Process Based Modelling of Phosphorus Losses from Arable Land

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Abstract Improved understanding of temporal and spatial Phosphorus (P) discharge variations is needed for improved modelling and prioritisation of abatement strategies that take into account local conditions. This study is aimed at developing modelling of agricultural Phosphorus losses with improved spatial and temporal resolution, and to compare the accuracy of a detailed process-based model with a rainfall-runoff coefficient-based model. The process-based SWAT model (Soil and Water Assessment Tool) was implemented for five river basins in central Sweden, and results compared with the rainfall-runoff coefficient-based model WATSHMAN (Watershed Management System) for one of these river basins. Parameter settings and attribute values were adapted to Scandinavian soil conditions, crops and management practices. Model performance regarding flow dynamics was overall satisfactory. Comparable results were achieved at several scales. The modelled P load was of high accuracy for the days when monitoring data were available for validation, generally once a month. Modelled monthly P load did not fit as well with averaged monthly monitoring load values, mainly since monthly monitoring often partly or entirely misses the peak flows. The comparison of SWAT and WATSHMAN gave slightly better results for the process-based model (SWAT). Better spatial resolution for input data such as Soil-P content and agricultural management practices will be required to reach modelling results that enable identification of measures adapted to local conditions.

Keywords Phosphorus modelling · Eutrophication · Agricultural leaking · SWAT

INTRODUCTION

Eutrophication manifested by massive algal blooms is the most acute problem of the Baltic Sea. Actions have been implemented for a number of the point sources during the last decade, but have resulted in only marginal reductions of the nutrient load. The main sources of Phosphorus (P) and Nitrogen (N) transport to the Baltic Sea are diffuse sources (HELCOM 2004; EEA 2001), mainly agriculture. In parts of the Baltic Sea basin, such as southern Sweden, actions e.g. change of agricultural practices and in some smaller river basins re-construction of former wetlands and construction of new wetland areas (Tonderski et al. 2005) have been taken. However, the Helsinki Commission (HELCOM) has found that the periodic pollution load compilations undertaken by HELCOM clearly indicate that losses from diffuse sources are still the main source of the excessive inputs of Nitrogen and Phosphorus entering the Baltic Sea (HELCOM 2004). Furthermore, the leakage from agriculture is likely to increase as the agricultural production in the new European member states increases.

At the same time, variation in nutrient transport from diffuse sources is large in time and in place. Improved understanding of this variation is a precondition for further developed transport models, which in turn is required for an efficient and cost-effective abatement strategy. The objectives of this research study were to:

- Improve current temporal and spatial resolution of Phosphorus modelling and enable modelling of agricultural leaching of Phosphorus at a level that will allow identification of locally adapted remedial measures, and to provide an uncertainty analysis.

- Compare a detailed process-based model and a rainfall-runoff coefficient-based model to identify differences in accuracy.
- Elucidate model performance at different scales, with different detail in input data.
- Analyse the effects of measurement data frequency on calibration and accuracy of results.

BACKGROUND: LEACHING AND TRANSPORT OF PHOSPHORUS

Surface runoff is considered to be the main pathway for P losses (Sharpley et al. 1994). In many agricultural catchments, leaching of P comes from a small part of the area during a few storm events (Pionke et al. 1997) or during snowmelt. In Sweden, water erosion occurs mainly during snowmelt and when frozen soil thaws (Alström and Bergman 1990). Flat topography and the presence of preferential flow pathways in structured clay soils or light-textured sandy soils with low P sorption capacity may also lead to increased P leaching losses (Djodjic and Bergström 2005a). Clay soils are also mostly tile drained which further increases the risk for P losses. Approximately 45% of Swedish agricultural land is tile drained (SCB (Statistics Sweden) 1997), including the majority of the structured clay soils (Djodjic and Bergström 2005a).

Reactive P (RP) and unreactive P (UP) differ in mobility in the transport pathways; surface runoff, matrix and preferential subsurface drainage (Djodjic and Bergström 2005b). Continuous cracks can enable roots to penetrate in clay (Kirchmann 1991) and in sandy loam (Kirchmann et al. 1999).

Unreactive P (UP) is mainly transported with surface runoff, whereas RP losses have been assumed to be associated with slow matrix flow (Djodjic and Bergström 2005b). Unreactive P mainly consists of particulate P, but it may also include dissolved organic P and inorganic polyphosphates (Ron Vaz et al. 1993). Bioavailable P is mainly inorganic orthophosphates, but certain soluble organic P compounds may act as sources of plant available P (Wild and Oke 1966) after enzymatic hydrolysis (Tarafdar and Classen 1988). Dissolved reactive phosphorus (DRP) constituted the main proportion of the Total P (TP) losses from a subset of the Swedish long-term soil fertility observation fields, generally more than 80% for loamy sand or sandy loam, and 60–70% for silty clay loam and clay (Djodjic et al. 2004). The soils with the smallest TP losses had the largest proportions of UP. Slow water movement and efficient retention of DRP may have resulted in larger proportion of particle transport and thus UP.

The water transport mechanism through the soil seems to be more important than the amount of P in the topsoil. P leaching has been found to be low in some soils in spite of high P fertilizing, due to high P sorption capacity in the subsoil (Djodjic et al. 2004). The same study observed that dominant preferential flow (macropores) could by-pass high sorption capacity in the subsoil and give high losses in other soils. No-till practices may enhance preferential flow (Persson 2001; Petersen et al. 1997; McDowell and Monaghan 2002).

