Handling scales when estimating Swedish nitrogen contribution from various sources to the Baltic Sea

Nitrogen
Hydrology
Modelling
Catchment
Scales

At the national and international policy level, there is an increasing demand for overall estimations of the contribution of the runoff from large regions or whole countries to the nutrient loadings of river basins and coastal areas. This article decribes a methodology involving scaling up data on nitrogen leaching and transport from the site scale to the scale of river basins and, eventually to the scale of Sweden as a whole. The upscaling methods are based on the linkage of leaching and transport models at the site scale with a nested model system involving regional hydrological models and source apportionment of N loadings towards the Baltic sea.

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The nutrient loads to the Baltic Sea have increased successively during the 20th century (Larsson *et al.*, 1985) and have resulted in an ongoing degradation of the environment (Cloern, 2001). These negative effects have taken such proportions that the riparian countries were forced to take remedy actions. One obvious strategy is to reduce the nutrient load from land to sea, and most countries have reduced their point sources by 50% for phosphorus (P). However, this goal has not been achieved for the largest point sources, which are situated in Poland and Russia (Lääne *et al.*, 2002). Nitrogen (N) reduction from point sources, as well as the overall reduction of load from diffuse sources, has in most countries been less successful. Recent estimates based on official statistics indicate that load from agriculture constitutes approximately 60% of the anthropogenic N load and more than 25% of the anthropogenic P load to the Baltic Sea (Lääne *et al.*, 2002). The largest reduction achieved for arable leaching is mainly related to the economic breakdown of the agricultural sector in the transition countries. So far it has been difficult to monitor the effects, which is mainly due to large storage of nutrients in the soil and water systems (Stålnacke *et al.*, 2002). The nations around the Baltic Sea regularly report their national load to the Helsinki Commission (HELCOM), and for the latest pollution load compilation it was also obliged to specify the contribution from various sources.

Water management in Sweden is going through dramatic changes at present, related to the adoption of the EU Water Framework Directive, a new Environmental Code and revised Environmental Quality Objectives. New policies including catchment-based management plans have been suggested, which also demand catchment-based knowledge of nutrient transport processes and appropriate tools for landscape planning. Although Sweden has effectively reduced the nutrient load from treatment plants and industries during the past decades, the problem of eutrophication is not yet solved due to nutrient leaching from diffuse sources, such as arable land, rural households, and traffic. These sources are difficult to monitor and models must be applied to quantify their load, and to quantify possible load reductions, which have been or will be achieved in management programs (Figure 1).

A catchment model for the national scale (HBV-N) has therefore been developed to be used both for international reporting and for scenario estimates for more efficient control strategies. This paper provides an example of an interdisciplinary methodology that focuses on water quality and management issues at different scales (Figure 2). It includes upscaling of leaching models from the site scale to whole river basins in order to enable estimation of the N loading from the entire country with relatively high spatial and temporal resolution. The paper mainly describes how the transfers between scales have been handled and gives some model results from the application of the model concept for the whole country of Sweden (about 450 000 km^2).

