Nordic Hydrology, 32 (1), 2001, 29-48

Internal HBV-96 Variables and Phosphorus Transport Processes

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The high data requirements of total phosphorus (TP) transport prediction tools limit their application. Recently, research has therefore started in Sweden to use a conceptual hydrological model, HBV-96, as a base for TP estimation. A first step is, however, to understand the relationship between model variables and natural processes. A review of particulate and dissolved material transport enabled the most important TP transport processes to be found for small Swedish catchments. A probabilistic flow categorisation technique based on the internal HBV-96 variables is suggested. Days with a high probability of saturated overland flow are identified with an overland flow index based on the water content of the upper response box and rainfall/melt rates. Further categorisation into intermediate and base flow is done on the basis of water contents in the lower and upper response boxes of the model. The flow categorisation technique was tested in a catchment with TP and suspended sediment records. The results show significantly different concentration distributions and median values between the flow categories. The HBV-96 internal variables, in general, are more highly correlated to concentration than is observed river runoff and it may thus be beneficial to apply the model to assess TP transport compared to using observed runoff directly. Model parameter interdependence is highlighted as a shortfall in the general use of HBV-96 for flow categorisation.

Introduction

Total phosphorus (TP) transport in Sweden has during recent decades been recognised because of the growing eutrophication problems in lakes and brackish coastal waters (*e.g.* Forsberg 1994). The deteriorating water quality has led to an increased demand on water quality management, which however is hampered for two main reasons; data scarcity due to expensive and time-demanding measurement techniques and lack of reliable and user-friendly tools for interpreting the measured data. Available models for TP transport assessments (Lørup and Styczen 1996; Thorsen *et al.* 1996) are generally very data demanding, which often make them economically infeasible and impractical for the user.

In Sweden catchment-scale conceptual models with limited input data demands have successfully been used for runoff and riverine nitrogen mass transport (*e.g.* Bergström 1995; Arheimer and Brandt 1998). However, phosphorus transport has generally been considered impossible to simulate with lumped models because of the distributed and complex transport processes. No extensive research has therefore been focused on using the same model approach for TP transport simulations. Recent studies have, however, indicated phosphorus as the limiting substance for eutrophication rate (Hellström 1996; Tyrell 1999), increasing the demands for modelling tools applicable for large river basins. Within the Baltic HOME (Hydrology, Oceanography and Meteorology for the Environment) funded by SMHI (Swedish Meteorological and Hydrological Institute) research has therefore started on applying the HBV-96 hydrological model (Lindström *et al.* 1997) as a base for phosphorus transport estimation.

A first major step towards the use of a conceptual hydrological model as a base for TP simulation is, however, to understand and parameterise the major transport processes in nature and to relate them to model variables. For instance, can variables computed by the HBV-96 model explain the variance seen in riverine TP or can a flow categorisation based on information computed by the model separate occasions especially important for TP transport? The inclusion of observed precipitation and air temperature variables, which govern conceptualised measures of *e.g.* snow melt, soil moisture deficit or groundwater storage, would logically add information that is important for material transport. On the other hand, one can argue that the model introduces errors due to its approximate description of nature and the internal state variables have limited information since they are mean integrated values.

When lacking distributed data, observed river runoff is often used as explanatory variable in empirical models or traditional flow separation is applied to trace the origin of riverine TP concentrations (*e.g.* Probst 1985). The objective of this study was to investigate if it is beneficial to apply the HBV-96 model to assess TP transport instead of using the observed runoff directly. In a case study, the HBV-96 was therefore applied to a small South-Swedish catchment and model variables were correlated to observed TP concentrations to assess if they could explain more variance in riverine TP than could observed runoff. Based on the present knowledge on phosphorus transport processes and an analysis of HBV-96 internal state variables, a flow categorisation approach was suggested to assess if the variance in observed TP concentrations could be decreased by subdividing the data into groups according to the flow situation at the time of sampling. Evaluation of the suggested approach was done by comparison with traditional flow separation techniques based on observed river runoff alone. Because of the importance of particulate transport for TP load, suspended sediment (SS) transport was included in the study.

Phosphorus and Sediment Transport in Small Catchments

General for Scandinavian Conditions

The yield of SS and TP at the outlet of a watershed is the result of generation, transportation and deposition in that watershed (*e.g.* Gregory and Walling 1973). The two substances generally follow the same transport patterns because a large proportion of TP is believed to be transported while adsorbed to sediment particles (*e.g.* Holtan *et al.* 1988).

In Scandinavia the single most important factor for spatial variation of SS and TP data is land use. High SS and TP transport are usually found in agricultural areas (*e.g.* Andersson 1982) and a strong correlation between SS and TP concentrations in river and lake waters and percentage of arable land has been found in several studies in Sweden (*e.g.* Ahl 1988; Håkansson 1995). Bare soils and excessive use of fertilisers mainly explain the strong link between high transport loads and agricultural practices. Previous research has also shown the importance of soil texture (*e.g.* Alström and Bergman 1990) and deposition in rivers and lakes (*e.g.* Brandt 1990).

The temporal variation of riverine SS and TP transport is highly dependent on the climate variables and the hydrological processes in the catchment. In Sweden, river runoff is usually dominated by subsurface flow, *i.e.* pre-event water that is stored as groundwater in the saturated soil before the rainfall or snowmelt event (Rodhe 1987). Furthermore, the infiltration capacity of Swedish soils is usually sufficient to infiltrate rainfall or melt, which prevents Hortonian overland flow. The exception is melt on frozen agricultural soil when the infiltration capacity is close to zero. Thus, overland flow in Sweden generally is rare and occurs mainly as saturated flow on discharge areas close to the streams during very wet conditions or as Hortonian flow on frozen soil.