The impact of instream physical and biological processes on regulation of P fluxes through river systems is still poorly understood (Stålnacke et al. 2003). Sorption onto bottom sediments and to a lesser extent uptake by aquatic plants is the main causes of retention (Hill 1981). Physical, chemical and biological processes are likely to transform a portion of the dissolved P to particulate P (Meyer and Likens 1979). An additional weakness in catchment-scale modelling tools has been the modelling of lake nutrient dynamics, including resuspension from lake sediments. Biogeochemical or ecological lake models, such as the one-dimensional BIOLA model (Pers 2002) and the two-dimensional, low resolution LEEDS model (Dahl and Pers 2004) have not been incorporated in catchment-scale modelling. Focus in this study was, however, not to improve modelling of instream or lake P retention.

A number of semi-empirical modelling tools for nutrient source apportionment and load calculations have been developed during the last decade (Kronvang et al. 1999; Neitsch et al. 2002; Ekstrand 2001; Andersson et al. 2005; Krysanova et al. 2005; Bicknell et al. 2001). They differ in complexity and in time and space resolution and need different levels of details in terms of input data. Until recently, they were focussed on N, resulting in the capacity to quantify N losses with good accuracy, while P modelling has been hampered by insufficient capacity to account for flow pathways in different soil categories and under varying rainfall conditions.

For this study, the model needed to be able to account for spatial variations within the basin and within sub-catchments. High geographic detail is necessary if the modelling results are to be used for prioritisation of abatement actions on local scale. Dynamic modelling normally provides daily calculation steps for both water and nutrient transport, and this is a minimum requirement to account for the temporal variations in water flow and nutrient concentrations. Most basin-scale source apportionment models have daily time steps for water flow, but use mean annual nutrient concentrations for different land uses to calculate nutrient loads. Calculation of daily nutrient concentrations should improve the dynamics of nutrient load calculations.

MATERIALS AND METHODS

Models

Two models were chosen for the study, based on the requirements emanating from the objectives presented above. The detailed, process-based model was the Soil and Water Assessment Tool (SWAT; Neitsch et al. 2002) with its ArcView user interface, AvSWAT and the simpler rainfall-runoff coefficient-based model was Watershed Management System (WATSHMAN; Ekstrand 2001). The major part of the study was based on AvSWAT modelling, since the higher spatial resolution of that model was required to reach some of the objectives.

Soil and Water Assessment Tool (SWAT) is a catchment scale model developed for the United States Department of Agriculture's (USDA) Agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment and agricultural chemical yields in complex watersheds. A detailed description of the SWAT model is provided by (Neitsch et al. 2002). SWAT can be classified as semi-spatially distributed. The basin is divided into sub-catchments, and further sub-divided into Hydrologic Response Units (HRUs) consisting of lumped, homogeneous land areas within the sub-catchment composed of specific land cover, soil and management combinations. Calculations are completed at the HRU spatial unit. The average HRU size was 140 ha.

The hydrological cycle simulated by SWAT is based on water balance as the driving force including precipitation, soil water content, surface runoff, evapotranspiration, water entering the vadose zone from the soil profile and return flow from groundwater. The HRU water balance is represented by four storage volumes; snow, soil profile, shallow aquifer and deep aquifer. Flow, sediment, nutrient and pesticide loadings from each HRU in a sub-basin are summed and routed through channels, ponds and/or reservoirs to the watershed outlet. The model supplies several options for calculation of surface runoff and evapotranspiration. In this study, daily rainfall and the Curve Number method (Chow et al. 1988) were used to calculate surface runoff and the Penman–Monteith method was used to calculate evapotranspiration. Water movement between the 10 soil profile layers and the two aquifer layers are described in Neitsch et al. (2002).

Soil and Water Assessment Tool (SWAT) simulates plant growth using a unique set of parameters for each crop and natural vegetation type (Williams et al. 1984). The transformation and movement of N and P within an HRU are simulated as a function of nutrient cycles consisting of several inorganic and organic pools. Losses of nutrients from the soil system occur by crop uptake, surface runoff,

percolation below the root zone, lateral subsurface flow and emission to the atmosphere. The model uses data on management practices for daily adjustments on how the soil surface changes and when different actions are taken. Soil type data is used for the calculation of the soil layer's hydraulic conductivity, available water capacity and potential crack volume. The size of the different fractions of silt, clay and sand in the soil helps determine the sorption capacity.

The WATSHMAN modelling package consists of four calculation modules that model source apportionment and transport of nutrients at catchment scale; runoff modelling, pollution pressure calculation, retention calculation and transport calculation. The model generally presents results for sub-catchments with sizes of 10–50 km². However, runoff is calculated for each specific combination of crop/land use and soil type within the sub-catchment. Compared to SWAT, one of the major differences is that the WATSHMAN model is not process-based. Differences in, e.g. management practices, crop uptake, P content in the soil, erosion related P transport and macropore flow, e.g. are not considered except when summarized in the transport coefficients for different categories of arable land. The rainfall-runoff model of WATSHMAN computes runoff dependent on land cover, soil type and soil moisture together with daily rainfall data, using the Curve Number method (Chow et al. 1988). A snow routine has been developed to account for the freeze–thaw conditions in Nordic countries (Zakrisson et al. 2003). Surface and drainage water leakage is calculated using leakage coefficients for land cover and soil type categories together with modelled runoff. After the addition of discharge from point sources and rural households, the retention of P in the water courses and the transport of water and P between sub-catchments is calculated. The retention calculation is based on results from Johansson and Kvarnäs (1998) and simplified to be dependent only on water temperature and acreage of open water bodies, where the dependency on these two factors expressed as a simple regression function has been empirically established. For P, this is an oversimplification that most likely accounts for a substantial part of the difference between simulated and measured P load at downstream stations.

