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Nutrient Transport Modelling in the Daugava River Basin

Andrea Wallin

ABSTRACT

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Eutrophication is one of the most serious threats to the Baltic Sea environment. Nutrient loading into the sea therefore needs to be quantified by available mathematical models. The Generalised Watershed Loading Functions (GWLF), a lumped-parameter model that predicts hydrology and monthly nutrient loads, was applied to the Daugava River Basin, discharging into the Baltic Sea. The aim of the study was to model historic transport of nutrients into the Baltic Sea and thereby produce estimates of parameters and input data needed for a spatial extension of the GWLF to surrounding river basins. Calibration data were taken from the 1990's and validation data from the 1980's. Yearly nitrogen loads were modelled with an R^2 value of 0.78 for the calibration period. Predicted yearly nitrogen loads for the validation period were about 30 % lower than reported values, probably depending on decreasing groundwater and runoff concentrations between the 1980's and 1990's. Phosphorus loads were underestimated compared to reported values, the main reason probably being the exclusion of septic systems and too low reported point sources.

Modifications of the model are suggested for long-term predictions of nutrient loads and the need for harmonised, up-to-date and generally accessible data for nutrient transport modelling discussed

Keywords: runoff, nutrient, modelling, GWLF, Baltic Sea drainage basin

REFERAT

Modellering av näringsämnestransport i Daugavas avrinningsområde

Andrea Wallin

Övergödning utgör ett av de allvarligaste hoten mot Östersjöns miljö. Storleken av näringsbelastningen till havet behöver därför bestämmas med hjälp av tillgängliga matematiska modeller. Modellen ”Generalised Watershed Loading Functions” (GWLF), en icke-distribuerad parametermodell som uppskattar hydrologi och månatlig näringsbelastning, tillämpades på avrinningsområdet till Daugava som mynnar i Östersjön. Syftet med studien var att genom modellering av historisk transport av näringsämnen till Östersjön ta fram parametrar och indata som sedan kan användas vid applicering av GWLF på omkringliggande avrinningsområden. Data från 1990-talet användes för kalibrering av modellen och data från 1980-talet för validering. Årlig kvävebelastning modellerades med R^2-värdet 0,78 för kalibreringsperioden. Modellerad årlig kvävebelastning för valideringsperioden underskattades med ungefär 30 % vilket troligen beror på att kvävekoncentrationer i grundvatten och ytavrinning minskade mellan 1980- och 1990-talen. Fosforbelastningen underskattades jämfört med rapporterade värden vilket troligen beror på att enskilda avlopp inte inkluderades och att rapporterade punktutsläpp är för låga.

Modifikationer av modellen föreslås för prediktion av näringsbelastningar under lång tid och behovet av harmoniserad, uppdaterad och lättillgänglig data för näringstransportsmodellering diskuteras.

Nyckelord: avrinning, näringsämnen, modellering, GWLF, Östersjöns avrinningsområde

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PREFACE

This thesis is part of a Master of Science degree in Environmental and Aquatic Engineering at Uppsala University. Supervisors were Fredrik Hannerz and Jerker Jarsjö, Department of Physical Geography and Quaternary Geology, Stockholm University. My supervisor in Uppsala was Lars-Christer Lundin, Department of Earth Sciences, Air and Water Science, Uppsala University.

The study is part of the MARE (Marine Research on Eutrophication) project at Stockholm University. The MARE project aims to develop a decision support system, Nest, which will help decision makers in the Baltic region to find the most cost efficient measures to take against eutrophication of the Baltic Sea. In this study the runoff model that will be used in Nest has been applied to the river basin of Daugava, one of the largest rivers in the Baltic Sea region.

The work was conducted parallel and in collaboration with Evelyn Dahlberg, student of Department of Physical Geography and Quarternary Geology, Stockholm University, who has applied the same model to the river basin of Nemunas.

I would like to thank my supervisors, Fredrik and Jerker, for support and guidance during the project. Additionally I would like to thank Georgia Destouni, Department of Physical Geography and Quaternary Geology, Stockholm University, who contributed with guidance and expert knowledge. I would also like to thank Magnus Mörth, Department of Geology and Geochemistry, Stockholm University, for answering questions regarding the simulation system and the model in general.

Stockholm, February 2005

Andrea Wallin

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1. INTRODUCTION

During the 20th century and especially during the last 50 years, the loads of nutrients (nitrogen and phosphorus) to the Baltic Sea have increased dramatically (SWEPA, 2005). In order to master the problems of eutrophication in the Baltic Sea, proper water management is needed. A decision support system called Nest is presently being developed at Stockholm University within the frameworks of the scientific projects MARE (Marine Research on Eutrophication) and ELME (European Lifestyles and Marine Ecosystems). The aim of Nest is to help decision makers and managers working with Baltic Sea environmental issues to take the most cost effective measures against the eutrophication of the Baltic Sea. The main user target groups are the decision makers within the HELCOM (Helsinki Commission) and people in the region working on the implementation of the EU WFD (Water Framework Directive). Nest consists of interlinked models that combine knowledge in ecology, physical oceanography, biogeochemistry, and economics (MARE, 2005). However, the sub-model for prediction of nutrient loads from the river basins of the Baltic drainage area is not satisfactory. Therefore it has been decided that a better watershed model for the determination of nutrient loads to the Baltic Sea shall be incorporated in the system. The chosen model is GWLF (Generalized Watershed Loading Functions). A number of river basins have been selected in order to test this model in the Baltic Sea region, among these is the river basin of Daugava.

Runoff from the entire drainage basin of the Baltic Sea has previously been modelled with the use of the HBV model. The HBV model is like the GWLF model a conceptual, lumped parameter model and it has been concluded that such models can be useful for macro scale hydrological modelling (Bergström and Graham 1998). Another conceptual runoff model much like the GWLF, the METQ98 model, has been successfully applied to the Daugava basin by Ziverts and Jauja (1999). The basin was then divided into 22 sub-basins that were modelled separately (Ziverts and Jauja, 1999).

The temporal trends in nitrogen and phosphorus concentrations in the Daugava River have been analysed by Stålnacke et al. (2003). A small but significant (one-sided test at the 5 % level) decrease in dissolved inorganic nitrogen was found during the years 1987-1998, but no significant decrease in total phosphorus was found. It could seem remarkable that the decrease in nutrient concentration was not greater considering the dramatic decrease in use of fertilisers and the change in agricultural practices due to the collapse of the Soviet Union. Stålnacke et al. (2003) suggest two main explanations for this; the first one is a substantial time lag due to long water-transit times and the other one is mineralization of large pools of organic nitrogen that have accumulated in the soil during the years of immense application of fertilisers.

Modelling of nutrient loads from various drainage basins of the Baltic Sea has also been done. The PolFlow model has for instance been applied to the basins of Lake Mälaren (Darracq et al., 2005) and lake Peipsi (Mourad et al., 2004), which both fall into the Baltic Sea. However, modelling of nutrient loads from the entire Baltic Sea drainage basin has so far not been done.