Although overland flow is rare, almost all detailed studies of soil erosion and phosphorus generation in Scandinavia indicate that occasions with overland flow cause the majority of SS and TP transport to the rivers (*e.g.* Alström and Bergman 1990; Lindén *et al.* 1993; Ulén 1995). It has been shown that snowmelt generally produces larger soil and phosphorus losses than rainfall events, which is explained by a longer duration of water input to the soil by presence of frozen soil, giving higher probability of overland flow. Alström and Bergman (1990) also emphasise the importance of thawing, which makes the soil particles highly erodible. In addition to sheet and rill erosion on fields, extensive erosion of material through drainage pipes (Ulén 1998) and within the river channel (*e.g.* Hasholt 1988) has also been reported in Scandinavia during high flow conditions.

Phosphorus concentration in freshwater is dependent on biological and chemical processes in the water and sediment phase (*e.g.* Persson and Jansson 1988). Dissolved phosphorus is directly accessible for biological uptake, while particulate phosphorus must undergo desorption before uptake. The bed sediment may work both as a sink through deposition and a source through mobilisation and mineralisation processes (Boström *et al.* 1988).

Observed Riverine Suspended Sediment and Phosphorus Data in Sweden

The Swedish Agricultural University (SLU) has since the late 1980s monitored nutrient transport in small agricultural catchments in southern Sweden (Kyllmar and Johnsson 1998). Studying six basins with an average of 8 years TP records shows loads of 0.04-0.29 kg d^{-1} km^{-2} and median concentrations of 0.05-0.21 mg l^{-1}. Particulate phosphorus, defined as particles greater than 0.45 μm, contributes in average with 13-44% of the total load, showing that dissolved phosphorus is dominating. The catchments areas range from 7-19 km^2 and the percentage of arable land is high for Swedish standards, 53-93%.

Observations of SS transport in small catchments are rare in Sweden. A monitoring network for sediment transport was run by SMHI from 1967-1994 (Brandt 1996) but only six stations have catchment areas less than 100 km^2. Data from these catchments, which are located in central and southern Sweden, show 0.8-22 tonnes $year^{-1}$ km^{-2} and average concentrations of 4.3-107 mg l^{-1}. The percentage of organic material in SS varies between 21 to 90%. The land use is of mixed nature and catchment areas range from 3-21 km^2. The variation in transport is large between the catchments, which is explained by differences in land use, with forest dominated catchments showing low SS load and high organic content. Brandt (1996) concludes that the specific SS load from these small catchments is large compared to that from larger river basins included in the monitoring network.

Categorisation of Transport and Flow Processes

Assessment or modelling of natural processes needs in almost all cases a categorisation and simplification of the real processes due to their complexity. The categorisation of TP transport processes defined here (Table 1) is based on the above review and assuming small catchments without lakes. Chemical and biological processes in the water and sediment phase can therefore be neglected. Table 1 is valid also for SS transport considering only the particulate mode of transport.

Four generation processes for particulate phosphorus are separated. Erosion causing particulate transport occurs either because of Hortonian overland flow, saturated

Table 1 – Categorisation of the most important processes for phosphorus transport in a small Swedish catchment.

Transport mode	Generating process	Conveyance mechanism to nearest stream
Particulate	Erosion by Hortonian overland flow on frozen or thawing soil	Overland flow
	Erosion by saturated overland flow caused by rain or snow melt	Overland flow
	Channel erosion	Direct input
	Erosion in drainage pipe surroundings	Drainage pipe flow
Dissolved	Leakage from agricultural land	Groundwater flow and drainage pipe flow
	Leakage from point sources	Groundwater flow or direct input

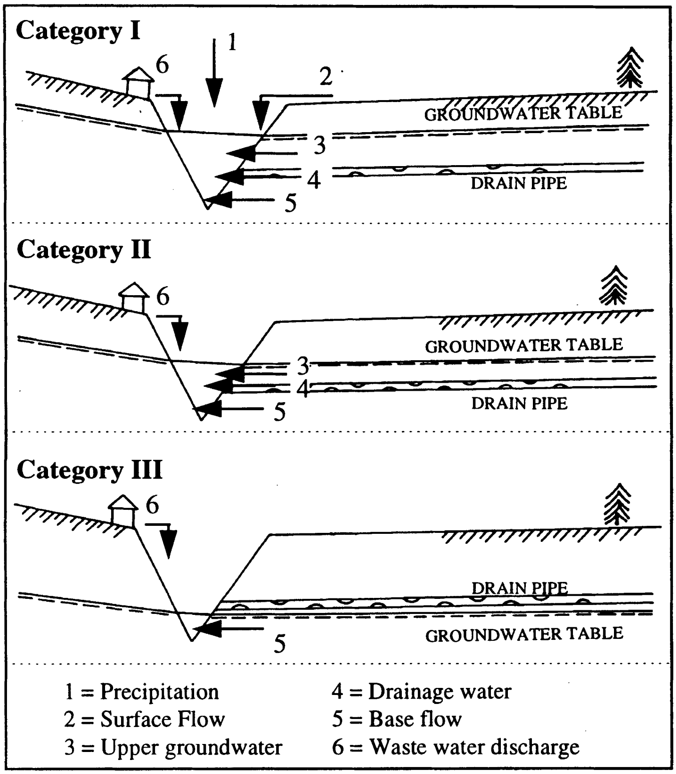

Fig. 1. Separation of flow categories important for TP generation and transport.

overland flow, channel flow or groundwater flow around drainage pipes. Dissolved phosphorus is assumed to be generated either as leakage from agricultural lands or from point sources. Major transport mechanisms from source to nearest stream are overland flow, groundwater flow and drainage pipe flow. The categorisation may seem to give a bias towards particulate phosphorus transport, which contradicts the observations in Sweden. However, the processes are not to the same extent contributing to the TP transport but depend on the characteristics of the catchment.