Study Area

The five studied catchments are Sagån (864 km²), Svartån (730 km²), Hedströmmen (1,100 km²), Köpingsån (284 km²) and Örsundaån (676 km²). They are all tributaries to Lake Mälaren, one of Sweden's and Europe's largest lakes with a surface area of 1,140 km² (Fig. 1). A total of 1.2 million people live around the lake and are all dependent on drinking water from the lake. In general, the lower parts of

Fig. 1 Sub-basins, stream network and DEM of Norrström River Basin

the five studied catchments are dominated by agriculture, while forested hills dominate the upstream landscape. The percentage of forest and agricultural land in the different catchments ranges from 46 to 65% of forest, and 20–43% of agricultural land. The amount of agriculture land versus forest land differs between the catchments, as well as the terrain, and the soils and crops cultivated. The catchments therefore represent a variety of conditions and offer a good opportunity to test model performance in various conditions. During the last 30 years the average water flow in the tributaries range from 1 to 12 m³/s. Average annual precipitation for the period 1961–1990 was 618 mm in the study area.

The catchments have had problems with nutrient transport causing eutrophication in the downstream Lake Mälaren and in the Baltic Sea. Following the introduction of chemical precipitation of sewage in the 1960s and 1970s the P loads were significantly decreased, but N and P from agriculture and to some extent rural households are still causing severe eutrophication problems.

Input Data

A digital elevation model (DEM) with 50 m × 50 m resolution, and river network maps from the Land Survey Office, were used to delineate sub-catchments. The mean slope of each sub-catchment and land use category were calculated and the results were applied as input data at the HRU level for the AvSWAT simulations. Twelve rain gauges were located in or close to the catchment and used for both models, as well as one meteorological station located in the area. The meteorological parameters, that were used, were humidity, solar radiation, temperature and wind speed. Measured water

flow data were used for calibration and validation of the SWAT model. The compiled reported grown crops from farmers (the IAKS database, Integrated Administrative Control System, Swedish Board of Agriculture), gave the crop distribution on arable land for each property. Other land uses were obtained from Corine Land Cover 2000 data, available across Europe with 25 m resolution.

Information on harvest index, leaf area index, root depth, nutrient concentrations in seeds and plants at different development stages, and other crop parameters were taken from Statistics Sweden (www.scb.se), Swedish Board of Agriculture (www.sjv.se) and literature sources (Blombäck 1998; Alavi 1999; Johnsson and Mårtensson 2002).

Regional management data regarding sowing and harvesting time, timing and rate of applied manure and fertilizer and tillage operations were obtained from Statistics Sweden, production region 6, and from the summary by (Eriksson et al. 1997). Both crop and management data are mean values for a longer time period. Since there are no data on distribution of tile drainage, it was assumed that tile drains are installed in all fields dominated by clay soils, after communication with farmers from the area. Soil type data were obtained by combining maps from the Swedish Geological Survey and interpolated, modified topsoil data from 3,100 points across Sweden (Wiklert et al. 1983) on soil texture, content of organic material, nutrients and trace elements. The soil parameter values in the SWAT soil database were adjusted to Swedish data and conditions. Soil profile descriptions, saturated hydraulic conductivity and data for moraine soils were taken from (Johnsson and Mårtensson 2002; Wiklert et al. 1983; Lind and Lundin 1990). The soil N and P from profile measurements in Eriksson et al. (1997) are valid only for the top layer (0–20 cm). Decreased, extrapolated values were set for the second soil layer, while for the lower layers the value was set to zero.

Values for P leaching from arable land vary depending on crop and soil type. A study conducted by the Swedish University of Agricultural Science on 11 different fields during 21 years shows an average value for P leakage of 0.4 kg/ha per year (Ulén et al. 2000). Variation between different fields can, however, range between 0.01–3.4 kg/ha per year and 0.01–1.8 kg/ha in different areas (Ulén 1997). A national study found that for Norrström and the surrounding area the P leakage values are below 0.3 kg P/ha for arable land, and below 0.03 kg P/ha for forest and transitional woodland shrub land use (Brandt and Ehjed 2002). These values were used for comparison with the SWAT output calculations.

Plant uptake of nutrients is related to crop yield and growth of biomass and is therefore not static. Uptake estimation models that present uptake related to yield are available for the public and can be found at Yara (www.yara.com) and Svenska Foder (www.svenskafoder.se). The

timing for the different management measures, such as tillage, sowing, timing and rate of applied manure and fertilizer and harvesting time were obtained from (SCB (Statistics Sweden) 1997; Abbaspour 2009). Point source data were collected from EMIR (the Swedish national emission database for point sources) and directly from wastewater treatment plants. The input data vary in resolution from monthly to yearly load depending on availability. The time periods for point source data were the same as for the modelled time period.

Calibration

When water flow monitoring stations with small upstream sub-catchments as well as one or more downstream monitoring stations with larger upstream catchments (encompassing the small upstream monitoring sub-catchment) were available, the SWAT model calibration process for the upstream catchment was used to gain experience that could be transferred to the larger catchment, e.g. on sensitive model parameters (see the Sagån catchment in Fig. 2). Model performance was measured by three statistical indicators: coefficient of determination (R^2), deviation of water flow volume (D_v), and Nash–Sutcliffe model efficiency (R_{eff}).