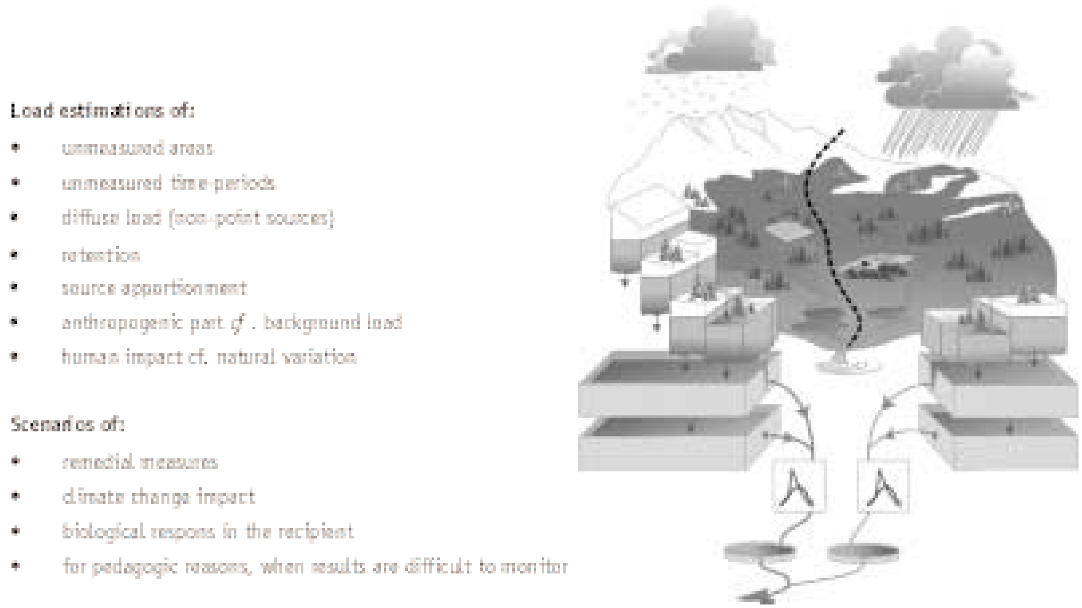


Figure 1. Several reasons why dynamic and predictive models are useful tools in environmental assessment, management planning, in the implementation process of measures, and to follow-up environmental goals (exemplified with the structure of the catchment model HBV).

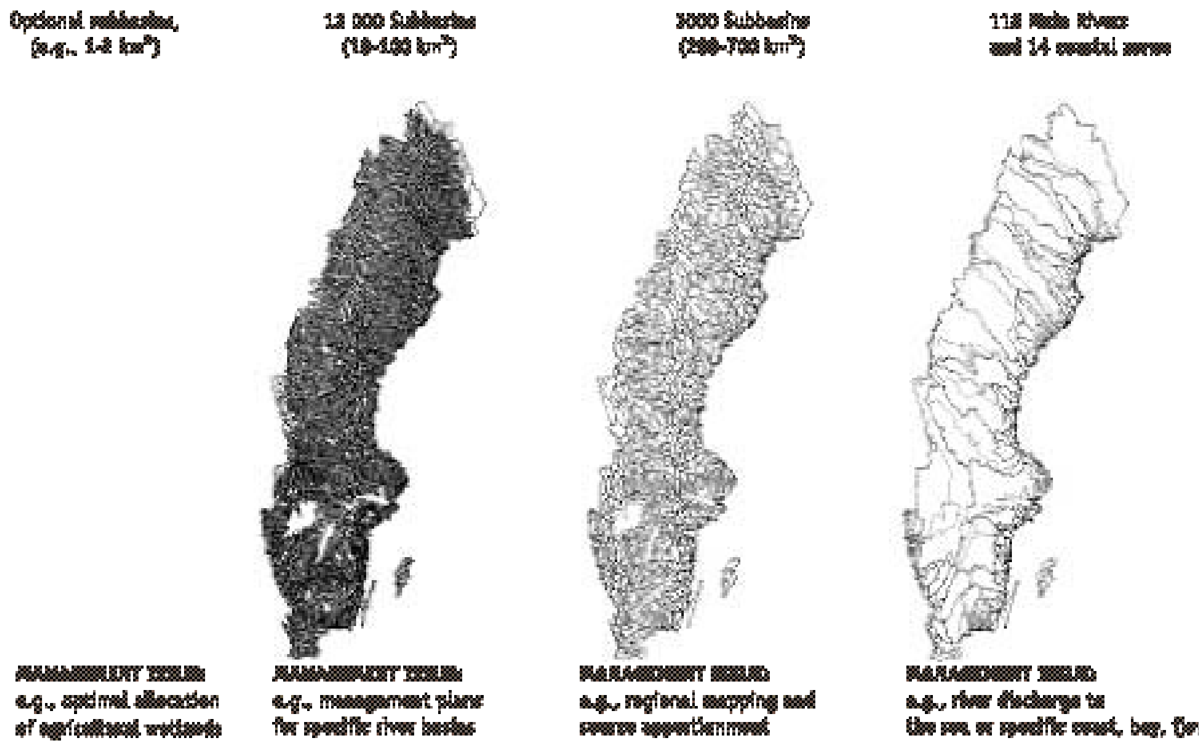


Figure 2. Various scales of catchment modelling with HBV-N in Sweden, using different databases for different management issues.