Considering the generation and transport mechanisms in Table 1, three types of flow conditions can be defined with different distributions of water and material input to the streams (Fig. 1). Category I is defined as rainfall and/or melt during wet conditions. Water and TP are then transported to the streams by overland flow, groundwater flow and through drainage pipes. During Category II, no infiltration from rain or melt occurs but conditions are still wet giving water and TP inputs through groundwater flow and drainage pipes. Finally, Category III is defined as conditions when the groundwater level is low and the only natural inflow to the stream is groundwater flow from deep levels.

The HBV-96 Model

Model Structure and Applications

The HBV-96 model (Lindström *et al.* 1997) can be classified as a semi-distributed conceptual hydrological model (Fig. 2). It uses subbasins as primary hydrological units with an area-elevation distribution and a crude classification of land use. The model consists of three main components; i) subroutines for snow accumulation and melt, ii) subroutines for soil moisture accounting, and iii) response and river routing subroutines. The model has a number of free parameters, values of which are found by calibration against runoff. It is usually run with daily time steps, but higher resolution can be used if data are available. Input data are precipitation, air temperature and monthly mean potential evapotranspiration. The HBV-96 structure, variables and parameters are described in detail by Lindström *et al.* (1997).

The model is mainly used for simulating river runoff on a catchment scale and has been applied to catchment sizes from a few square kilometres to 1.6×10^6 km^2 (Bergström 1995; Bergström and Graham 1998). The model structure has also proven successful for simulation of conservative and non-conservative dissolved transport; alkalinity and pH (Bergström *et al.* 1985), oxygen-18 (Lindström and Rodhe 1986) and nitrate (Arheimer and Brandt 1998; Lidén *et al.* 1999).

Variable Interpretation and Dynamics

The HBV-96 model is run continuously for a catchment based on the continuity principle. Water is stored and conveyed between different reservoirs representing snow cover, soil moisture and groundwater. The state of each reservoir in the model

RF	Rainfall
SF	Snowfall
EI	Interception evaporation
EA	Evapotranspiration
inf	Infiltration to soil
sm	Soil moisture
R	Recharge
CF	Capillary flow
h_{UZ}	Storage in upper zone
h_{LZ}	Storage in lower zone
PR	Percolation
EL	Lake evaporation
ilake	Lake area
Q_0	Outflow from upper zone
Q_1	Outflow from lower zone
Q	River runoff

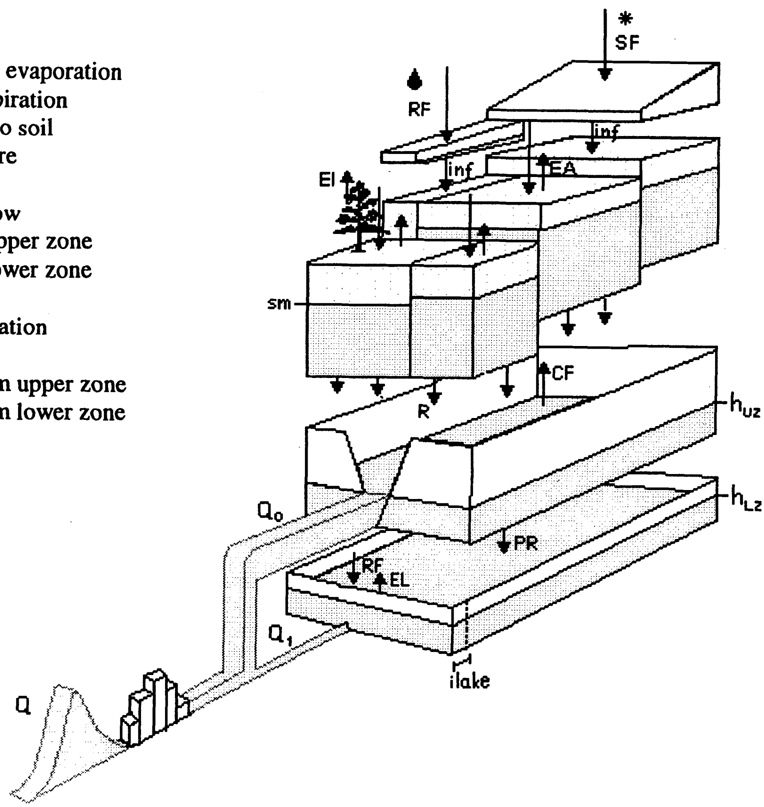

Fig. 2. The principle structure and variables of the HBV-96 model.

constitutes the internal variables of the model. An important feature of these variables is that they are lumped values for a non-homogeneous area, either a subbasin or a subzone (altitude and/or land use). If the model is run for a three-year period in the case study basin, a southern Swedish catchment, the variables may typically look like in Fig. 3.