Soil and Water Assessment Tool (SWAT) runoff calculations were performed for daily time steps. Both Priestly–Taylor and Penman–Monteith methods were

tested for the calculation of evapotranspiration. Comparisons of the obtained results with measurements were made at the sub-basin and HRU levels. All monitoring stations were used both for calibration and validation, but with different agrohydrological years used for calibration and validation, respectively.

Calibration of P Losses

The AvSWAT model includes a large number of parameters describing and affecting the water quality. Evaluating modelling accuracy for a region that has not been previously modelled by SWAT, such as Scandinavia, requires adjustment of parameter settings. The unit that was used for calibration was kg/ha per HRU and kg/ha sub-basin output. Since the number of measurements were limited, a necessary step in the calibration was to compare leached kg/ha with results from earlier studies in comparable agricultural areas. Calibration was carried out consecutively based on comparison of modelled versus observed loads at available measurement points.

Table 1 shows the AvSWAT model parameters in order of significance for which values were adjusted during the calibration process to obtain the best possible fit with the measured data. Nutrient calibration consisted to some extent of a trial and error process to determine the best fit values. An important input in the calibration process was the collection of information on parameters from literature and data sources described above, since the optimal parameter settings for the conditions studied were not known. The sensitivity analysis (Table 1) was used in the AvSWAT calibration process, when selecting parameters for tests with modified parameter values.

Watershed Management System (WATSHMAN) was not calibrated, since it is coefficient based with runoff coefficients defined using the SCS Curve Number method (Chow et al. 1988) and leakage coefficients for land use classes from (Brandt and Ehjed 2002). No scientific basis exists for modification of the leakage coefficients from (Brandt and Ehjed 2002). Modelled data were, however, validated using monitored data.

Sensitivity Analysis

A sensitivity analysis of the model parameters was conducted using the SWAT Calibration and Uncertainty Procedures model (SWAT-CUP Version 1.3.2), to assess the sensitivity of the output of the system to changes in the parameters, input variables or initial conditions. SWAT-CUP is developed for calibration of SWAT models. The program links different calibration and uncertainty procedures, such as GLUE, ParaSol, Sequential Uncertainty Fitting version 2 (SUFI-2) and MCMC procedures to

Fig. 2 Location of three measurement stations used for calibration for Sagån basin

Table 1 Ranking of most sensitive model parameters used for model, given for effect of changes on flow and Phosphorus calibration

Parameter name	<i>t</i> -Stat	<i>p</i> -Value
Phosphorus uptake distribution parameter	1.68	0.09
Initial SCS runoff curve number for moisture condition II	1.56	0.12
Groundwater 'revap' coefficient	1.55	0.12
Average slope steepness (m/m)	−1.43	0.15
Deep aquifer percolation fraction	1.38	0.17
Threshold depth of water in the shallow aquifer for 'revap' or percolation to deep aquifer to occur (mm H ₂ O)	−1.28	0.20
Groundwater delay times (days)	−1.23	0.22
Melt factor for snow on December 21 (mm H ₂ O/°C-day)	−1.20	0.23
Plant uptake compensation factor	1.08	0.28
Surface runoff lag coefficient	−0.97	0.33
Depth from soil surface to bottom of layer	0.87	0.38
Average slope length (m)	−0.84	0.40
Soil evaporation factor	−0.83	0.41
Phosphorus availability index	−0.81	0.42
Snow melt base temperature (°C)	0.71	0.48
Effective hydraulic conductivity in main channel alluvium (mm/h)	0.61	0.54
Baseflow alpha factor (days)	0.59	0.56
Maximum canopy storage (mm H ₂ O)	−0.57	0.57
Threshold depth of water in the shallow aquifer required for return flow to occur (mm H ₂ O)	0.53	0.60
Moist soil albedo	0.50	0.62
Available water capacity of the soil layer (H ₂ O/mm)	0.49	0.62
Snow pack temperature lag factor	0.48	0.63
Snowfall temperature (*C)	−0.47	0.64
Initial P organic content in the soil layer (mg/kg)	0.44	0.66
Phosphorus soil partitioning coefficient (m ³ /Mg)	0.33	0.74
Melt factor for snow on June 21 (mm H ₂ O/°C-day)	−0.23	0.82
Initial soluble P concentration in soil layer (mg P/kg soil or ppm)	0.19	0.85
Manning's 'n' value for the main channel	−0.18	0.86
Phosphorus percolation coefficient (10 m ³ /Mg)	0.04	0.97

SWAT. It enables sensitivity analysis, calibration, validation, and uncertainty analysis of the SWAT models. SUFI-2 was selected to optimize and analyze the AvSWAT model. SUFI-2 regress the Latin hypercube generated parameters against the selected objective function (Nash–Sutcliffe 1970; Abbaspour 2009). The analysis was conducted with focus on water flow and total phosphorus load. Latin Hypercube simulation (McKay 1988) is based on Monte

Carlo simulations, but uses a stratified sampling approach that allows efficient estimation of the output statistics. It is commonly applied in water quality modelling (Vandenberghe et al. 2001). A *t*-test is used to calculate *t*-stat and *p*-values which measure sensitivity and significance, respectively. A larger absolute *t*-stat value represents higher sensitivity, while a *p*-value closer to zero represents high significance. SUFI-2 uses a procedure that is applied to parameter sets, rather than individual parameters, which allows the analysis to account for the interactions between parameters, instead of trying to find the absolute sensitivity of an individual parameter by fixing all parameters and observing how the changes of a single parameter change the results of the objective function (Abbaspour et al. 2004).