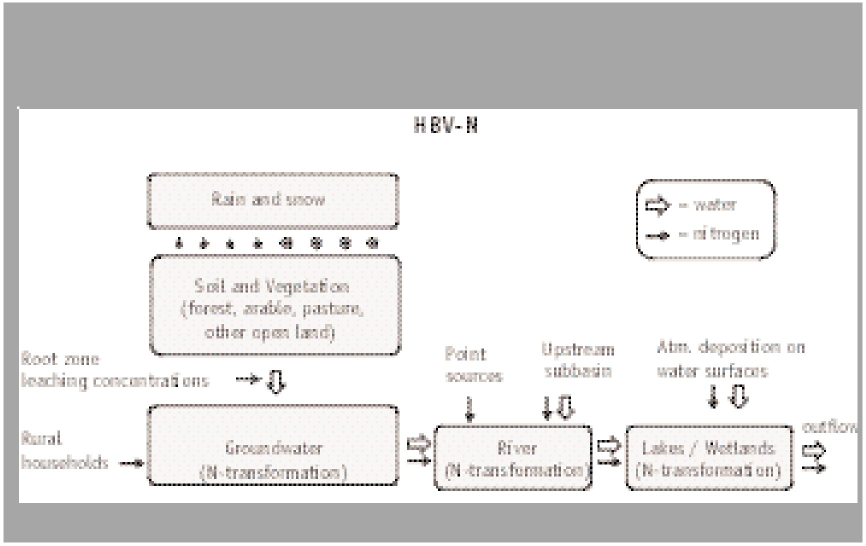


Figure 3. Schematic structure of the dynamic catchment model HBV-N.

Method

The catchment model HBV-N (Figure 3.) has been applied for the national scale within a nested model system, called TRK (Table 1), which calculates flow-normalised annual average of nutrient gross load, N retention and net transport, and source apportionment of the N load reaching the sea (Brandt and Ejhed, 2003). The TRK system consists of several submodels with different levels of process descriptions that are linked together (Bergstrand *et al.*, 2002). Dynamic and detailed models are included for arable leaching, water balance, and N removal. Daily simulations are made for a 20-year time-period. The results are subsequently aggregated over the entire 20-year period to cancel out short-term weather-induced variations. Landscape information, leaching rates and emissions are combined through GIS. N transport is simulated through the hydrological model, which accounts for transport and decay within subbasins, and routing through the river system, e.g., when passing lakes, towards the sea. During decay N removal may occur.

Up-scaling of root-zone leaching

Leaching concentrations from arable land is calculated with the physically based SOILN model (Johnsson *et al.*, 1987) for different field categories. General model input parameters are assumed to represent the average for a whole agricultural region, using the SOILNDB concept (Johnsson *et al.*, 2002). Sweden is then divided into 22 agricultural regions, based on climate and agricultural character. For each region separate calculations are made for 9 soil types, 13 crops, and 2 fertilisation strategies. A crop sequence generator is applied to obtain the average leaching concentration for all acceptable combinations in the crop rotation. Time-series of 20-30 years (calculated with a daily time-step) are used to consider weather-induced variability. Accumulation of the loads over the entire calculation period results in one aggregated concentration (i.e., not affected by temporal variations) for each combination of region, soil and crop. For each subbasin, an average root-zone concentration is then calculated based on land-use information of crop and soil distribution. This average leaching concentration is assigned to the water discharge from the root zone in the HBV-N catchment model (Figure 3).

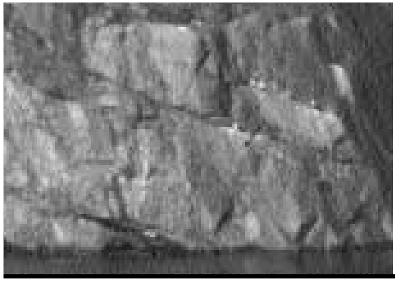
Up-scaling of water balance and discharge

The water balance at the catchment-scale is estimated by using the conceptual rainfall-runoff model HBV (Bergström, 1995; Lindström *et al.*, 1997), which makes daily calculations in semi-lumped subbasins that are coupled along the river network. The HBV model consists of routines for snow melt and accumulation, soil moisture, runoff response and routing through lakes and streams. The runoff generation routine is the response function, which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precip-

Table 1. Definition of spatial and temporal scales in the national model application within TRK, which is a cooperation between Swedish Environmental Protection Agency (NV), Swedish University of Agricultural Sciences (SLU), and Swedish Meteorological and Hydrological Institute (SMHI).

Dimension	Extent*	Support*	Coverage*
Spatial	Sweden (450 000 km^2)	1000 subbasins (200-700 km^2)	100%
Temporal	Normalised annual average	Daily time-series (15-20 years)	100%

* Terminology according to Bierkens *et al.*, 2000.



itation and evaporation on a part, which represents lakes, rivers and other wet areas. The function consists of one upper, non-linear, and one lower, linear, reservoir. These are the origin of the quick (superficial channels) and slow (base-flow) runoff components of the hydrograph.