The first five graphs show the variables from the snow accumulation and melt routine. Simulated areal air temperature and precipitation control the accumulation of water as snow, the snowmelt and the infiltration to the soil. Note that the simulated infiltration constitutes of both rainfall and/or snow melt. Further variables illustrated are the storage of water in the soil box, upper and lower response box and finally the simulated river runoff. Common interpretations of these variables are the water content in the unsaturated zone (soil moisture) and in the saturated zone (upper groundwater and deep groundwater). Interpretations like these are, however, user specific since the main purpose with the model structure is to simulate lumped estimates of groundwater recharge, quick runoff and base flow rather than describ-

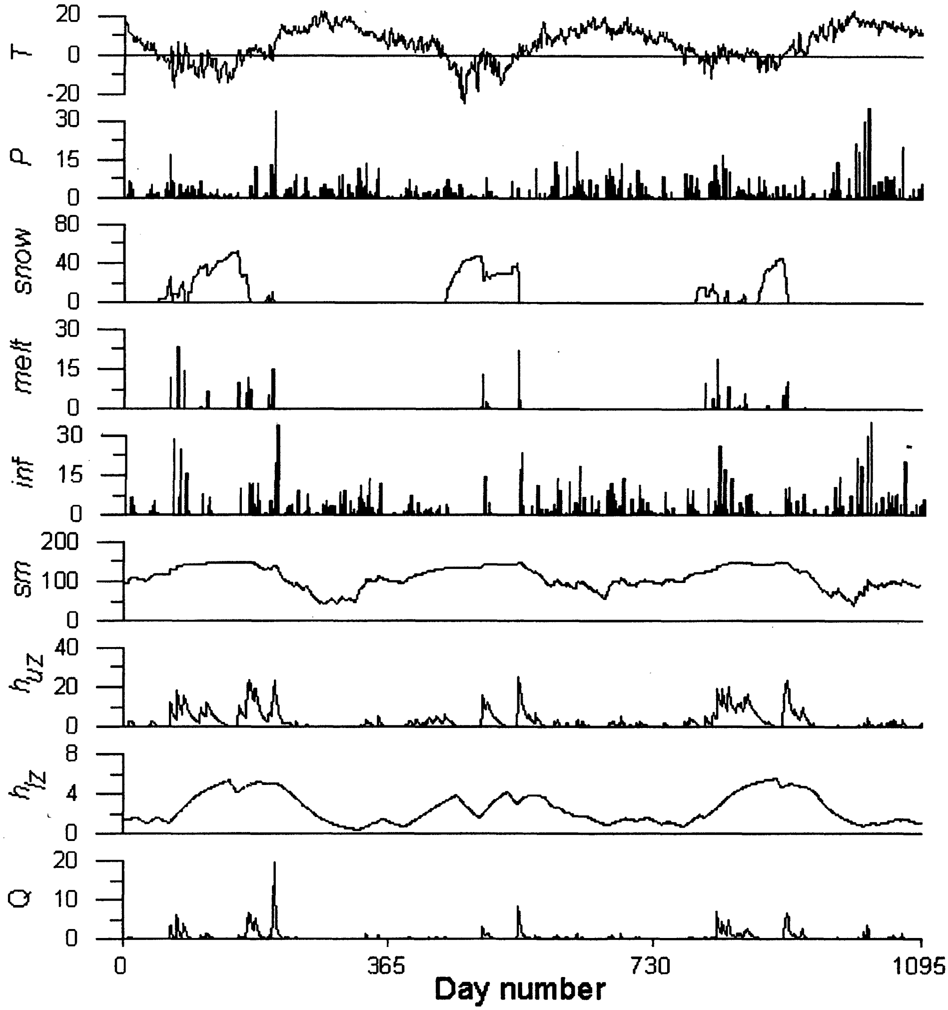

Fig. 3. Dynamics of HBV-96 variables for the Hestadbäcken catchment (7.6 km^2). *T* is areal air temperature (C°), *P* is areal precipitation (mm day^{-1}), *snow* is snow storage in water equivalents (mm), *melt* is snowmelt (mm day^{-1}), *inf* is infiltration to the soil (mm day^{-1}), *sm* is water storage in the soil box (mm), h_{uz} is water storage in the upper response box (mm), h_{lz} is water storage in the lower response box (mm) and *Q* is river runoff (mm day^{-1}). Day 1 equals 1/10/1985.

ing physical features in nature. An interesting observation is, however, the different dynamics of the four soil and response variables, *sm*, h_{uz}, h_{lz} and *Q* (Fig. 3). The cycle time for these variables are roughly in the order of one year for *sm*, a number of months for h_{lz}, one or two weeks for h_{uz} and a few days for *Q*. This means that the variables are different measures of the hydrological memory in a catchment. For instance, *sm* indicates if the summer was dry or wet, h_{lz} if the last months were dry or wet, h_{uz} if the last week was dry or wet and Q shows the present river flow.

The soil routine in the HBV-96 model has proven to be very robust (Bergström and Graham 1998) and the response box approach is used by a large number of hydrological models in the world (Singh 1995). Following the above-mentioned interpretations of the model variables, the model structure has also proven to accurately simulate the fluctuation of observed data in data-intensive catchments; snow storage (Brandt and Bergström 1994), soil moisture deficit (Andersson 1988) and groundwater levels (Bergström and Sandberg 1983). On the other hand the parameter interdependence problem often found in conceptual models may cause uncertainty. Seibert (1997; 1999) found through Monte Carlo simulations that an acceptable model performance could be obtained by a large number of HBV parameter combinations and concluded that calibration against more observed variables than river runoff was necessary if internal variables should be simulated accurately.