The purpose of this study was to apply the GWLF to the river basin of Daugava, which falls to the Baltic Sea, and thereby produce estimates of site specific parameters and input data needed by the model. The modelling was done using the Windows-based simulation system CatchmentSim. The purpose of the study is also to evaluate the model and the simulation system and point out strengths and weaknesses that should be considered when applying the model to the rest of the Baltic basin.

2. BACKGROUND

2.1 EUTROPHICATION OF THE BALTIC SEA

Nutrients such as nitrogen and phosphorus are vital to life on land and in water. Moderate input of nutrients to water systems may be beneficial for fish catches since it will increase the growth of macrophytes. However, an over-fertilization will lead to an excessive growth and the bacterial decay of organic matter may lead to oxygen depletion, especially at the deep bottoms of the sea. Due to this there will be an alteration of the ecological community structure. Some species will be favoured while others will be disadvantaged in the altered environment. This is called eutrophication (Clark, 2001). Phosphorus is usually the limiting nutrient in fresh water but also in some parts of the Baltic Sea, for instance the Bothnian Bay. In saline water, nitrogen is generally the limiting nutrient, which is the case in most parts of the Baltic Sea (BOING, 2002). The anthropogenic sources of nitrogen and phosphorus are leakage from agricultural land and forested land, point source discharges from waste water treatment plants and industries, leakage from septic systems, deposition from the atmosphere and release of phosphorus from the sediments during anoxic conditions (SMHI, 2005).

Eutrophication has long been considered to be one of the most serious threats to the Baltic Sea environment. The nitrate concentration in the Baltic Sea south of the Åland Sea increased almost threefold from the 1960's to the 1980's. A pronounced increase of plankton production has been noticed in this part of the Baltic Sea and the area of anoxic bottoms has likewise increased. Nowadays, about one third of the bottom area of the Baltic Sea is anoxic (SWEPA, 2003) and anoxic bottoms are found in more shallow areas than earlier. Since the 1970's, when the problem of eutrophication of the Baltic Sea became apparent, a lot of efforts have been made by the countries surrounding the sea in order to master the problem and reduce the nutrient loads (HELCOM, 2004). For example, in Sweden the regulations for storage and spreading of manure and for the proportion of cultivated land that has to be vegetation-covered during fall and spring have been sharpened. Artificial wetlands have also been constructed in agricultural areas and waste water treatment plants in southern Sweden have introduced nitrogen purification (SWEPA, 2003). However, in spite of all the efforts the nutrient loads from land have not decreased significantly. One reason for this is probably the long retention time of nutrients in agricultural soils. It is evident that it will take a long time until we will see an improvement of the situation in the Baltic Sea, but by active and coordinated measures taken by the countries in the region this time can be shortened (HELCOM, 2004a).

2.2 FEATURES OF THE NITROGEN AND PHOSPHORUS CYCLES

2.2.1 Nitrogen retention and leakage

Nitrogen interacts with the atmosphere through nitrogen fixation and denitrification. Nitrogen fixation is the process where certain microorganisms convert nitrogen gas of the atmosphere to nitrogen-containing organic compounds. Denitrification, on the other hand, is the process where nitrate is converted to gaseous forms of nitrogen by a series of biochemical reactions. Nitrogen in the watershed may thus leave the system through denitrification before it reaches the mouth of the river. It is difficult to predict the magnitude of denitrification, but 5 to 20 % of the nitrogen in some streams may be lost by nitrification. Due to this nitrogen retention the net amount of nitrogen that reaches the sea is smaller than the gross amount that has been added in the watershed (Brady and Weil, 2002).

Nitrate is generally the predominant mineral form of nitrogen in most soils. Since the nitrate ion is negatively charged it is not adsorbed to the negatively charged colloids that dominate most soils. Therefore, nitrate ions easily move downward with drainage water and are readily leached from the soil into the groundwater. The leaching rate depends on the rate of percolation through the soil, the concentration of nitrogen in the drainage water and the texture and structure of the soil. Great nitrogen losses may come from agricultural land if the input of nitrogen exceeds the amount removed by harvest, but with proper management the losses can be reduced (Ibid).

2.2.2 Phosphorus leakage and erosion

Unlike nitrogen, phosphorus is not lost from the soil in gaseous form. Leaching losses are also generally very low since soluble, inorganic forms of phosphorus are strongly adsorbed by mineral surfaces. However, leaching losses may still be large enough to contribute to eutrophication in downstream waters. The more common pathway of phosphorus leaving the soils is through erosion of phosphorus-carrying soil particles (Ibid).

2.3 GENERAL MODEL DESCRIPTION

The Generalized Watershed Loading Functions (GWLF) is a mathematical model that estimates monthly loads of nitrogen and phosphorus from watersheds. The mathematical structure of the model is simple. Surface runoff, groundwater flow and point sources of nutrients are included in the model. Examples of required input to the model are climate data and information on land use and soil types in the basin. The original GWLF model was described by Haith and Shoemaker in 1987 (Dai et al., 2000). An overview of the hydrological part of the GWLF model is shown in figure 1. In this study the computer program CatchmentSim has been used. CatchmentSim is a Windows based simulation system for simulating nutrient yields from watersheds. The system is based on a modified version of the GWLF model and it has been developed at Stockholm University (Mörth, 2004). From now on in this report GWLF will refer to the modified version of the GWLF that has been used in the study if nothing else is stated.