Driving model variables are daily precipitation and temperature. These are achieved from optimal interpolation (i.e., kriging) of climate observations considering topography, wind speed and direction in a national grid of 4x4 km (Johansson, 2000; 2002). In the model, subbasins can be disaggregated into elevation zones (for temperature corrections) and land-cover types.

One of the most important parts of the HBV model is the soil moisture routine, which is based on the oversimplified bucket approach, but with the very important additional condition that the water holding capacity of the soil in the subbasin has a statistical distribution (Bergström & Graham, 1998). This leads to a contributing area concept as concerns runoff generation. Only those parts that have reached field capacity will contribute to runoff in the event of rain or snowmelt. It is very important to note that this approach thus implicitly accounts for the subbasin variabilities in both soil water holding properties and input in the form of rain or snowmelt, without explicit separation of the two. The parameter values of the model thus reflect the physical properties of the ground as well as their statistical distribution, and they also reflect the random character of the input. It is similar to the cumulative distribution function used for soil moisture saturation in the ARNO rainfall-runoff model (Todini, 1995), an approach that has also found its way into climate modelling (Dümenil and Todini, 1992) where sub-grid variability is a critical issue.

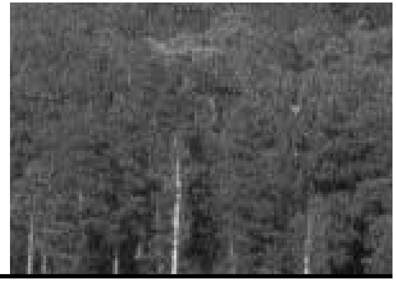
The application of Sweden includes about 1000 subbasins, ranging in size between 200 and 700 km^2. The model is calibrated regionally against measured time-series of water discharge.

Up-scaling of land cover, emissions and atmospheric deposition

For each subbasin land cover is aggregated into the classes: arable field-type (13 crops on 9 soils in 22 regions; i.e., 2574 types), forest type (3 types), clear-cut forest (additional leaching according to atmospheric deposition rate), urban, and lakes (3 types according to position in the catchment). Emissions are classified as industrial point sources, municipal treatment plants, and rural households. The first two are based on empirical data, while the latter is based on population statistics and coefficients considering average treatment level in the region. The emissions are aggregated into one value for each type and subbasin. Atmospheric deposition is calculated for each lake surface by using seasonal results from the MATCH model (Langner *et al.*, 1995) and aggregated for each lake type (20x20 km; up- or downscaling depending on lake size).

Up-scaling of nitrogen removal processes

The HBV model calculates average storage (and residence-time) of water and N between root-zone and stream, in rivers and in lakes for each subbasin. In the N-routine (Arheimer and Brandt, 1998), leaching concentrations are assigned to the water percolating from the unsaturated zone of the soil to the groundwater reservoir. Different concentrations are used for different land-covers, and the load from rural households is added separately. Removal processes in groundwater are considered before the water and N enter the stream, where additional loads from industry and treatment-plants may be added, as well as river discharge from upstream subbasins. Removal processes may occur during transport in the river and in lakes, and atmospheric deposition is added to lake surfaces (for other land covers it is included in the soil leaching). The equations used to account for



daily removal are conceptual and mainly based on empirical relations between load, temperature and concentration dynamics. The N removal is spatially lumped on a subbasin level into the three categories groundwater, rivers and lakes.

Model calibration and validation

The catchment model includes a number of free parameters, which must be calibrated against time-series of daily observations. The parameter values (coefficients) are tuned to minimise the relative volume error and to maximise the explained variance. About 10 parameters are calibrated for the calculation of water discharge, and 5 to simulate N removal. Calibration is done simultaneously for several observation sites in a region to get robust parameter values, which are then transferred to all subbasins in that region. For N, the calibration procedure is made step-wise, starting with parameters for groundwater, then rivers and finally lakes (Pettersson *et al.*, 2001). Both calibration and validation is done on a daily basis at the subbasin outlet.