Flow Categorisation Through HBV-96 Variables

According to Table 1 and Fig. 1, the riverine TP load depends on the distribution between overland flow, drainage pipe flow and groundwater flow. A flow categorisation would therefore augment the assessment of different transport processes. As mentioned above, the HBV-96 variables are lumped both in space (subbasin) and in time (in this case daily mean), which means that a flow categorisation by using the HBV-96 model must be on a probabilistic basis. For instance a large h_{uz} means high probability for high groundwater levels and thus also high probability for saturated overland flow in the catchment. Based on this approach the three flow categories in Fig. 1 are suggested to be separated according to

Category I:

$$ofi = \frac{h_{uz}\, inf}{h_{uz,\mathrm{median}}\, inf_{\mathrm{median}}} \geq 1 \tag{1}$$

where *ofi* (dim.less) is a saturated overland flow index, h_{uz} (mm) is the water in the upper response box, *inf* (mm) is infiltration on open fields (arable land and pasture areas), *i.e.* snowmelt or rain that reaches the soil and $h_{uz,median}$ and inf_{median} are the corresponding long-term median values for days with values larger than zero.

Category II:

$$h_{uz} > 0,\ ofi < 1 \tag{2}$$

Category III:

$$h_{uz} = 0 \tag{3}$$

The *ofi* was chosen to separate extreme situations in a catchment when a combination of high groundwater levels and high melt or rainfall rates are present causing high probability for saturated overland flows close to the streams and ditches. Saturated overland flow appears as soon as the groundwater level reaches the surface, *i.e.* independent on rainfall or melt. However, the overland flow rate and thus the erosion increases with high rainfall and melt intensities, which explains the infiltration rate in Eq. (1). The use of median values instead of threshold values for h_{uz} and *inf* was chosen since a threshold value is highly dependent on the model parameters and thus uncertain due to the shown parameter interdependence in the HBV-96 (Seibert 1997). The value of 1 in Eq. (1) was chosen arbitrary. Unfortunately it is inevitable to include some subjectivity in the proposed methodology in a similar way as traditional flow separation techniques (*e.g.* Hewlett and Hibbert 1967) include arbitrary choices. Category II is characterised by rather high groundwater levels but no significant overland flow. High groundwater level gives a higher probability of having drainage pipe flows, which thereby differs from Category III when only groundwater flow from deep levels contributes to the river runoff.

The suggested flow categorisation using internal HBV-96 variables was tested in a case study where SS and TP concentration data were divided into the different flow categories depending on the conditions during the day of sampling. To assess the influence of snowmelt on frozen soils the precipitation was classified into two further categories, *i*) rainfall and *ii*) snowmelt.

Case Study: Hestadbäckens Catchment

Study Area and Database

Hestadbäcken catchment is located in southeastern Sweden (Fig. 4). The catchment area is 7.6 km^2; the altitude difference within the catchment is small (<100 m); land cover consists of arable land (53%), forest (42%) and pasture (5%); till is the dominating soil type; the population is scarce (16 inhabitants per km^{-2}). No industrial or urban nutrient point sources exist but a number of rural households have local waste treatments systems. The climate is temperate with freezing degrees occurring generally every winter season and a mean annual precipitation of 565 mm. Quick runoff peaks caused by rainfall or snowmelt characterise the river flow in Hestadbäcken. The distribution of daily runoff is very skewed (skewness +5.17) and shows high variance (coefficient of variation 246%). The mean annual runoff during the studied period 1977-1993 was 196 mm.

Daily hydrological data were compiled from SMHI stream gauge and daily precipitation and air temperature were available from the SMHI meteorological station located inside the catchment area (Fig. 4). SMHI and SLU performed sampling of SS and TP at the stream gauge. 474 data of SS were available for the period 1977-93 and 446 data of TP were available for the period 1988-93.

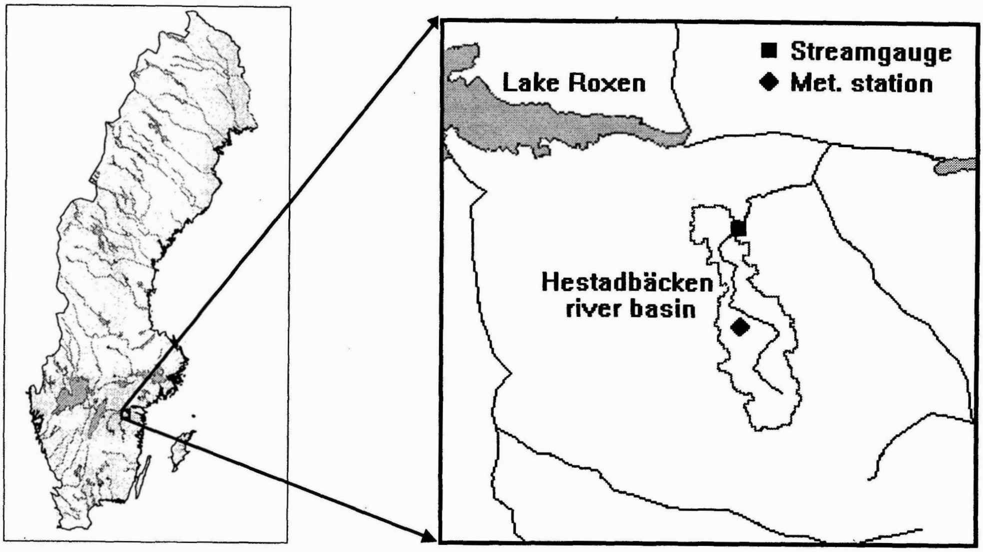

Fig. 4. The case study area Hestadbäcken catchment (7.6 km^2) in southeastern Sweden