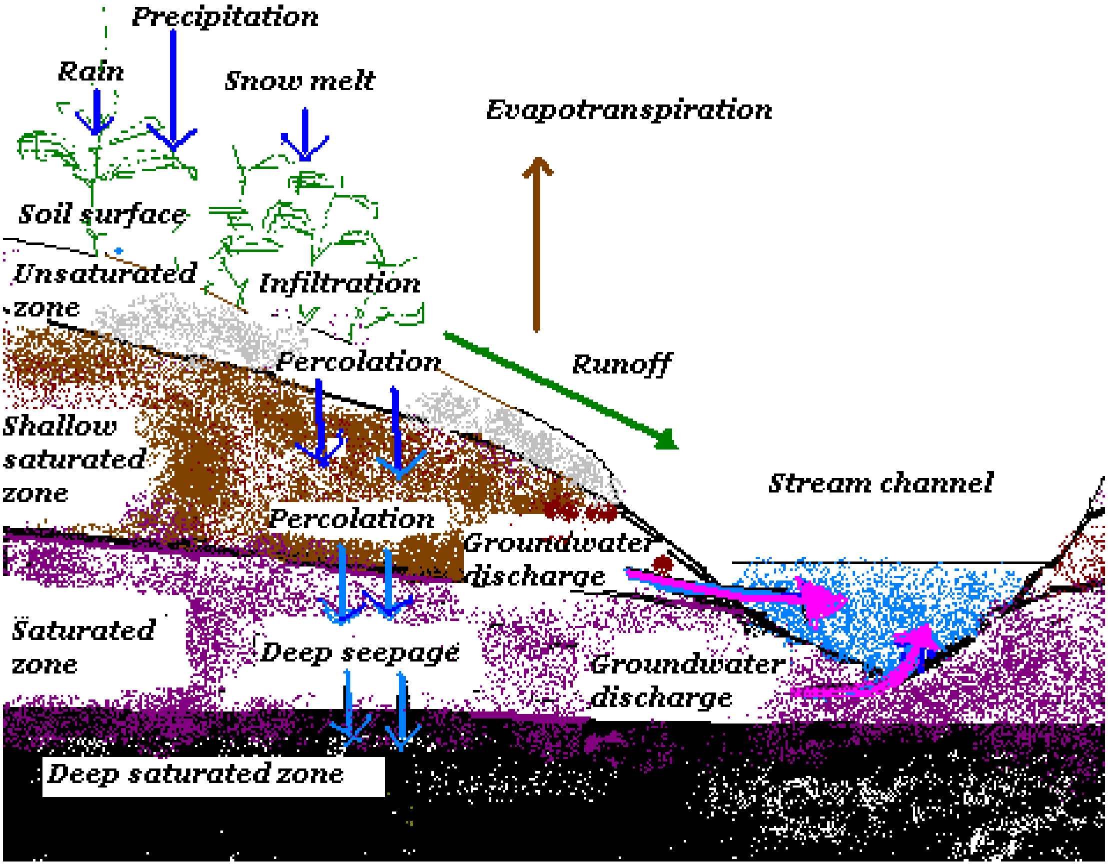


Figure 1. The hydrological part of the GWLF model.

3. MATERIALS AND METHODS

3.1 SITE DESCRIPTION – THE DAUGAVA RIVER BASIN

3.1.1 Geography and hydrography

The Daugava River is the third largest river in the Baltic Sea basin (Lundin, 2000). The river begins in the western part of Russia and flows through Belarus and Latvia where it enters the Baltic Sea in the Gulf of Riga (figure 2). The total length of the river is 1 005 km (Klavins et al., 2002). The river basin has a small difference of elevation within the basin. Only a few hills are higher than 250 m above sea level (Ziverts, 1999). The catchment area is 85 900 km^2 (Hannerz and Destouni, 2005) and it is thus by definition a large river basin (Klavins et al., 2002). 32 % of the area belongs to Russia, 39 % to Belarus and 27 % to Latvia. The remaining 2 % of the basin belong to Estonia and Lithuania (Hannerz and Destouni, 2005).

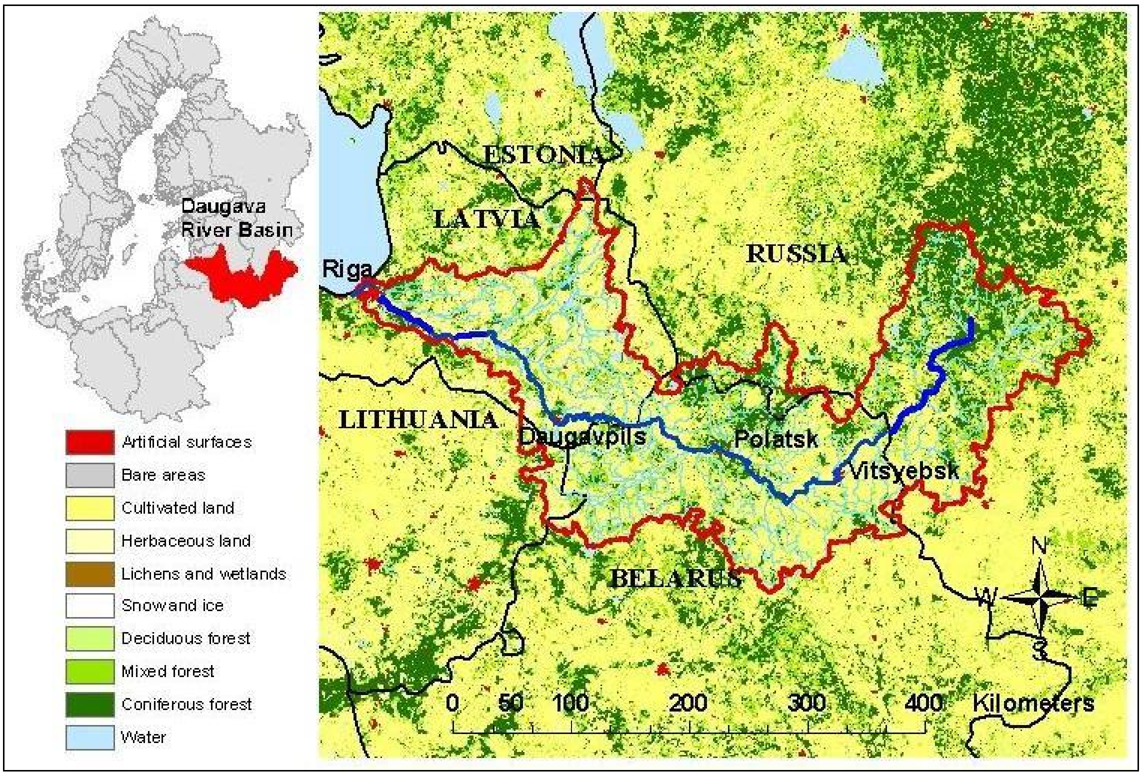
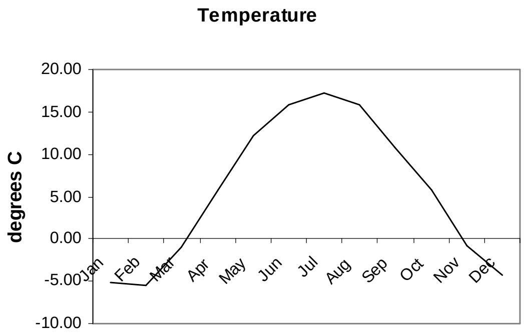


Figure 2. The Daugava River Basin.

The Daugava basin borders with the catchments of River Gauja in the northwest, Lake Peipsi and Lake Ilmen in the north, the Rivers Volga and Dniepr in the east, River Nemunas in the south and southeast and River Lielupe in the west. There are 5 000 tributaries and 95 % of them are less than 5 km. The width of the river varies between 12 and 300 m (Jourakova, 2003). Lake Dvineca in Russia is the origin of the river and here the river is only about six to eight metres wide (Rozins, 2001).

3.1.2 Hydrology and climate

The Daugava River has a mixed feeding from rain, snowmelt water and groundwater. Snowmelt water is the most important contributor as it composes 50-55 % of the river discharge. Accordingly more than half of the river discharge takes place during spring flood (Klavins et al., 2002). Daugava contributes about 5 % of the total water inflow to the Baltic Sea. The annual precipitation decreases from west to east and varies between 600 and 800 mm/year (Ziverts, 1999). 75 % of the part of precipitation that falls as rain falls between April and October (Jouravkova, 2003). The monthly average temperature varies between about -5 °C in January to about 17 °C in July (BALTEX Hydrological Data Centre data base, 2004). The climate can be characterised as humid and precipitation usually exceeds evapotranspiration (Klavins et al., 2002). In figure 3 the monthly average temperature and precipitation in the basin is displayed.