RESULTS

Validation of the hydrological modelling was done by applying the parameter values from the calibration period on the validation period, for each catchment. The only difference was that the meteorological data for the calibration period was replaced by data for the validation period, January 1, 2000 to December 31, 2001. Table 2 shows the accuracy of the simulated flows for all five catchments for the station closest to the outlet of each catchment. Figure 3 presents the measured and simulated water flow for these stations during the validation period.

Total P (TP) was measured at the different sites once or twice a month with the exception of Frögärdet in Sagån, which was monitored up to four times a month. For some of the catchments, such as Hedströmmen and Köpingsån measurements were only available for a few months during the year. Only Sagån and Svartån had nutrient concentration monitoring at sites with flow monitoring for full calibration and validation years, thus allowing validation of modelled loads with monitored loads. Comparisons can be made also for the other catchments by converting the loads from SWAT to concentrations, which can then be compared with measured concentrations. These comparisons showed that an acceptable fit between predicted and observed concentrations. The validation of loads in Sagån and Svartån shows good modelling accuracy, implying good accuracy also for the other three tributaries, Hedströmmen, Köpingsån and Örsundaån, which did not have any P measurements available for validation. The source apportionment is presented for all five catchments in Fig. 4.

The source apportionment diagram presents the amount of TP that leaves the HRUs and enters the water reach. This does not take into account the internal retention in the river system. Agriculture clearly dominates the P losses. For Sagån, the high value for point sources depends on a

Table 2 Accuracy of the SWAT hydrological modelling results for the five different catchments and their water flow stations

Catchment	Station	Calibration 1999–2000		Validation 2000–2001	
		Coefficient of determination (R^2)	Nash–Sutcliffe model efficiency (R_{eff})	Coefficient of determination (R^2)	Nash–Sutcliffe model efficiency (R_{eff})
Hedströmmen	Dömsta	0.61	0.47	0.59	0.46
Köpingsån	Odensvibro	0.57	0.57	0.55	0.47
Sagån	Frögärdet	0.76	0.68	0.58	0.34
Sagån	Gränvad	0.73	0.67	0.65	0.63
Sagån	Sörsätra	0.72	0.66	0.76	0.71
Svartån	Åkesta	0.76	0.74	0.5	0.44
Örsunda	Härnevi	0.64	0.64	0.49	0.32

Fig. 3 The measured and simulated water flow for the stations closest to the outlets during the whole validation period. For Sagån the figure represents Gränvad which is a sub-basin

Fig. 4 P source apportionment based on SWAT modelling for the five catchments

temporary malfunctioning in the chemical precipitation step of the major point source in the catchment.

As noted, the measured TP for Svartån and two of the three stations in Sagån are monthly values, and for the Frögärdet station at the best weekly. Since the measured values are not proportional to flow (sampled when a specified volume of water has passed), it is more accurate to compare the exact dates than to let the measured values represent a monthly average value. P losses display high temporal variations, and with only one or a few values per month it is very likely that peak losses will be incorrectly modelled, since the modelled P concentrations during high peak flows have not been adequately calibrated to monitored concentrations during peak flows. In addition, although the hydrologic modelling shows good accuracy (Fig. 3), it does not capture all peak flows, which is when most of the P is transported. Figures 5 and

6 present the modelled and measured load for the dates of the measurements. Table 3 shows the coefficient of determination and the Nash–Sutcliffe model efficiency for TN and TP for the calibration period as well as the validation period.

At Sagån the nutrient results are also good for the validation period, while they are less than satisfactory at Svartån for the validation period. This is largely because there are fewer monitoring stations in Svartån. The validation period had considerably higher rainfall than the calibration period, which resulted in somewhat underestimated flows for all catchments except Sagån, where more calibration stations partly compensated for the short calibration period (only one year). Figures 5, 6, 7, 8 and 9 only present results from the calibration period since rainfall conditions during the validation period were abnormally high and were not represented during the

Fig. 5 Daily Phosphorus loading for Svartån, Åkesta monitoring station

Fig. 6 Daily Phosphorus loading for Sagån sub-basin at Frögärde station sub-basin

Table 3 Accuracy of SWAT nutrient load modelling results for Sagån (Frögärdet) and Svartån (Åkesta)

Catchment	Station	N R_{eff}	N R^2	P R_{eff}	P R^2
Calibration					
Sagån	Frögärdet	0.2	0.5	0.92	0.98
Svartån	Åkesta	0.63	0.71	0.78	0.86
Validation					
Sagån	Frögärdet	0.68	0.82	0.45	0.47
Svartån	Åkesta	−0.51	0.38	−0.36	0.12

For the other three basins, there were no flow measurements at the nutrient stations. R^2 refers to the coefficient of determination, and (R_{eff}) to the Nash–Sutcliffe model efficiency

calibration period. Figures 7 and 8 show how important it is to have frequent measurements; in January and March, the measurements miss the peaks, which resulted in opposite outcomes. In January, the peak does not last long and therefore the averaged value for January is higher than the modelled, while in March, the situation is the opposite. Without flow-proportional measurements, it is not possible to know if the model over- or underestimates. Many earlier research studies calibrated to monthly nutrient measurements, which is likely to be the main cause of problems for modelling peak flow situations correctly. It should be noted that the nutrient concentration varies with flow, but in different ways for different types of catchments in terms of

Fig. 7 Monthly Phosphorus loading for Svartån sub-basin calculated with measurement as average load for the whole month

Fig. 8 Daily simulated Phosphorus load for Svartån at Åkesta station compared to measured load

Fig. 9 Comparison of the monthly total Phosphorus loading at Åkesta station in Svartån

soil characteristics, terrain, land use etc. (Zakrisson et al. 2003; Abbaspour 2009).