In the TRK application covering Sweden, water flow was calibrated against measured daily discharge at the outlet of 230 subbasins, and independent time-series from another 130 subbasins were used for model validation. For N concentrations, time-series from 300 subbasin were used for calibration, while 200 subbasins were used for independent validation. This procedure resulted in a spatial validation of water flow, N-concentrations and transport in the river, according to the proxy-basin concept (Abbott and Refsgaard, 1996).

Monthly grab samples were normally available for N concentrations in rivers, but most time-series only covered part of the period studied. If possible, both water discharge and N concentration were calibrated on a daily basis for the period 1987-1997, and validated for the periods 1983-1986 and 1998-1999. Thus, the temporal dynamics in the model was validated by split-sample test of independent daily time-series.

Up-scaling of results to national level

Source apportionment for different coast segments or for the entire nation is achieved by adding sources for different categories in all subbasins. This is done separately for gross and net loads to illustrate the influence of removal processes. Net load is the remaining part of the gross load, which eventually reaches the sea after the cumulative N removal in groundwater, rivers and lakes downstream a specific source and subbasin (Wittgren and Arheimer, 1996).

Results and Discussion

Model results

The model produces time-series that give the daily variation in water flow, N concentrations and N transport. The time-series show rather good agreement with measured values (Figure 4), both regarding levels and dynamics. In general, it is easier to achieve good correspondence at large river outlets than for individual subbasins. The river flow is regulated by the waterpower industry in most Swedish rivers, which highly influences the dynamics of discharge, especially in the northern part of the country. The diagram at the right upper corner in Figure 4 shows that the model manages to reproduce the general hydrograph, but not the intensive fluctuation in water release for energy production.

The results are spatially distributed as results are achieved from each subbasin included in the modelling. Mapping of the results from the TRK application gives the spatial distribution for the whole country. Figure 5 show the spatial distribution of annual water discharge, as well as the difference between a dry and a wet year. This information

