is 0.64. The performance of the model could have been improved by using a more detailed management practices description for the whole watershed. However, due to the lack of information, one unique yearly management plan was used for each land use. The model captured well also the seasonality of the nitrate concentration in the stream on a monthly basis (Figure 4c). The highest concentrations occur in April, which corresponds to the fertiliser application, and mineralisation increases due to warmer temperatures.

DISCUSSION

Once validated the SWAT model was used to estimate the contribution of each source of nitrogen of the phosphorus and nitrogen to the total load. For nitrogen, the considered sources included atmospheric deposition, diffuse emission including emissions from agricultural land and from natural areas (forest, etc.), and point emission from waste water treatment plants, industries. Concerning phosphorus the source included only point emission and diffuse emissions. The source apportionment (along with the standard deviation of the estimates) for the Vantaanjoki is shown in Figure 5. The diffuse contribution to total load is rather stable in time, especially for nitrogen. As shown by Rekolainen (1989), the total load of nitrogen is closely linked with the percentage area of agricultural land. The agricultural area being constant through the study period explains why the contribution of agricultural and natural areas is rather stable in time. The diffuse losses are mostly controlled by areas for crop growing. A finer analysis of the SWAT results indicates that agriculture including, cropping and livestock farming, which occupies around 26% of the whole catchment, contributes to 54% and 63% of the total nitrogen and phosphorus loads, respectively. Point source contribute to 14% of the total nitrogen load and to 9% of the measured phosphorus load.

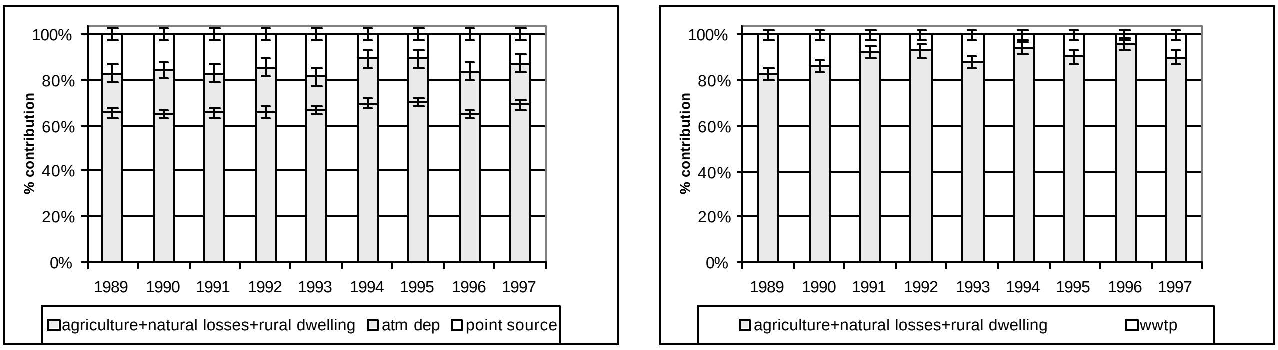

Figure 5. Contribution of the various source to the total nitrogen load (left) and phosphorus (right) for the Vantaanjoki catchment.

The results for the source apportionment over a five year period for the Ouse catchment and Ure sub-catchment are illustrated in Figure 6 for the whole simulation period. It can be clearly seen that the Ure sub-catchment is less affected by point sources coming from urban and industrial activities, while the Ouse outlet is impacted by industry and urban activities taking place around the town of York. One also can note the variability of the impact of atmospheric deposition which exhibits a strong gradient in the catchment. In the western highland wet deposition of nitrogen can be as high as 30 kg-N/ha/year while it is around 15 kg-N/ha/year close to the catchment outlet.

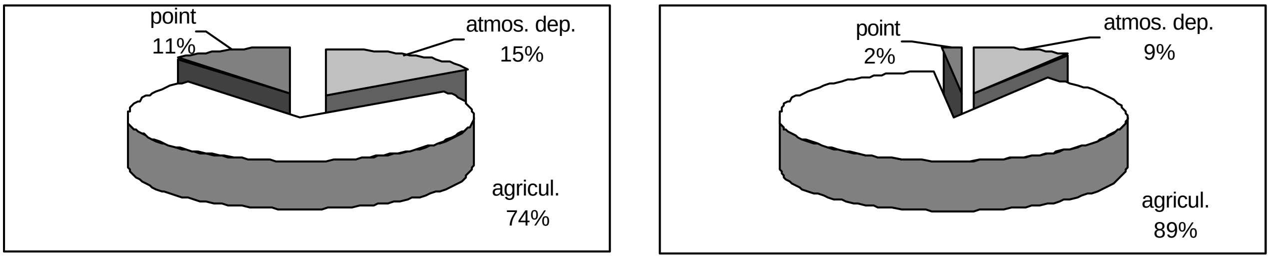

Figure 6. Contribution of the various source to the total nitrogen load for the whole Ouse catchment (left) and for the Ure sub-catchment (right).

As explained previously, the diffuse and point contribution can vary very significantly in space, but also in time. This is illustrated in Figure 7 where the source apportionment was done for 1986 and 1989 for the whole catchment. The year 1986 is a very wet year (precipitation of 960 mm) while 1989 is very dry with a yearly precipitation around 700mm. During the dry year the contribution of point source soars to 20% while during the wet year it drops to 7%. Thus to get a good estimate of the source apportionment, multi-year time series of water quality and quantity are thus necessary. It is extremely important to quantify the impact of climate on nutrient losses, in order to evaluate accurately the impact of alternative management practices and ensure that the predicted impact is larger than the observed natural variations.

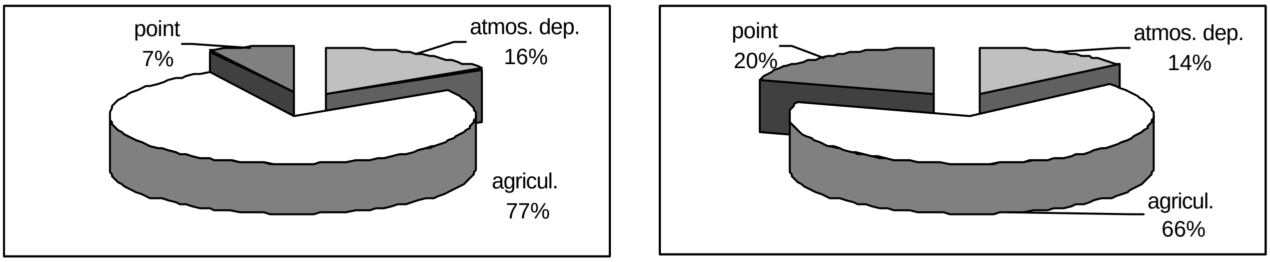

Figure 7. Contribution of the various source to the total nitrogen load for the whole Ouse catchment for year 1986 (left) and for 1989 (right).

CONCLUSIONS

The SWAT model was applied to two different watersheds characterised by different dominant hydrologic processes and with contrasting climate and land-use. The performance of the model was successful in the Ouse and Vantaanjoki cases in reproducing water, and nutrient losses. SWAT has proven to be a useful tool in assessing the impact of anthropogenic activities on surface water quality and will provide a valuable support in elaborating economically and environmentally sustainable management plan for reducing diffuse emission to surface waters. The model was shown to perform adequately both in terms both of loads and concentrations. On the Vantaanjoki catchment, even if agriculture accounts for 26% of the total are, it contributes to 54% and 63% of the total nitrogen and phosphorus loads, respectively. For the Ouse catchment agriculture is responsible for 74 and 89% of the total nitrogen and phosphorus loads, however with large spatial and temporal variability.

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