The modelling results for TP loads at the monitoring stations for the specific monitoring days are good. The strong relationship with monitored data for these days shows that SWAT modelling based on the input data generally available in Sweden and the revised parameter setting provides very useful results. However, the fit could be improved at peak flow events which are important since a majority of the P is released during winter snow melt occasions, spring flow and autumn rainfall peaks (Zakrisson et al. 2003).

The comparison on a monthly basis has a weaker relationship. Figure 7 shows the fit between monthly values when monitoring once every month is interpolated to compute monthly means and monthly total load for Svartån. The simulated P loss peak in Fig. 8 is missed by the monthly measurements, but is by chance largely compensated with an overestimate for the weeks before and after when interpolating monthly monitoring values to compute monthly losses in Fig. 7. If by chance, the monthly measurement would have been at the peak, the overestimate of P loss would have been very large in the averaged monthly ‘measurement’ data. The good correlation between modelled and measured values for both Sagån and Svartån achieved for the exact dates of the measurements (Figs. 5,

6), strongly indicates that the model results are reliable. Therefore, the modelled total monthly load is likely to be closer to the actual total monthly load than the monthly mean calculated from one or two measurements. Figure 7 illustrates the problem with monthly measurements. In January and February–March, the model for Svartån simulates two peaks in leakage that were missed by the monthly measurements. The situation is the same in Sagån. For P as well as for N, there is a clear need for more frequent measurements.

The model sensitivity analysis (Table 1) provided an overview of which parameters that are the most sensitive, and have the highest influence on the model performance. For the uncertainty analysis, the SUFI-2 method was used.

Table 4 Comparison of monthly results for the models WATSHMAN and SWAT during the agrohydrological year 1999–2000 for Svartån

	WATSHMAN		SWAT	
	Flow	TP	Flow	TP
Slope of the regression line	0.94	0.49	1.09	0.82
R^2	0.83	0.72	0.86	0.72
R_{eff}	0.63	0.63	0.74	0.56

R^2 refers to the coefficient of determination, and (R_{eff}) to the Nash–Sutcliffe model efficiency

SUFI-2 performs a combined optimization and uncertainty analysis using a global search procedure and can deal with a large number of parameters through Latin hypercube sampling (Abbaspour and Johnson 2004).

Sequential Uncertainty Fitting Version (SUFI-2) uses two factors, a P-Factor to describe the goodness of fit, and R-Factor to measure the degree to which the calibrated model accounts for uncertainties. The P-factor is the percentage of measured data which is bracketed by the 95% Prediction Uncertainty (95PPU), while the R-Factor quantifies the strength of an uncertainty analysis which is the average thickness of the 95PPU band divided by the standard deviation of the measured data (Abbaspour 2009). After the model was manually calibrated in AvSWAT (Statistical results are shown in Table 4), the SWAT-CUP interface was used to calculate the uncertainty of the model. SUFI-2 was not used to calibrate the model. All of the calibrated hydrological and P parameters were tested, allowing variations in parameter values within the range ± 0 –30%, which is based on expert judgment of uncertainty in the input parameters. It should be noted that the uncertainty for each input parameter is unknown and cannot be calculated with any detail. Therefore, the uncertainty was set to a range reasonable for each parameter according to the characteristics of the Swedish agricultural landscape, and the model results for 2,000 model runs with parameter variations within these ranges were compared with the measured flow and P data. The SUFI-2 analysis and uncertainty results are shown in (Fig. 10) and the statistical values are shown in (Table 5).

For the set up that has been used in the modelled catchments, the parameters connected to water flow that constitute the highest uncertainties were those related to soil data and groundwater flow. Soil properties can vary significantly within a small spatial area, and it is difficult to know how well the data collected from a few field tests represent the soil in a HRU, sub-basin or in the catchment. The SCS curve number parameter and groundwater parameters were parameters that had considerable effect on the water dynamics in the model. The SCS curve

Table 5 SUFI-2 analysis and uncertainty results

Variable	<i>p</i> -factor	<i>r</i> -factor	R^2	NS
Results	0.43	0.53	0.63	0.57

The *p*-factor is a percentage factor (range 0–1) indicating the goodness of fit, and the *r*-factor shows the uncertainty (range 0–infinity), a lower *r*-factor represents lower uncertainty

number has an influence on the amount of water that divides into surface runoff and percolation through the soil profile, thereby affecting both water hydrology and nutrient loading. Regarding the parameters on snow melt dynamics and the rate of snow melt very few studies were found in literature and model settings were therefore based on calibration. For the nutrient leaching calculations, it is crucial to achieve high accuracy for the simulated water flow. In addition, it is important to have representative information on the chemical status of the soils and how it changes with soil depth. In SWAT, the chemical status is represented by the chemical parameters describing the N and P pools in the soil for the different layers. These values can change quickly within small spatial areas and with depth, making it hard to set a fixed value even if considerable amounts of field data are available, which was not the case here. In the modelled catchments, the data available have been interpolated to reduce these uncertainties but even so, the uncertainties related to soil nutrients values are substantial. Since the soil chemical status can be both lower and higher than set values, and there are relations between nutrient leakage and high nutrient status, it is hard to know if the model over or underestimates the nutrient leakage from different soil types. Regarding the accuracy of management data and fertilizer loads, the loadings and management operations were based on comprehensive data collection that builds on a large number of agricultural study areas (Johnsson et al. 2008), and is considered to be reliable on a regional scale. As noted below, however, local management data could improve the results.