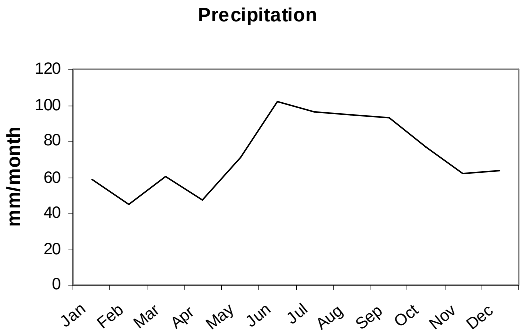


Figure 3. Monthly average temperature and precipitation in the Daugava basin, 1980-1999 (BALTEX Hydrological Data Centre data base, 2004).

3.1.3 Geology and land use

The Daugava River basin is covered by glacial deposits to depths of 200 m. Most of these deposits consist of Weichselian (Latvian) Glacial characterised by till, sandy till and glaciolacustrine sand. There are also alluvial deposits from after the ice age (Rozins, 2001).

About half of the basin area consists of agricultural land. The Belarusian part of the basin has the largest area of cultivated land. In the Russian part of the basin there is also a considerable amount of agricultural land, but more than half of the land in this area is forested. In the Latvian part of the basin about half of the land is agricultural and 30 % is covered with forests (Hannerz and Destouni, 2005). The percentage of different land uses in the part of each country that belongs to the Daugava Basin is presented in table 1. In figure 2 the distribution of different types of land use in the basin is shown. This is the GIS data that were used to determine the area of each land use which is required as model input by the GWLF. Artificial surfaces include urban areas and roads. Cultivated land consists of managed areas and mosaic areas of crops and trees. Herbaceous land is natural scrub, pasture, steppe and heath. Lichens and wetlands is a quite heterogeneous land use category and include lichen, moss, bog, peat and flooded herbaceous areas. Forests are divided into three land use categories; coniferous forest, deciduous forest and mixed forest (both coniferous and deciduous trees). The last land use category represented in the basin is water, which includes all open water surfaces like lakes and rivers (Ibid.).

Table 1. Percent of each land use in the part of each country that belongs to the Daugava River basin and for the entire basin (Hannerz and Destouni, 2005)

Land use category	Area percentage for each country and for the entire basin					
	Latvia	Belarus	Estonia	Lithuania	Russia	Daugava Basin
Artificial surfaces	1	0	0	0	0	1
Cultivated land	47	63	38	41	42	51
Herbaceous land	18	1	2	19	0	6
Lichens and wetlands	0	0	0	1	1	1
Forest	31	34	57	32	54	40
Water	2	1	3	7	1	2

3.1.4 Population and anthropogenic influence

The population in the area is about two million, of which 1.4 million live in the Latvian part of the basin. About 83 % of the Latvian population is living in urban areas. The major cities in the basin are Riga (800 000 inhabitants) in Latvia and Vitsyebsk (400 000 inhabitants) in Belarus. The population of the Russian part of the basin is only 250 000. There are tendencies of a decrease in population in the upper (Russian) parts of the basin and an increase in the lower (Latvian) parts. There is also an ongoing shift of people from rural to urban areas (Gooch et al., 2002).

The economic development is well correlated with the distribution of the population in the basin. In the Russian part of the river basin there are few industries and only one hydroelectric power station. Agriculture is rather extensive (Ibid.).

The industry in the Belarusian part of the basin is more developed. The main branches of industry are energy production, oil processing facilities, light industry and food production. The city of Navapolatsk is a major source of pollution of the Daugava due to its oil processing, refinery plants and developed chemical industry. Other important sources of pollution are thermoelectric power stations and municipal waste water treatment plants. Agriculture is also quite well developed in the region (Ibid.).

In the Latvian part of the region there are many different branches of industry, for example food and energy production, textile and wood industries and different kinds of machinery and chemical industries. There are three Latvian hydroelectric power plants along the river; Plyavins, Kegums and Riga. After the construction of hydroelectric power stations, the Daugava lost its importance as a transport route. Today the river is only navigable at certain stretches and the intensity of navigation is low. However, sea transport is still important and the port in Riga is one of the biggest ports around the Baltic Sea (Ibid.).

3.1.5 International cooperation in the Daugava basin

Since 1997 the Swedish Environmental Protection Agency (SWEPA) has supported the work of bringing about a trilateral agreement between Latvia, Belarus and Russia for managing the Daugava basin. In 2003 a draft international cooperation agreement on managing the river basin according to the EU Water Framework Directive (WFD) was compiled and accepted by the three countries. A complete agreement has also been written and will be signed by all three countries as soon as Russia has finished the national preparation (SWEPA, 2004).

A bilateral Latvian-Swedish project with the aim to develop a river basin district management plan for Daugava according to the EU WFD was completed in 2003 (Vattenresurs AB, 2004). However, the Daugava River Basin District only covers the Latvian part of the Daugava River basin and thus this management plan will not be sufficient for proper management of the basin. It is of great importance that also Belarus and Russia become involved in the river basin management process.

3.2 MODEL DESCRIPTION

3.2.1 An overview of the model

The GWLF model simulates monthly stream flow and monthly loads of phosphorus and nitrogen from any watershed. Hydrology is the driving force of the model. There are three types of water storage; soil water (unsaturated zone), shallow groundwater (groundwater box 1) and deeper groundwater (groundwater box 2). The amount of water in these three storages characterises the system at each moment and determines the evapotranspiration, surface runoff and groundwater flows. The catchment is divided into land use categories with different characteristics (different parameter values). Surface runoff from each land use area and groundwater flow from the entire catchment to the river are predicted from data on daily precipitation and temperature. The user has to state the nutrient concentration in surface runoff, groundwater and in eroded material. The nutrient load is obtained by multiplication of the nutrient concentration by the water flow. Point sources of nutrients are added in order to obtain the total nutrient load. In the original GWLF model the nutrient load from septic systems in the catchment is included. This part of the model has been excluded in the study due to difficulties with finding data on the number of people that have different kinds of septic systems. Figure 4 shows a schematic picture of the model.

