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Assessing nutrient and sediment transport for Water Framework Directive purposes using the SWAT model – a case study in SW Finland

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Abstract

The ecological status of lake Pyhäjärvi, located in south-western Finland, may be classified as moderate due to its elevated nutrient concentrations and algal biomass production. Thus, the Yläneenjoki river basin, accounting for >50% of the total phosphorus loading to the lake, was chosen as the Finnish test catchment in the *Benchmark models for the Water Framework Directive* project. One aim of the project was to test the suitability of models like the catchment scale model SWAT for the assessment of nutrient and sediment transport and management options needed to meet the surface water quality requirements. The modelling approach comprised two distinct phases: 1) an evaluation of SWAT utilising the available monitoring data along the Yläneenjoki reach and its main tributaries, and 2) participation of the Finnish stakeholders in the modelling process and communication of the analysis results. This process included the development of a benchmarking protocol to guide modellers and water managers in the case-specific selection of the most appropriate modelling approach.

1. Introduction

The EU Water Framework Directive (WFD) mandates Member States to develop river basin management plans for each river basin district. To achieve this the responsible authorities must have tools to assess alternative management options. Effects of environmental conditions and agricultural practices on nutrient leaching can be studied in field trials but due to the complexity of the soil-water-plant interaction mathematical modelling tools have been developed to generalise the effect of environmental conditions and agricultural practices on nutrient losses. The SWAT model has previously been applied in Finland to the Vantaanjoki basin to estimate retention of total N and P. The model performance was found to be satisfactory, the Nash-Sutcliffe index for the simulation of discharge and total N and total P loads ranged for validation from 0.43 to 0.57 (Grizzetti *et al.* 2003).

One aim of the EU-funded project *Benchmark models for the Water Framework Directive* (BMW) was to establish a set of criteria to assess the appropriateness of models for the use in the implementation of WFD. This concept developed from being a set of generic questions (Saloranta *et al.* 2003) to a document that can be used as a basis for the dialogue between a modeller and a water manager (Hutchins *et al.* in print; Kämäri *et al.* in print). The dialogue process was supported by modelling case-studies in selected catchments. The Finnish test case was the catchment of Lake Pyhäjärvi. In order to test the applicability of SWAT for this purpose, the model was applied to the Yläneenjoki catchment draining directly to Lake Pyhäjärvi and contributing over 50% of the P load reaching the lake (Ekholm *et al.* 1997).

Lake Pyhäjärvi is one of the most widely studied lakes in Finland. In the 1970s, the water quality of Lake Pyhäjärvi was classified as excellent, but in the classification carried out in the 1990s, the water quality was only estimated as good. The eutrophication of the lake has progressed at a rapid pace over the last few years. Lake Pyhäjärvi is currently mesotrophic. Of the total catchment area 22% is cultivated, the remainder comprises forest, peatland and housing areas. It has been estimated that field cultivation and animal husbandry comprise 55% and 39% of the external total P and total N load to Lake Pyhäjärvi, respectively (Ekholm *et al.* 1997).

2. Materials and methods

The SWAT model (Soil and Water Assessment Tool) is a continuous time model that operates on a daily time step at catchment scale (Arnold *et al.* 1998; Neitsch *et al.* 2001). It can be used to simulate water and nutrient cycles in agriculturally dominated landscapes. The catchment is generally partitioned into a number of sub-basins where the smallest unit of discretisation is a unique combination of soil and land use overlay referred to as a hydrologic response unit (HRU). SWAT is a process based model, including also empirical relationships. One objective of such a model is to assess long-term impacts of management practices. The model has been widely used but also further developed in Europe (e.g. Krysanova *et al.* 1999; Eckhardt *et al.* 2002; van Griensven *et al.* 2002). SWAT was chosen for this case study for three main reasons: its ability to simulate both P and N on catchment scale, its European wide use and its potential to include agricultural management actions.

The Yläneenjoki catchment, 234 km^2 in area, is located on the coastal plains of south-western Finland, thus the landscape ranges in altitude from 50 to 100 m a.s.l. The soils in the river valley are mainly clay and silt, whereas tills and organic soils dominate elsewhere in the catchment. Long-term (1961–1990) average annual precipitation is 630 mm (Hyvärinen *et al.* 1995). Average discharge in the Yläneenjoki main channel is 2.1 m^{3}s^{-1} (Mattila *et al.* 2001). The highest discharges occur in the spring and late autumn months. Groundwater contributions to stream flow are small. Agriculture in the Yläneenjoki catchment consists of mainly cereal production and poultry husbandry. According to surveys performed in 2000–2002 75% of the agricultural area is planted for spring cereals and 5–10% for winter cereals (Pyykkönen *et al.* 2004).

Data for only one precipitation and temperature gauge were available for the Yläneenjoki catchment. The station for global radiation was located approximately 60 km outside the catchment. The regular monitoring of water quality of river loads has been started as early as 1970s in the Yläneenjoki catchment. Monitoring of ditches and brooks entering the river or lake started at the beginning of 1990s. The nutrient concentrations have been monitored in the Yläneenjoki river by taking and analysing, in general bi-weekly, water samples and measuring the daily water flow at one point (Vanhakartano, situated ca. 4 km from the river mouth). Furthermore, water quality was monitored on a monthly basis in three additional points in the main channel and in 13 open ditches running into the river Yläneenjoki in the 1990s.