Fig. 10 SUFI-2 results from a 2,000 run simulation

Also, data on rural household wastewater treatment facilities are associated with uncertainty. For the majority of the 6,500 rural households that are not connected to municipal sewage treatment plants in the catchment, no information on the type of sewage treatment facility is available. The national averages regarding percentage of infiltration beds, tanks and other treatment techniques were used. The uncertainty associated with such an assumption is that the local situation could be slightly better, reducing the discharge with up to 1 ton TP or, more likely, judging from limited local inventories, the local situation could be worse with an increase of household discharge of up to 3 tons of TP. This could shift the source apportionment by up to 8% for rural households and agriculture.

The comparison between SWAT and WATSHMAN was carried out to provide an understanding of the potential difference in accuracy between a detailed process-based model such as SWAT and a rainfall-runoff coefficient-based model such as WATSHMAN. The differences between the models have been described above. The comparison was made for the output variables water flow and total Phosphorus. The WATSHMAN model calculates the water runoff on a daily basis, but the result of both the water flow and nutrient calculations are presented with a monthly time step. In the SWAT model, all the calculations are made on daily basis, but the user has the option to present the results in different time periods. The agrohydrological year 1999–2000 was used to compare the different models. The results are displayed in (Table 4). Figure 9 shows the comparison of total Phosphorus load at Åkesta station in Svartån for the two models at a monthly time step level. It is important to remember that the nutrients were only measured once a month, and therefore part of the difference between simulated and ‘measured’ values may be attributed to summing up ‘measured’ values from measurements once a month. The monthly ‘measured’ value was calculated from the measured concentration (one occasion) and multiplied by the total monthly

flow. An example in Fig. 9 is the month of April, for which the measurement average clearly seems to be an overestimation. Table 3 and Fig. 8 show good results for the SWAT model concerning nutrient loadings, however, but the uncertainty remains due to the limited number of measurements.

For Sagån, SWAT showed a TP load of 30 tons for the average year between 1998 and 2001, while WATSHMAN modelled 43 tons for the same years. The measured average yearly value for Sagån was 36 tonnes of Phosphorus. The more detailed modelling of P from agriculture provided by SWAT gives a significantly lower loss from arable land than the coefficient-based WATSHMAN model. The average P loss calculated at Sagån for the years 1998–2001 is 0.5 kg P/ha for the WATSHMAN model, while the corresponding figure for SWAT is 0.36 kg P/ha. The measured average P loss for the period is 0.42 kg P/ha. SWAT underestimates TP for Sagån, but not for Svartån. As noted in the uncertainty analysis above, the main reason for this is likely to be that the actual local management practices, e.g. manure handling, were significantly different from the practices given by regional statistics and used in the modelling. Thus, collection of local information from farmers seems to be necessary to reach high accuracy. The two models give similar source apportionment results, although the lower agricultural contribution with SWAT (Fig. 11). The difference is that SWAT gives more detail for agricultural leaching, and specifically in action scenario modelling, but in cases where point sources are the major problems conceptual rainfall-runoff coefficient-based models, such as WATSHMAN provide less time-consuming modelling with similar or better accuracy.

A discussion of how the model deals with the differences in scale is important to identify the range of applicability of the model in question. The Sagån catchment has a number of rain gauges and one meteorological station and on the larger scale these stations give a good representation of the weather conditions. On the smaller scale, such as a

Fig. 11 Comparison of source apportionment for Sagån, modelled by SWAT and WATSHMAN

sub-basin, the risk of the meteorological data not accounting for local variability increases. A problem for soil data parameters is that on the larger scale, spatial variability of the soils may be evened out by the size of the study area, while on the smaller scale the low resolution of data input may give a false representation. SWAT proved capable of coping with water hydrology and dynamics on both a large and small scale with good results. The water dynamics and the nutrient loss results for both a larger catchment (Svartån; Table 3; Fig. 5) and a smaller sub-catchment (Frögärdet; Table 3; Fig. 6) were satisfying.

Table 1 shows the ranking of the sensitivity analysis. Parameters concerning snowmelt were ranked to be important for water flow as well as nutrient modeling. This illustrates the importance of having an adequate representation of meteorological data. The good fit between modelled and measured hydrology dynamics on both the larger and smaller scale indicates that this was the case in Sagån. Parameters on nutrient content in the soil layers were together with depth from soil surface to bottom of layer, root depth and bioturbation of high priority for the nutrient leakage. It is therefore important to reduce uncertainty associated with soil conditions, e.g. by input from local farmers.

DISCUSSION

Although the calibration process is time-demanding and values from peer-reviewed papers were not available for many of the calibration parameters, for the region studied (for some parameters only for parts of the United States and central Europe), detailed process-based modelling gave results of high accuracy on the scales studied. The modelling results, however, still have uncertainties associated with shortages in input data, and with a lack of knowledge on leaching dynamics caused by this data shortage. These factors are discussed as follows.

Soil Nutrient Status

The scarce information on the soil's initial nutrient status causes part of the uncertainty, especially for forest soils where no measurements have been made. For better information on the arable soils' nutrient status, it would be necessary to contact the local farmers who, in Scandinavia, usually have detailed and updated information through soil surveys.