Methodology

The HBV-96 model was set up and calibrated automatically (Harlin 1991) for the studied catchment using daily input data from the SMHI runoff and meteorological stations from 1977 to 1993. Updating according to the procedure for operational hydrological forecasting in Sweden was performed (IHMS Manual 1998). Each day was then classified into different flow categories (Fig. 1) according to Eqs. (1)-(3) and different precipitation categories according to the *inf* and *melt* variables. Samples of SS and TP were grouped into categories after the runoff or precipitation type during the day of sampling and statistical analyses were performed on concentration data for each category as well as for all data. Because of skewed SS and TP distributions a non-parametric test, Wilcoxon rank sum test, was used to compare samples taken during the different categories and the Kendall's τ correlation analysis was conducted to find the most correlated variable simulated by the HBV-96 model (Table 2).

For comparison, the Kendall's τ correlation analysis was also conducted between the concentration data and observed runoff. Analysis was done for both all the data and for groups subdivided according to three methods: (*i*) low, medium and high flow separated by the observed flows with duration of 10% and 50% according to the duration curve for 1977-93, (*ii*) increasing and decreasing flow and, (*iii*) days with quick flow and days with only delayed flow separated according to Hewlett and Hibbert (1967).

Table 2 – HBV-96 variables included in the Kendall's τ correlation analysis.

Variable	Unit	Explanation
Q	$l\ s^{-1}$	Daily mean runoff at the catchment outlet simulated by the HBV-96 model
Q_3	$l\ s^{-1}$	Average of the preceding three days runoff simulated by the HBV-96 model
h_{uz}	mm	The volume of water in the upper response box in the HBV-96 model
inf	mm	HBV-96 estimate of areal infiltration, i.e. rainfall or snowmelt
inf_3	mm	Average of the preceding three days infiltration
ofi	–	The overland flow index defined according to Eq. (1)
sm	mm	HBV-96 estimate for the average soil moisture in the studied basin

Results

Table 3 shows the results of the statistical analysis of SS concentrations. The Wilcoxon rank sum test disclosed a statistically significant ($P<0.05$) difference between SS concentrations for Category I, II and III days. Significantly different distributions could, however, not be found for concentration series with different types of precipitation even if the large difference in skewness (2.12 for days with rain and -0.11 for days with melt) indicated that the data have different distributions. Furthermore, the analysis showed large differences in median values between the different flow categories (120, 46 and 16 mg l^{-1} for Category I-III and 93 and 166 mg l^{-1} for rain and melt), which emphasises that the flow condition is very important for the SS concentration in the catchment studied. The analysis showed that days with high risk for overland flow gave by far the highest median concentration. Notable was also the large difference between the median values for days with melt and days with rainfall.

The analysis of the TP concentrations (Table 4) gave quite different results from the analysis of SS concentrations, indicating that the particulate phosphorus may not be dominant in the studied catchment. Observed data for a short period also showed that in average only 43% of the TP was transported as particulate matters. However, similar to SS concentration the Wilcoxon rank sum test revealed that the distributions for the different runoff categories differed significantly ($P<0.05$). The TP concentrations during Category I and III days showed high levels (median 0.34 and 0. 27 mg l^{-1}), while the lower values were found for Category II days (median 0.16 mg l^{-1}). The high TP values and the negative correlation with runoff during Category III showed the importance of point sources, which probably originated from the rural households in the catchment studied.

The correlation analysis showed that internal model variables were generally more correlated than simulated river runoff against both SS and TP concentrations. However, in general, the Kendall's τ showed low correlation values, especially for SS data. Subdividing the data according to flow categories did not improve the correlation, the exception being TP concentrations during days with base flow and

Table 3 – Statistical analysis of SS concentration data sampled at the Hestadbäcken river flow station.

Category	No. of samples	Median (mg l^{-1})	CV (%)	Skew-ness	Most corr. variable	Kendall's τ
All data	474	32	140	3.28	huz	+0.45**
Category I: Days with overland flow	73	120	88.6	1.77	huz	+0.19*
Category II: Days with intermediate flow	152	46	55.8	1.85	inf3	+0.30**
Category III: Days with base flow	249	19	132	3.97	inf3	+0.14**
Days with rainfall	89	93	102	2.17	huz	+0.37**
Days with snowmelt	17	166	62.0	-0.11	huz	+0.41*

Table 4 – Statistical analysis of TP concentration data sampled at the Hestadbäcken river flow station.

Category	No. of samples	Median (mg l^{-1})	CV (%)	Skew-ness	Most corr. variable	Kendall's τ
All data	446	0.23	67.6	1.66	*sm*	-0.40**
Category I: Days with overland flow	41	0.34	48.6	0.98	inf_3	+0.31**
Category II: Days with intermediate flow	149	0.16	65.0	1.77	inf_3	+0.42**
Category III: Days with base flow	256	0.27	64.5	1.59	Q_3	-0.46**
Days with rainfall	83	0.26	69.2	1.27	inf_3	+0.38**
Days with snowmelt	15	0.32	53.3	1.11	*inf*	+0.58**

snow melt. For SS concentrations, the water content in the upper response box, h_{uz}, was most correlated during melt or rain events, while the average three-day running mean infiltration, inf_3, was most important during periods of little or no melt or rain. For TP, significant correlations ($P<0.01$) were found for all categories. Infiltration was most correlated against concentration values. The exceptions were during base flow when river runoff, Q, was negatively correlated probably due to point sources, and for the entire data set when soil moisture, *sm*, was found to be most important. In general, when observed runoff alone was correlated to SS and TP concentration data (Table 5), lower Kendall's τ values were obtained than the ones obtained for the most correlated HBV-96 simulated variables. Significant correlations ($P<0.05$) were for instance not found between observed runoff and TP concentration during days with high, increasing or quick flows.