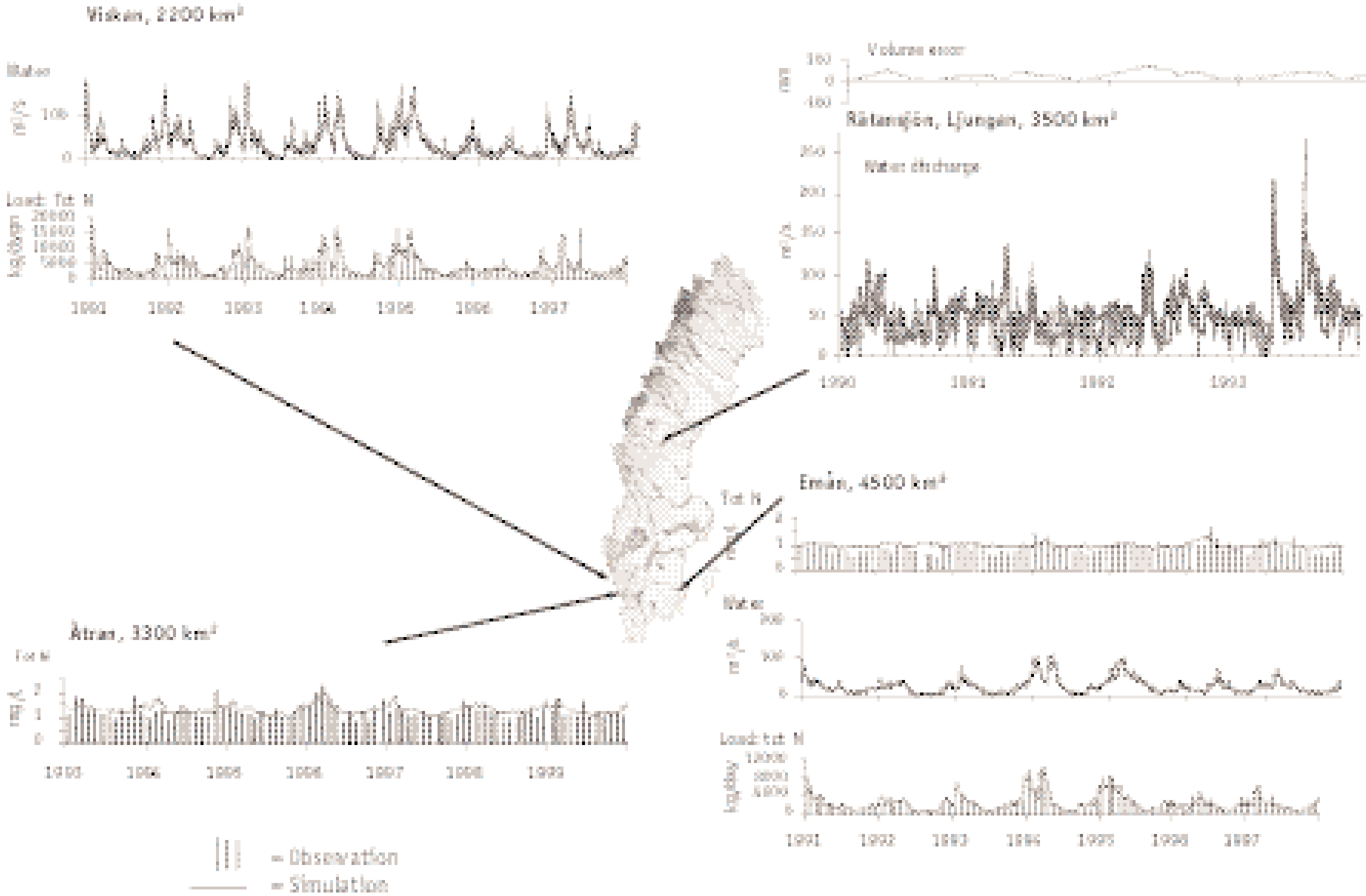


Figure 4. Model performance of simulated time-series compared to observed values (bars). The figure shows examples of independent validation sites, i.e., these time-series were not included in the model calibration procedure.

is important in environmental studies when comparing the nutrient export from one time with another, so that proper flow normalisation is considered to avoid weather impact on the judgement of anthropogenic impact. Similar maps as in Figure 5 will be produced for each year back to 1961, and the modelled time-series are prolonged every year so that the database is up-dated continuously.

The spatial variation in gross N load follows to some extent the pattern of water discharge (cf. Figure 5 and Figure 6) with higher load in the western part of the country. However, the pattern of N soil leaching also reflects the regions in Sweden with most intensive agriculture. For instance, the most southern part of Sweden does not have very high water discharge, but releases the highest N load (Figure 6B). When comparing gross load and net load it can be concluded that in general about 40-50% of the total N load in southern Sweden is removed during transport from the sources towards the sea. However, this downstream reduction in load is not equally distributed but depends very much on the lake distribution of the region and the character of the catchment area and river network downstream the sources. Some areas with intensive agriculture and some major inland point sources do not contribute very much on the N load to the sea (cf. Figure 6B and Figure 6C), while the south-western part has low N retention capacity and still contributes a lot to the total load. When comparing the contribution from various sources (Figure 6A) it can be concluded that the load from arable land is by far the largest source, although the N retention is also high on this load.

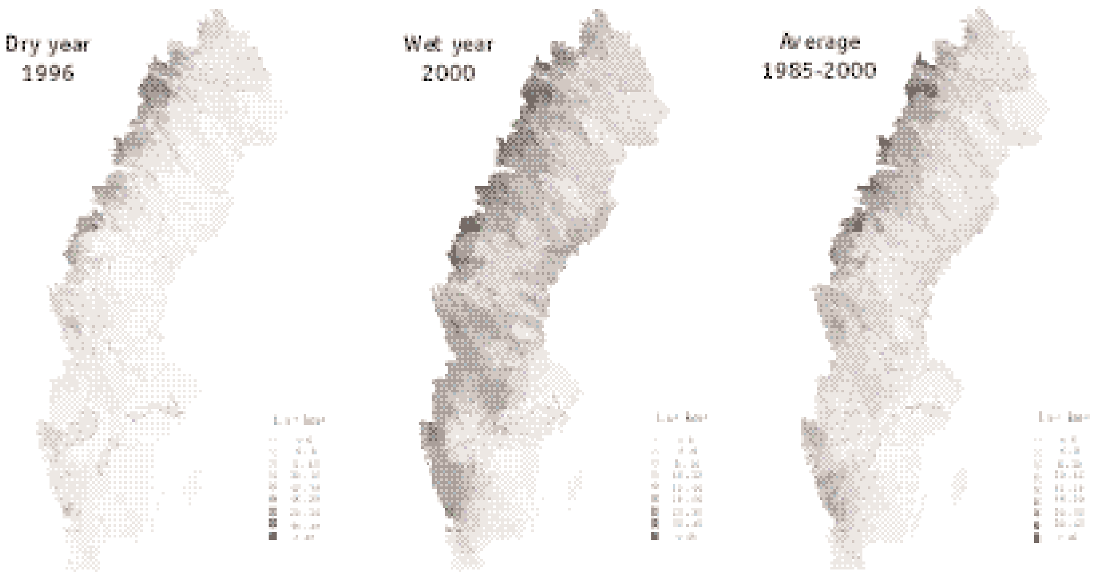


Figure 5. Swedish annual water discharge 1985-2000, according to HBV modelling (modified from Grahn *et al.*, 2002).