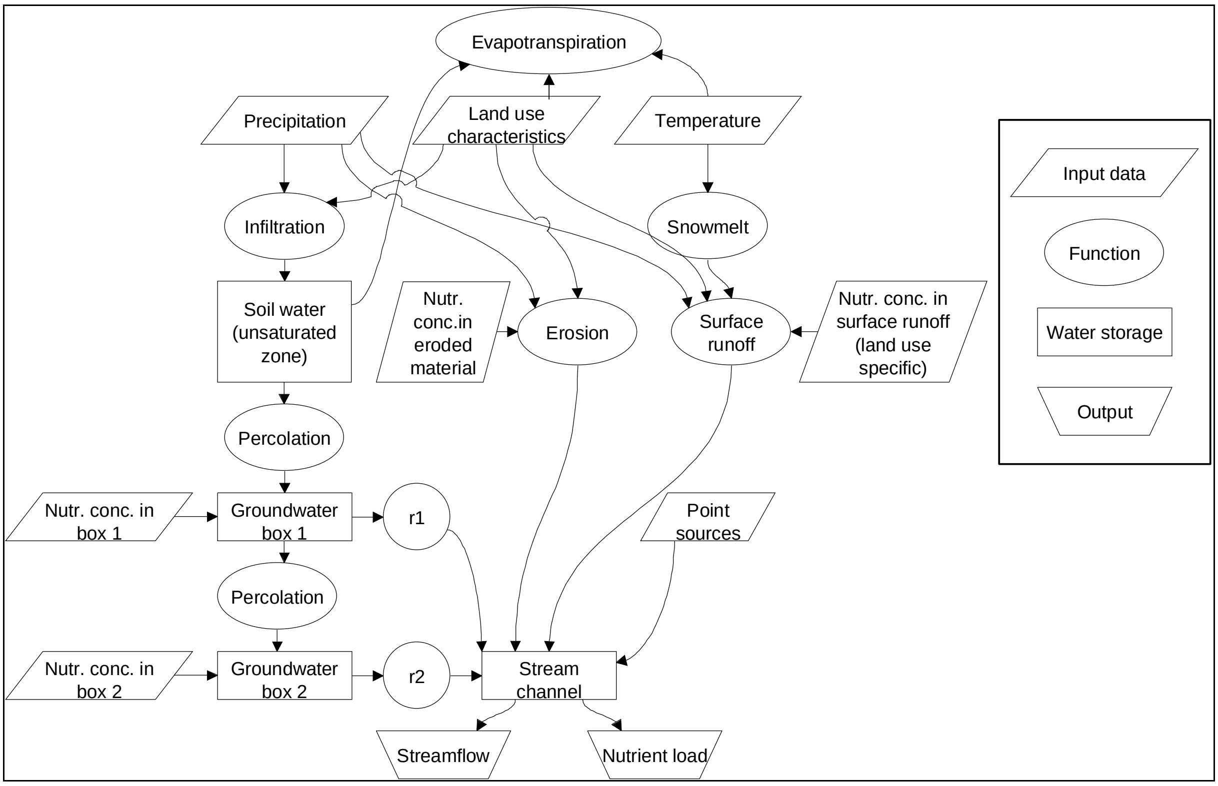


Figure 4. The structure of the modified GWLF model used in this study.

The model calculates flows and nutrient loads for each land use and the contributions from the different land uses are summed up in order to obtain the total flow/load from the watershed. In Appendix A there is a list of all the input data and parameter values used in this study.

3.2.2 Water flow

The structure of the hydrological part of the GWLF is shown in figure 1. The input needed for this part of the model is data on precipitation and temperature as well as the areas of each land use. Streamflow is computed as the sum of groundwater flow and surface runoff, as shown in equation 1. All the flows are divided by the watershed area which is how the unit centimetre is obtained.

$$Streamflow_t = Q_t + G1_t + G2_t \qquad (1)$$

where
$Streamflow_t$ = streamflow on day t [cm]
Q_t = surface runoff to the stream channel on day t [cm]
$G1_t$ = flow from groundwater box 1 to the stream channel on day t [cm]
$G2_t$ = flow from groundwater box 2 to the stream channel on day t [cm]

Surface runoff is computed from weather data by the U.S. Soil Conservation Service's Curve Number Equation. This is further described in Appendix B.

Water that does not contribute to surface runoff will infiltrate the soil. Infiltrated water will then either be lost to the atmosphere through evapotranspiration or percolate to the groundwater zone. Evapotranspiration is limited by available soil moisture in the unsaturated zone and by potential evapotranspiration:

$$E_t = Min(CV_t \cdot PE_t ; U_t + R_t + M_t - Q_t) \qquad (2)$$

where
CV_t = evapotranspiration cover coefficient
PE_t = potential evapotranspiration [cm]
U_t = unsaturated zone moisture [cm]
R_t = rainfall on day t [cm]
M_t = snowmelt on day t [cm]
Q_t = surface runoff from land use k on day t [cm]

The evapotranspiration cover cover coefficient CV_t is dependent on land use and season. It has a higher value during the growing season since the transpiration of the vegetation is then greater. CV_t values for different land uses and for dormant season and growing season respectively are given in The BasinSim 1.0 User's Guide (Dai et al, 2000). Potential evapotranspiration for each day is calculated from number of daylight hours, saturated water vapour pressure and daily mean air temperature. The equations for determining potential evapotranspiration are given in Appendix C.

Percolation is assumed to occur each day, so that every day all the unsaturated zone moisture percolates into the saturated zone. It is thus assumed that the unsaturated zone is completely emptied each day. If there is no moisture in the unsaturated zone, there will be no percolation:

$$PC_t = Max(0 ; U_t+R_t+M_t-Q_t-E_t) \qquad (3)$$

Groundwater discharge to the river channel and percolation from groundwater zone 1 to groundwater zone 2 is calculated from recession coefficients, so that for each day

$$G1_t = r1 \cdot S1_t \quad (4)$$

$$G2_t = r2 \cdot S2_t \quad (5)$$

$$G_t = gr \cdot S1_t \quad (6)$$

where
$G1_t$ = flow from groundwater box 1 to the stream channel [cm/day]
$G2_t$ =flow from groundwater box 2 to the stream channel [cm/day]
$r1$ = recession coefficient from box 1 [day^{-1}]
$r2$ = recession coefficient from box 2 [day^{-1}]
$S1_t$ = soil moisture in groundwater box 1 [cm]
$S2_t$ = soil moisture in groundwater box 2 [cm]
G_t =flow from groundwater box 1 to groundwater box 2 [cm/day]
gr = coefficient for groundwater flow from box 1 to box 2 [day^{-1}]

In the model, there is also a possibility to include deep seepage, which is interpreted as water leaving the system by percolation from groundwater box 2 to a deep aquifer. This water will not contribute to the streamflow. However, assuming that all water entering the system as precipitation will leave the system either as evapotranspiration or end up in the stream channel the deep seepage has been set to zero in this study.

3.2.3 Nutrients

In the GWLF model loads of dissolved and solid nitrogen and phosphorus are estimated for each day. Daily values are summed to provide monthly estimates of nutrient loads. It is assumed that streamflow travel times are much less that one month. Dissolved nutrients are assumed to origin from surface runoff, point sources (as known, constant mass flows) and groundwater discharge to the stream. Thus, monthly loads of dissolved nitrogen or phosphorus in streamflow are:

$$LD_m=DP_m+DR_m+DG_m \quad (7)$$

where
LD_m= total dissolved nutrient load in month m [kg]
DP_m= point source dissolved nutrient load in month m [kg]
DR_m= rural runoff dissolved nutrient load in month m [kg]
DG_m= groundwater dissolved nutrient load in month m [kg]

The sources of solid-phase nutrients in the model consist of rural soil erosion and wash off of material from urban surfaces:

$$LS_m = SR_m+SU_m \quad (8)$$

where
LS_m= total solid phase nutrient load in month m [kg]
SR_m = solid phase rural runoff nutrient load in month m [kg]
SU_m = solid phase urban runoff in month m [kg]