For the SWAT simulations the available data on land use and soil types had to be aggregated. The SWAT parameterisation was performed for 7 land use types: water, field, forest cuts and recently planted forest, active forest, old forest, peat bog and sealed areas. The soil was divided into 6 general types: clay, till and other coarse soils, open bedrock, turf and silt.. The fields were parameterised to be spring barley since spring cereals are the most common crop type in the catchment. The discretisation of the Yläneenjoki catchment resulted in 43 subbasins. With a threshold value of 10% for land use and for soil types the number of HRU's is 267. The parameterisation of soils and vegetation was based on measurements, expert judgement and previous field scale modelling work. Clear information gaps for the Yläneenjoki data set concerned a wide range of parameters (ca. 30 parameter, Bärlund *et al.* in print) where model default values are now used.

3. Results and Discussion

The uncalibrated SWAT run showed clear faults in the ability to describe observed discharge behaviour. This concerned mainly three phenomenon: too much snow melt during winter months, timing and amount of snow melt in spring and too many and partially over-predicted peaks during summer (Bärlund *et al.* in print). Calibration took place against discharge and sediment and nutrient concentration measurements as well as calculated daily loads at Vanhakartano. The calibration period was 1990–1994: 13 parameters affecting discharge only, 9 parameters affecting both discharge and NO_3-N, 1 parameter affecting NO_3-N only, 1 parameter affecting sediment concentration, 2 parameters affecting PO_4-P and 2 parameters affecting total P, i.e. in total 28 parameters, were used for calibration. The validation period was 1995–1999.

The calibration result was evaluated using the Nash-Sutcliffe index (NSI) and the linear goodness-of-fit values (R^2). The NSI varied between –263 and 0.43, the R^2 values between 0.01 and 0.57. The best result was achieved for discharge and nutrient loads. Except for sediment, the load simulation performed better than the concentration simulation. An evaluation of the time-series of all output variables shows that, except for NH_4-N and PO_4-P concentrations, the calibration result is reasonable since the main features of the inter-annual behaviour can be depicted. The overall impression is that the constant point load that is now used for scattered settlements, not connected community waste water networks, is not working properly. It seems to be difficult to estimate the correct unit loading. The mismatch has strong influence during low flow periods where the daily flow is usually less than 0.1 m^3s^{-1}. Additionally, it is obviously not enough to base the calibration on a limited number of catchment or subbasin wide parameters but the singular HRU's and subbasins have to be thoroughly examined for their output.

The validation result shows that, with the exception of sediment load and concentration, the validation performance is poorer than the calibration result. The same issues as for the calibration period play a role but additionally in early autumn 1999 there is a period of elevated measured nitrogen concentrations, which are overestimated by the model by a factor of 10.

A second validation experiment concerned the average concentrations of total nutrients along the main stream. This analysis reveals further major problems in the present model set-up to describe catchment dynamics. The measured average concentrations for the years 1991–1994 indicate a rise from the river mouth to the agriculturally intensive upper parts of the catchment – the simulation results show just the opposite. This result indicates that the main catchment element affecting the simulation result are the processes in the stream, not the loading from land reflecting land use. The effect of calibration can be seen as the best fit at Vanhakartano.

A simplified representation of buffer strips is included to SWAT. The only input parameter governing buffer strip efficiency is its width, which is a parameter in the SWAT input file describing the HRU's. The efficiency reduces the sediment as well as the soluble and sediment bound nutrient amounts leaving the HRU in surface runoff. The exponential equation is based on empirical data from the U.S. on buffer strip efficiency (Srinivasan, personal communication). Finnish measurements (e.g. Uusi-Kämppä *et al.* 1996 and 2000; Puustinen 1999) indicate that the buffer strip performs differently depending on the variable studied (soluble vs. particle bound). In SWAT the efficiency is the same for all output variables. The buffer strip option was used on three different areas in the Yläneenjoki catchment: the agriculturally dominated areas up-stream, along the main channel and to a second intensive agricultural area in the middle part of the catchment. The result shows clear differences in the reduction of the total nutrient load at the river mouth but this has so far only qualitative importance due to the poor calibration and validation status of the model in this area.

The model benchmarking protocol that was created within the BMW project consists of a set of 23 questions for the water manager and modeller to be considered in a common model selection session. The issues are divided into four sections after which each a GO or NO GO decision has to be made:

1. Definition of the management and modelling tasks
   GO/NO GO: Is modelling needed?
2. Model functionality and data
   GO/NO GO: Is the model code suitable for this task?
   GO/NO GO: Can the model be used for this application?
3. Model performance assessment
   GO/NO GO: Does the model perform in an acceptable way in this application?
4. A posteriori review
   GO/NO GO: Can the model be used for the management tasks at hand?

Benchmarking based on the Yläneenjoki case showed a clear GO for the two first steps even though certain reservations were noted concerning e.g. model structure, data availability and examples of regional model use. The model performance assessment (step 3) was not completed during the project due to the time consuming calibration and validation effort of a complex model like SWAT.

4. Conclusions

The approach to assess SWAT model performance in the Finnish Yläneenjoki catchment reveals so far that the model can be calibrated to a certain extent to discharge and nutrient loads using a limited parameter set of ca. 30 input parameters. With regard to this part of the evaluation, the SWAT set-up would be acceptable to the end-user to be used for management actions like buffer strips. The validation within the catchment shows, however, that the calibration and validation to one point is not enough to prove an understanding of the dynamics of such a complex model like SWAT. Three options remain: 1) improve calibration using smaller scale information and pay more attention to in-stream processes; 2) improve the model by changing certain routines; 3) choose another model. Giving the situation that the availability of models in Finland which fulfil the requirements of simulating both P and N on catchment scale and including agricultural management actions is limited – and that the simple exercises performed so far using the present set-up for buffer strip efficiency is what the local water manager is looking for – a further improvement of the calibration and a consideration of model improvements is recommended. The appropriate use of a model like SWAT is time consuming and requires an experienced user. This is a further aspect that has to be considered when planning to use the model for practical water management issues.

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