Management Information

Depending on how the soils and crops are managed, the P loss can vary considerably under the same climate

conditions. Regarding application of manure and fertilizers, timing is crucial. Farmers usually try to avoid fertilizing when rain is expected, but the standard values for application times that are used in the model can result in situations where application of fertilizer and rainfall coincide or that the time in between is too short. This can then cause a simulated result where a major part of the fertilizer application is washed out. To avoid this, fertilization was set to dates when no rain came prior to fertilization or within a few days afterwards.

The amount of fertilizer is another important factor. Do the farmers adjust the fertilizer application to the nutrient status in their soils and do they have data on the concentrations in the animal manure? The way the fertilizer is applied is also influential. The fertilizer can be applied when sowing or later on. There are also different techniques for spreading manure and the amount of leakage can depend on how well the fertilizer is being incorporated in the soil. Local information from farmers regarding these factors was not available for this study. Also, information on tile drainage could potentially have contributed to improved results. In situations where preferential flow occurs and the water reaches the tile drainage systems, the P loss is likely to increase significantly.

Measurement Data

The variation in P load with flow calls for flow-proportional measurements. The results from the catchments show that the P concentration changes with flow in a manner that is highly dependent on the characteristics of soils, land use and lake area in each basin, and is therefore to some extent unpredictable. Large data sets from various conditions on the relationships between flow and P concentrations are needed. Flow-proportional measurements enable detailed analyses of relationships between flow and nutrient concentrations, and if high variability in flows is covered during one or a few years of measurements in each catchment, long time series are not required. The peak losses during high flows with associated high concentrations are often missed with monthly measurements.

Retention

An important factor in nutrient modelling is the retention calculation of nutrients in the water stream network. The SWAT in-stream water quality function calculates daily algae primary production, moving P from inorganic to organic algae P and then back again as the algae die. This process, however, resulted in a considerable addition of P, assumed to be an error either in the model or in the parameter settings, since total in-stream P should not change due to the algae dynamics with the exception of

settling algal P that will reduce the transported load. The default parameters set by the model were deemed unrealistic for Swedish conditions and no reliable data could be found on algal growth and settling for the specific region. The focus of the study was nutrient losses from agriculture, and, therefore, it was decided to model without the in-stream and lake retention function. Since lakes are few and small in the studied catchments, the retention is low and is not likely to have had significant influence on calibration, validation and results. Still, part of the remaining differences between simulated and measured loads depends on retention. In WATSHMAN, the retention calculations are simpler and based on temperature and the area of lakes and streams together with concentration and a nutrient constant. From 1997 to 2001, the retention in Sagån was calculated to within 5% of the gross P load with WATSHMAN (Zakrisson et al. 2003). This supports the assumption that in this case, the retention does not have a significant effect on nutrient loads.

Modelling Period

A calibration period of one year and a validation period of the same length is a comparatively short modelling period. A longer period may have reduced some of the uncertainties, by allowing calibration under a wider range of meteorological conditions. However, data availability in terms of water quality data as well as land cover data hampered modelling for a longer period. The latter was available only for the year 2000. Land cover and agricultural management practices generally do not change quickly, but in part of the study catchments, urban development has been rather intense. It should be noted that temporally stable management practices does not contradict the conclusion that the spatial variation of management practices calls for more detailed data.

CONCLUSIONS

The results from the adaptation of SWAT modelling to Scandinavian conditions are promising. Overall, model performance regarding flow volumes and flow dynamics was satisfactory. Comparable results were achieved at several scales. For instance, the sub-basin area for the chosen calibration points within Sagån basin varied from 7.4 km² (Frögärdet) to almost 600 km² (Sörsätra, Table 2). The model captured the daily flow dynamics at these varying scales in spite of the complexity of the studied catchments regarding varying land use and soil type distributions. The achieved results regarding water flow provided an adequate basis for nutrient modelling. However, observed remaining discrepancies between measured and

simulated water flow must be taken into consideration when evaluating the results of nutrient modelling.

The transport of P varied considerably, with extreme peaks during a few occasions during the year. This agrees well with findings of previous studies (Jordan et al. 2003) who found that influxes and outfluxes of P to and from wetlands were extremely high during a few weeks of the year, accounting for a high proportion of the annual net flux, and (Gentry et al. 2007) who concluded that a few overland runoff events greatly affected annual TP loads. At Sagån (Frögärdet station) 76% of the annual TP was discharged between December 24, 1999 and January 10, 2000.

The modelled P load was of good accuracy for the days when monitoring data were available for validation, which generally was once a month. However, an underestimation is observed for Sagån, which indicates that further future modelling should focus on use of more local data from farmers regarding their management practices and soil characteristics. Modelled monthly P load did not fit as well with averaged monthly monitoring load values, mainly due to the fact that the P load peaks during spring and autumn are often partly or entirely missed with monthly monitoring. The problem thus lies in scarce monitoring data rather than in model performance. The high P loss during a few events calls for flow-proportional water sampling for better model calibration. This conclusion supports the findings of Jordan et al. (2003) that event-based sampling might be needed to reveal correlations between concentrations and flow rates. Only then will a more detailed analysis of model performance be possible. This also stresses the importance of synchronized monitoring and modelling efforts. The in-stream and lake retention function of SWAT needs to be further adapted to Scandinavian conditions for applications in catchments where retention is more significant than in the catchments studied here.

With a broader application of the model the knowledge regarding the importance and sensitivity of different model parameters will increase. The results presented here as well as further improvement of input and monitoring data will enable further adjustments and development of SWAT and other models for different conditions. Further improvements in the resolution of input data such as P content in the soil and agricultural management practices will, however, be required to reach modelling results that will enable identification of optimal programmes of measures adapted to local conditions.

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