Rural runoff nutrient loads

Dissolved rural runoff loads. The dissolved rural runoff nutrient load for each land use is obtained by multiplying runoff by nutrient concentration. Nutrient concentration in runoff from different land uses is thus an input needed by the model. By summing daily contributions from different land uses the monthly load from the total watershed is obtained:

$$DR_m = 0.10 * \sum_k \sum_{t=1}^{dm} \left(Cd_k \cdot Q_{kt} \cdot AR_k \right) \qquad (9)$$

where
Cd_k = nutrient concentration in surface runoff from land use k [mg/l]
Q_{kt} = surface runoff from land use k on day t [cm] (from equation B1)
AR_k = area of land use k [ha]
dm = number of days in month m
0.10 = dimensional factor associated with the units of the rest of the factors in the equation

Solid-phase rural runoff loads. The solid-phase rural nutrient loads (SR_m) are given by the product of monthly sediment yields from the watershed and average sediment nutrient concentration:

$$SR_m = 0.001 \cdot Cs \cdot Y_m \qquad (10)$$

where
Cs = average sediment nutrient concentration [mg/kg]
Y_m = monthly watershed sediment yield [ton]

The definition of sediment yield is “The total amount of eroded material which does complete the journey from source to a downstream control point” (Chow, 1964). The monthly watershed sediment yield is inter alia depending on soil and land use characteristics and rainfall. Equations for calculating the monthly sediment yield are given in Appendix D.

Urban runoff nutrient loads

Urban surfaces are assumed to be impermeable. Nutrients accumulate on urban surfaces over time and are washed off by runoff events. With increasing time the accumulated amount of nutrients on the surface approaches an asymptotic value as the depletion rate approaches the accumulation rate. During the next rainfall event nutrients will then be washed off. Equations used and assumptions made for calculating this load are given in Appendix E.

Groundwater nutrient loads

The groundwater nutrient load to the stream is obtained by multiplying the flow from each groundwater box by the groundwater nutrient concentration. The monthly groundwater nutrient load is thus calculated as follows:

$$DG_m = 0.1 * AT(C1_g \sum_{t=1}^{dm} G1_t + C2_g \sum_{t=1}^{dm} G2_g) \qquad (11)$$

where
$C1_g$ = nutrient concentration in groundwater box 1 [mg/l]
$C2_g$ = nutrient concentration in groundwater box 2 [mg/l]
AT = watershed area [ha]

3.3 AVAILABLE OBSERVATION DATA USED IN THE STUDY

3.3.1 Climate data

Climate data (daily precipitation and mean air temperature) for the years 1980 to 2000 were taken from the BALTEX Hydrological Data Centre data base administrated by SMHI. The value of daily temperature and precipitation is a spatial and temporal mean of several measuring points in the basin and several times of measurement during the day (Danielsson, 2005).

3.3.2 Streamflow and nutrient load data

The reported data consist of monthly means of streamflow, total nitrogen load and total phosphorus load from 1970-2000 (Wulff and Rahm, 1990; Stålnacke 1996) with some data gaps during the 90's. In figure 5 the reported streamflow and the reported loads of nitrogen and phosphorus from the Daugava are displayed. Data from 1970-1990 were compiled by Stålnacke (1996) with help from data obtained from the Latvian Hydrometeorological Agency in Riga. Gaps in the data series were filled in by the use of statistical interpolation and extrapolation methods. Different sampling sites were used and it is not clear where the sampling sites are located, but they are probably situated a considerable distance from the mouth of the river. Since the areas of different land uses in the basin have been calculated from the mouth of the river this means that the drainage area used as model input is overestimated with respect to the drainage area of the sample stations. Also, the impact of Riga is not included in reported data, since Riga is situated at the mouth of the Daugava. Considering the data from the 90's, there is little information on how the data series were compiled and where the sample station is located.

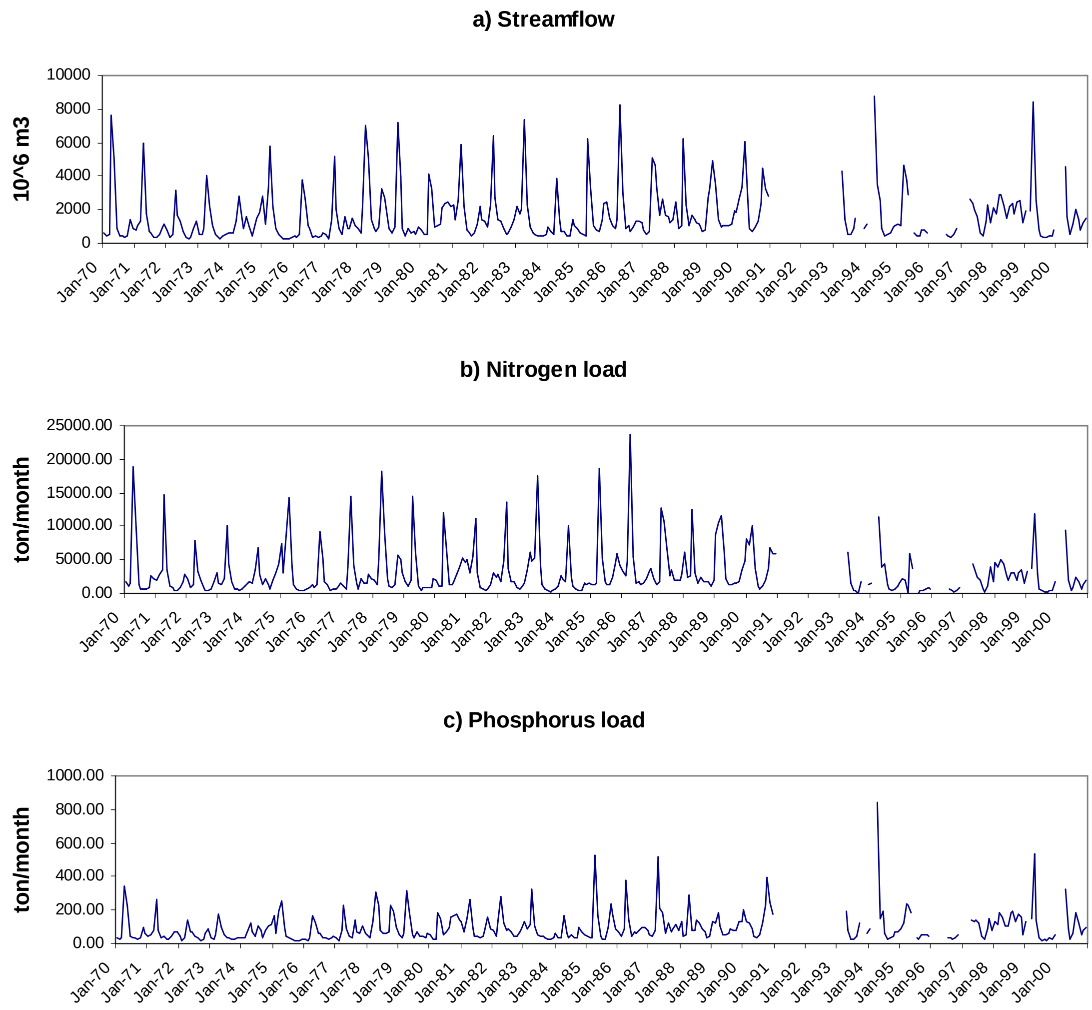


Figure 5. Reported monthly streamflow (a) and load of total nitrogen (b) and phosphorus (c) from the Daugava River for the years 1970-2000.