Handling scales

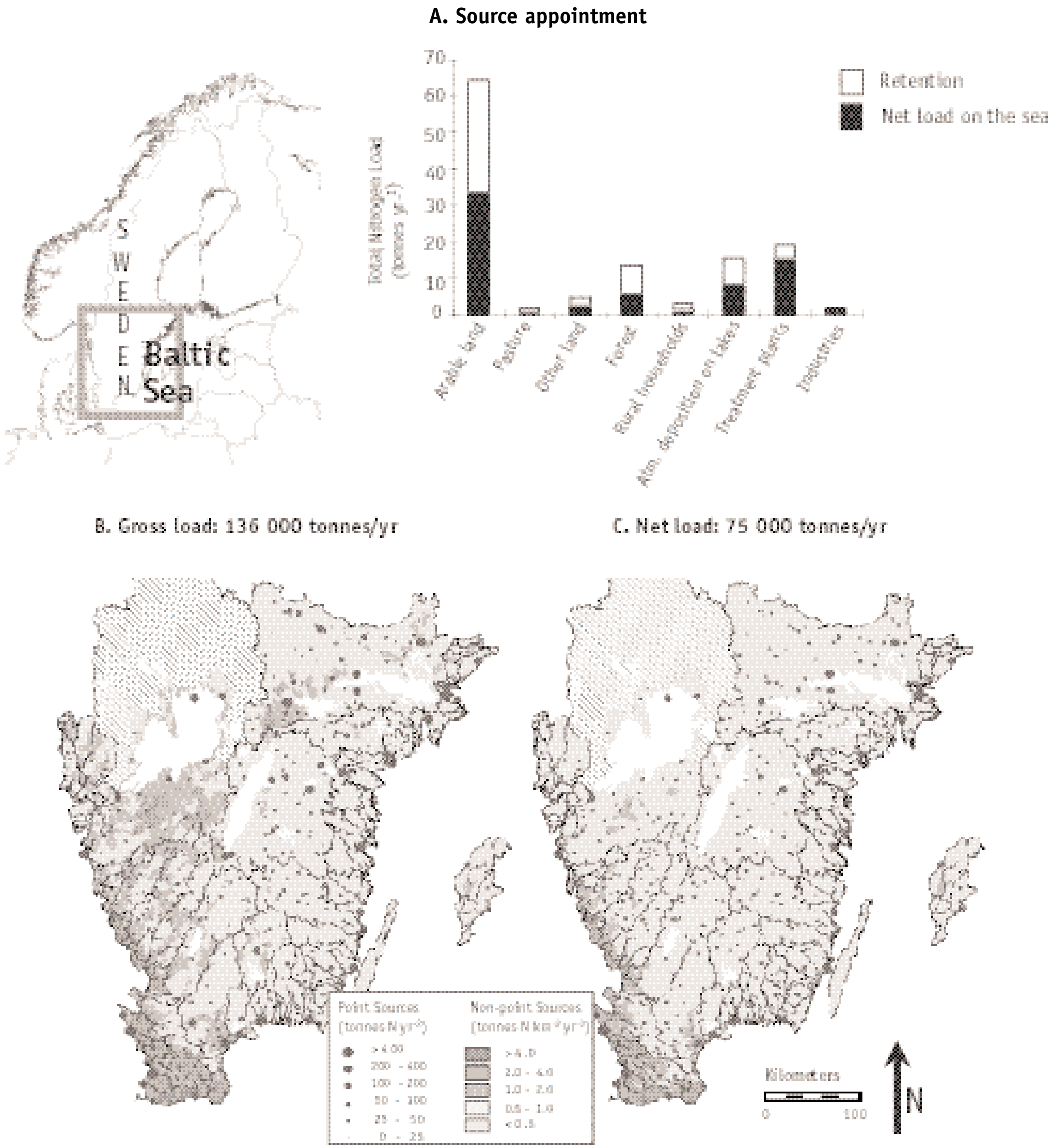
Temporal scaling is done when the results are presented as aggregated values. These are based on time-series of 20-30 years with a daily time-step to consider weather-induced variability. An average value for the entire period is considered as normal, i.e., it is assumed not to be affected by specific short-term variations between days, seasons or years. All dynamic modelling of hydrology should be done for at least 20 years if averages are to be considered representative for Swedish conditions. Previous studies show that ten years time-series is not enough to avoid natural hydrometeoroloical variations (Andersson and Arheimer, 2001).