Table 5 – Kendall's τ correlation analysis between SS and TP concentration data and observed runoff at the Hestadbäcken station. High flow is defined as flow with less than 10% duration, low flow is defined as flow with more than 50% duration, and quick flow and delayed flow are defined according to Hewlett and Hibbert (1967).

Category	SS No. of samples	Kendall's τ	TP No. of samples	Kendall's τ
All data	474	+0.40**	446	-0.28**
Days with high flow	58	+0.05	25	+0.07
Days with medium flow	174	+0.28**	167	+0.12*
Days with low flow	242	+0.06	254	-0.41**
Days with increasing flow	72	+0.08	59	+0.03
Days with decreasing flow	402	+0.39**	387	-0.32**
Days with quick flow	134	+0.28**	95	+0.10
Days with only delayed flow	340	+0.18**	351	-0.46**

Discussion

First and foremost, a prerequisite of using a conceptual hydrological model such as HBV-96 for an assessment of material transport is that runoff can be reasonably well simulated. If the runoff is simulated incorrectly also at least one internal variable is probably wrong or the model structure is inappropriate. By the aid of the updating procedure, where the precipitation and temperature input data were allowed to be slightly corrected, the model efficiency (Nash and Sutcliffe 1970) was 80% for the calibration period in the case study catchment. This indicated that the model structure could sufficiently describe the complicated hydrology with snow accumulation and melt several times every winter season in the catchment studied. The result for the independent validation period (Fig. 5) also showed that the HBV-96 model performed well for prediction purposes despite the use of only one climate station for input data. The model efficiency was 71% for the validation period.

Another possible argument against the use of HBV-96 for particulate transport assessment may be that overland flow is not explicitly described in the model. Instead overland flow is conceptually treated as a part of the non-linear outflow from the upper response box (Fig. 2), which has proven to be sufficient to simulate river runoff correctly. The solution suggested here is to use a probabilistic approach, i.e. a relationship between model variables and the likelihood of certain events in the catchment is assumed. This approach can not quantify the overland flow or describe where in the catchment it occurs. However, since overland flow has been shown to be so important for particulate transport (*e.g.* Alström and Bergman 1990; Ulén 1995) the information that it probably occurs somewhere in the catchment may be very useful. When lack of data hinders the application of distributed models, the

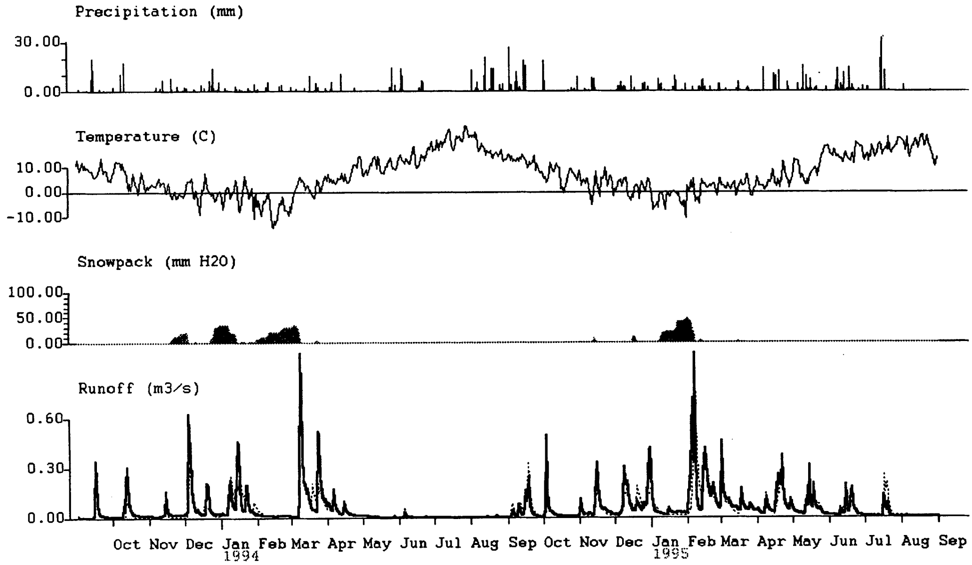

Fig. 5. Graph showing the results of the HBV-96 model for Hestadbäcken catchment for the independent validation period. Simulated runoff is shown as bold and observed runoff as dashed lines.

probabilistic approach suggested in combination with a lumped conceptual model thus provides an interesting alternative for assessment of overland flow dependent transport.

The test of the suggested flow categorisation technique through a case study gave no simple answer whether the HBV-96 based methodology is sound or not. The categorisation of flow and precipitation clearly assisted in showing the importance of different flow and precipitation conditions on the level of SS and TP concentrations. However, the purpose of dividing the SS and TP samples into different groups was also to decrease the variance in concentration for each group. Even if the variance around the mean decreased for some of the categories compared to if all samples were analysed (Tables 3 and 4) the maintained high CV-values showed that the division was not sufficient. Higher correlations between concentration data and hydrological variables were generally not obtained for the subdivided data compared to the ones obtained in the analyses for all data. The same flow categorisation used in this study was also used in a parallel study (Arheimer and Lidén 2000) for prediction purposes. These results, based on multiple regression analysis, indicated that no better prediction is obtained for the validation period if data, as in the present study, are separated into flow categories compared to if all data are analysed directly.