3.4 CALIBRATION AND VALIDATION

The model was applied to the Daugava drainage basin with the input data and parameter values presented in Appendix A. In the appendix it is also described which parameters were calibrated.

Climate data were not available for the 1970's, which is why only the 1980's and 1990's could be used for calibration and validation. Seven years during the 1990's (1993-1999) were used for calibration. They were chosen because they were the most recent years and the desire was to achieve a calibration as close to the present situation as possible. As a first step calibration was done for the hydrological part of the model. The evapotranspiration cover coefficients (CV_t), curve numbers ($CN2_k$) and coefficients for groundwater flow (r1, r2 and gr) were used as calibration parameters. In order to obtain the best fit several aspects were taken into consideration. It was a trade off between obtaining an average value over the seven years of the predicted streamflow as close to the observed average value as possible, minimising the average percentage error and reaching the observed top flows. The process was iterative and since there is no built-in calibration procedure in CatchmentSim the work had to be done manually.

There is therefore no guarantee that the calibrated values are the optimal values. When the calibration was complete the validation was done on data from the 1980's.

When the hydrological part of the model was calibrated, the next step was to add nutrient concentrations in groundwater and surface runoff, erosion of solid nutrients and nutrient loads from point sources. The concentration in the groundwater boxes 1 and 2 were used as calibration parameters. Focus was placed on achieving the best fit for loads, but concentrations were also studied. The calibration was done in the same way as for the hydrological part; by studying the quotient between predicted and observed average values, the average percentage error and how well top flows/concentrations were predicted.

As for streamflow, validation was done on data from the 1980's.

3.5 IMPACT OF THE CURVE NUMBER ON NUTRIENT SOURCE APPORTIONMENT

The curve number (see Appendix B) determines the fraction of precipitation that will go to surface runoff. The curve number varies between 0 and 100. Curve number 0 means that all precipitation will infiltrate and curve number 100 means that all precipitation will go to surface runoff. There are different views on how to choose the curve number for each land use. In the original GWLF manual curve numbers are suggested for different land use types. However, in communication with Stefan Löfgren (2005) it was decided that in this study the same curve number should be used for all vegetation-covered surfaces. Since the curve number determines surface runoff and since surface runoff is the main contributor to nutrient loads from a certain land use, the curve number will have a large impact on the nutrient source apportionment from different land uses. In order to illustrate this, the model was run both with the calibrated curve numbers that were used in the rest of the study (Approach A) and with the curve numbers suggested by the original GWLF manual (Approach B). The nutrient contributions from each land use were studied for the two cases.

3.5 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted in order to determine which model parameters have the greatest influence on the output. The parameters chosen for the sensitivity analysis were recession coefficients 1 and 2 (r1 and r2), the coefficient for groundwater flow between box 1 and 2 (gr) and the nutrient concentration in groundwater box 1 and 2 ($C1_gN$ and $C2_gN$). The output that was studied was the average monthly load of nutrients. The calibrated values of the chosen parameters were multiplied by a fixed factor one at a time and the impact on the average load of nutrients was studied. The factors chosen were 0.5, 0.75, 1.25 and 1.5.

4. RESULTS

4.1 CALIBRATION AND VALIDATION

The result of the modelling can be seen in figure 6, where observed and modelled monthly values for streamflow and nutrient loads are presented for the calibration period (1993-1999) and the validation period (1980-1989). For the calibration period the model predicts streamflow and nitrogen rather well although top flows are sometimes underestimated. Streamflow is also fairly well predicted for the validation period. Nitrogen loads are underestimated for this period, especially during peak flows. When it comes to phosphorus the model greatly underestimates monthly loads for both the calibration period and the validation period.

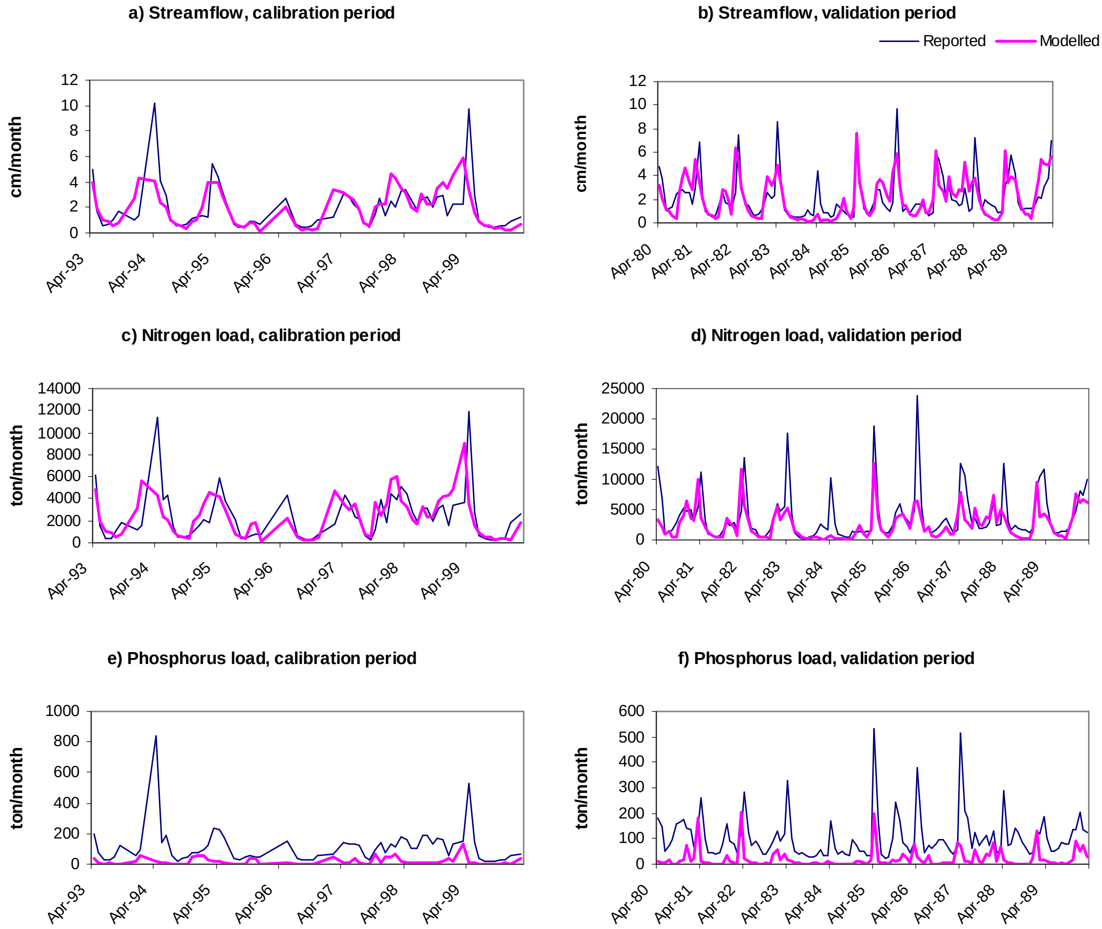


Figure 6. Reported and modelled values of monthly means of streamflow, nitrogen loads and phosphorus loads from the Daugava River for the calibration period (1993-2000) and the validation period (1980-1990).