Aggregated values are requested to separate human impact from natural variations. However, during this up-scaling procedure information is lost that may be of critical concern for environmental management. Extreme values of water quality may have severe impact on biology although they appear rarely. Thus, in some situations the extreme situations or seasonal concentrations are of more importance than average conditions. For instance, the daily situation may be of great concern in order to make forecasts on algae concentration close to beaches in the summer time.

Statistical soil moisture distribution and water recharge, along with adding, delaying and subtracting loads along the river course mainly does spatial scaling in HBV-N. The hydrological model accounts for transport and decay within subbasins, and routing through the river system, e.g., when passing lakes, towards the sea. Removal of N may occur during the transport from the sources to the recipient, especially during residence in various water storages, which is considered in the model. The model concept is the same when applied on small river basins and the entire Baltic basin, but the model parameters must be recalibrate when changing the subbasin size. The parameter values of the model reflect the physical properties of the ground, statistical distribution, as well as the random character of the input. The values of the parameters in different basins will therefore be identical as long as the basinwide distribution functions are the same. The model will then be independent of, or at least only mildly sensitive to scale (Bergström and Graham, 1998). This means that to some extent the handling of scales is taken care of within the basic hydrological model concept. Nevertheless, the parameter values consider variability of the environmental conditions and are thus scale dependent.

Once the division into subbasins has been made when setting up the HBV-N model, there is no further spatial resolution and both sources and flow paths are lumped. For analyses on a more detailed scale, new subbasin division

Figure 6. Annual nitrogen transport from land to sea for the southern half of Sweden, based on catchment modelling with HBV-N: A.) the contribution from various sources (i.e., source apportionment); B.) gross load from diffuse and point sources, respectively; C.) net load after nitrogen removal in the fresh-water system between sources and the river outlet (modified from Arheimer and Brandt, 1998)



must be made and the model must be recalibrated against observed values at the new spatial level. The resolution must thus be adapted to the environmental issue in question. As shown in Figure 2, the HBV-N model has been applied at various scales depending on modelling purpose. However, restrictions in site specific information, e.g. precipitation or observation sites for calibration, normally makes very detailed modelling less reliable. It is not advised to apply the HBV-N model for subbasins less than 1 km² if the regular national Swedish databases are used as input data.

Conclusions

- Handling of scales in the HBV-N model is mainly done through up-scaling procedures combined with the basic hydrological model concept. The model is rather insensitive to scale, but parameter values that consider spatial variability of environmental conditions may be scale dependent.
- Temporal and spatial resolution should be adjusted to the purpose with the modelling, as information gets lost at up-scaling. However, it is important that the model can be validated at the highest resolution for which results are presented.
- Integrated catchment models are useful tools in eutrophication management for estimation of nitrogen sources and sinks in the landscape. The coupling of rainfall-runoff models (e.g., HBV) with detailed, field-scale models (e.g., SOIL-N) and GIS may estimate nitrogen load over a range of scales.

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Abstract

There is a request in Sweden of useful tools for more efficient international reporting of nutrient load, and also for eutrophication management and control planning. An integrated catchment model (HBV-N) has therefore been developed. The model has been applied for the national scale (450 000 km²) within a nested model system, called TRK, in which several models with different levels of process descriptions are linked together. Dynamic and detailed models are included for arable leaching, water balance, and N removal. Landscape information, leaching rates and emissions are combined through GIS. The HBV-N model calculates nutrient load, N retention and source contribution to the sea with a relatively high spatial and temporal resolution. The transfer between scales is mainly handled through up-scaling procedures, combined with the basic HBV hydrological model concept. The model is rather scale insensitive, but temporal and spatial resolution should be adjusted to the purpose of the modelling, input data available and possibilities for calibration and validation. The model is validated against monitored time-series of water discharge and nitrogen concentrations. The results show that integrated catchment models are useful tools in eutrophication management for estimating nitrogen sources and sinks in the landscape.

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