On the other hand, the Kendall's τ correlation analyses for the case study catchment showed that internal HBV-96 variables were the most correlated variables for both SS and TP concentration (Tables 3 and 4). In fact, they could explain more of the variance in concentration than observed river runoff. However, for SS concentration, in particular, the τ values were very low, thus no extensive conclusion could be made. If a flow categorisation is needed, the results of the correlation analyses (Tables 3-5) also indicated that the HBV-96 model approach was superior to using observed runoff data alone. Any flow categorisation based on a model or a traditional flow separation technique is, however, arbitrary which makes a comparison between methods difficult.

A valid problem is that actual flow variables as well as internal variables in a hydrological model are correlated, which makes interpretations of the statistical analyses difficult. The overland flow and the total runoff are highly correlated in small catchments and in the HBV-96 model the river runoff is, except for base flows, directly related to h_{uz}. It is thus not possible to verify if the high median concentration values during Category I are a result of field or in-stream erosion. Another problem is the model parameter interdependence or equifinality (Beven 1993), which gives the possibility of having good results for river runoff even if internal variables are wrong. Since the model variables often have little physical resemblance in nature they can seldom be validated through direct comparison with observed values and even if data exist, validation is limited to relative fluctuations of point observations, *e.g.* groundwater levels. Flow categorisation based on the storage in the HBV-96 upper and lower response boxes depends on the model parameters chosen. As a result of parameter interdependence, different flow categorisations can thereby be obtained by choosing different parameter combinations, all of which may give the same agreement between simulated and observed river runoff. The suggested approach for flow categorisation or use of HBV-96 model variables as driving variables for TP transport can thus not be generalised to other river basins unless the calibration methodology is standardised or internal model variables can be validated. Due to lack of distributed data, the internal HBV-96 model variables for Hestadbäcken catchment could not be validated. The issue of validation is essential and efforts to validate internal variables as far as possible must be emphasised.

Finally, the fact that lumped internal variables in the HBV-96 model describe the average condition in a catchment causes further uncertainty. A catchment-scale model like HBV-96 can not describe locally high erosion due to, for instance, locally extreme topography or manmade influences, which may partially explain the low correlation values in Tables 3-4.

Summary and Conclusions

Based on a review on SS and TP transport in Scandinavia together with observed data from small catchments in southern Sweden, the most important transport and flow processes for phosphorus transport were categorised. The main generating processes for particulate phosphorus are field erosion by Hortonian overland flow on frozen soil or by saturated overland flow as well as erosion within the river channel and drainage pipes. For dissolved phosphorus leakage from agricultural lands and point sources were emphasised. Major conveyance processes to nearest stream are overland flow, groundwater flow and drainage pipe flow. Based on the interpretation and dynamics of the HBV-96 hydrological model variables, a flow categorisation technique was then suggested based on internal model parameters. Days with high risk for saturated overland flow were defined as days with a high overland flow index (*ofi*) based on water contents in the upper response box (h_{uz}) and infiltration rates (*inf*). Remaining days were divided into days with drainage pipe flow ($h_{uz}>0$, $ofi<1$) and days with only base flow ($h_{uz}=0$).

A case study in a small Swedish catchment was done to test the suggested flow categorisation technique. Observed SS and TP data were grouped into flow categories depending on the condition during the day of sampling and statistical analyses were performed. The results showed significantly different distributions and median values of SS and TP concentrations between the different flow categories and HBV-96 internal variables were in general correlated more to concentration data than was observed river runoff. High water contents in the upper response box (h_{uz}) seemed to be the most important variable for high SS concentration, while rainfall or melt (*inf*) were essential for the dynamics of TP concentration. The evaluation of the suggested methodology was, however, difficult since flow variables are highly correlated, which makes the interpretation of the statistical analyses uncertain. Model parameter interdependence causing uncertainty in internal variables, even if river runoff is accurately simulated, was highlighted as a problem for a general use of the HBV-96 for flow categorisation.

The Conclusions of the Study are

1) Internal HBV-96 model variables can be used in a probabilistic way to separate flow conditions which show significantly different distributions of TP and SS concentrations for small agricultural catchments. The suggested flow categorisation approach gave higher correlations between concentrations and hydrological variables for subdivided data compared to a categorisation based on traditional hydrograph separation techniques.
2) Internal HBV-96 model variables were generally more correlated to TP and SS concentrations than was observed river runoff. Thus, it may be beneficial for assessment of TP and SS transport, to apply the HBV-96 hydrological model instead of using observed river runoff directly.
3) Parameter interdependence in the HBV-96 model hampers the suggested approach so that it can not be generalised to other areas unless the calibration methodology is standardised or internal model variables can be validated.

Acknowledgement

This study has been a part of the Baltic HOME project (Hydrology, Oceanography and Meteorology for the Environment of the Baltic Sea), which has been financed by the Swedish Meteorological and Hydrological Institute (SMHI). The access to nutrient data from the Swedish Agricultural University (SLU) is acknowledged. Prof. Lars Bengtsson has given valuable comments on the manuscript and Berit Arheimer and Joakim Harlin have given input to the discussion on the subject. The two referees are acknowledged for constructive criticism and suggestions.

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Received: 11 October, 1999
Revised: 6 March, 2000
Accepted: 22 August. 2000

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