The model output is monthly means of loads and streamflow, but since the purpose of the model is to estimate long-term loads it is of interest to see how well the model predicts yearly means. In figure 7 the reported and modelled yearly means of streamflow and nutrient loads are presented. The model seems to estimate yearly streamflow quite well, both for the calibration period and the validation period. There are, however, tendencies towards a higher variance for modelled yearly flows than for observed yearly flows. Yearly nitrogen loads are well estimated by the model for the calibration period, but for the validation period nitrogen loads are underestimated.

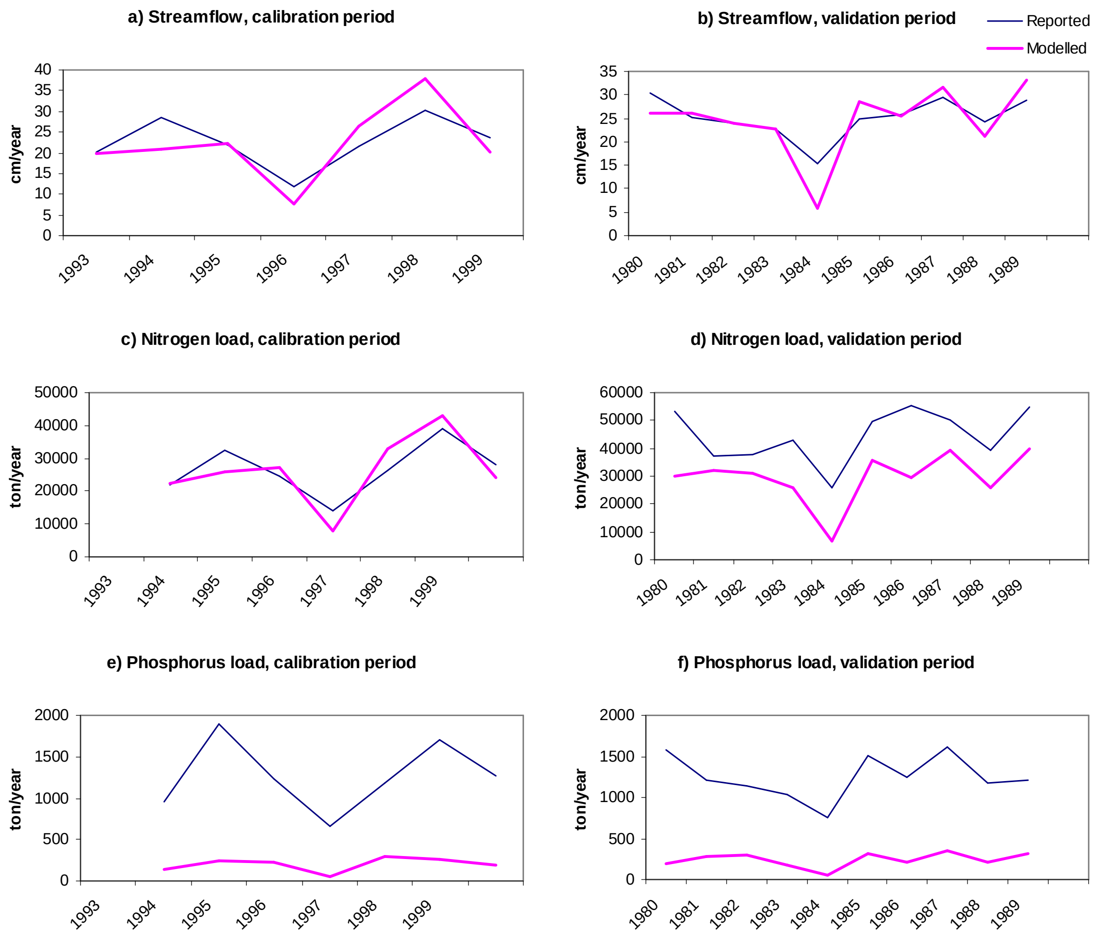


Figure 7. Reported and modelled values of yearly means of streamflow, nitrogen loads and phosphorus loads from the Daugava River for the calibration period (1993-2000) and the validation period (1980-1990).

Table 2 shows a statistical summary of the comparison of observed and predicted values. Generally, the prediction of yearly values is a lot better than the prediction of monthly values. Regressions lines were made between reported and modelled values. The R^2 value of the regression of modelled and reported yearly nitrogen loads is 0.78 and the corresponding slope of regression is 1.17. The R^2 value for yearly phosphorus loads is 0.5, but since the regression slope is only 0.14 the ability of the model to predict phosphorus loads must be considered to be very low. The regression slope for monthly means is generally much lower than for yearly means. This is due to the fact that the model underestimates peak flows. For yearly values the impact of peak flows is not so significant, which is why the regression slope for yearly means is higher than for monthly means. Plots of the regressions are found in Appendix F.

Table 2. Comparison of reported and modelled values

	Calibration period, 1993-1999		Validation period, 1980-1989	
	Monthly means	Yearly means	Monthly means	Yearly means
Stream flow:				
Modelled mean/reported mean for entire simulation period	1	1	0.99	0.99
Mean absolute percentage error	45	18	48	13
Slope of regression between reported and modelled values	0.48	1.21	0.7	1.58
R^2 of regression between reported and modelled values	0.36	0.67	0.53	0.82
Nitrogen load:				
Modelled mean/reported mean for entire simulation period	1	1	0.67	0.67
Mean absolute percentage error	59	18	44	35
Slope of regression between reported and modelled values	0.47	1.17	0.41	0.57
R^2 of regression between reported and modelled values	0.32	0.78	0.44	0.75
Phosphorus load:				
Modelled mean/reported mean for entire simulation period	0.16	0.16	0.2	0.2
Mean absolute percentage error	80	84	83	81
Slope of regression between reported and modelled values	0.016	0.14	0.18	0.24
R^2 of regression between reported and modelled values	0.006	0.5	0.18	0.47

The contribution to the modelled streamflow is divided by flow from surface runoff, groundwater box 1 and groundwater box 2 respectively. In figure 8 the distribution of these three flows over two years is shown. Flow from groundwater box 1 is the main contributor to streamflow. The largest flows occur during spring. Surface runoff only occurs during periods of rainfall and/or snowmelt, see Appendix B. The contribution from groundwater box 2 is generally lower than from groundwater box 1. On the other hand, the flow from box 2 is more constant over the year, and during fall and winter the contribution from box 2 at times exceeds the contribution from box 1.

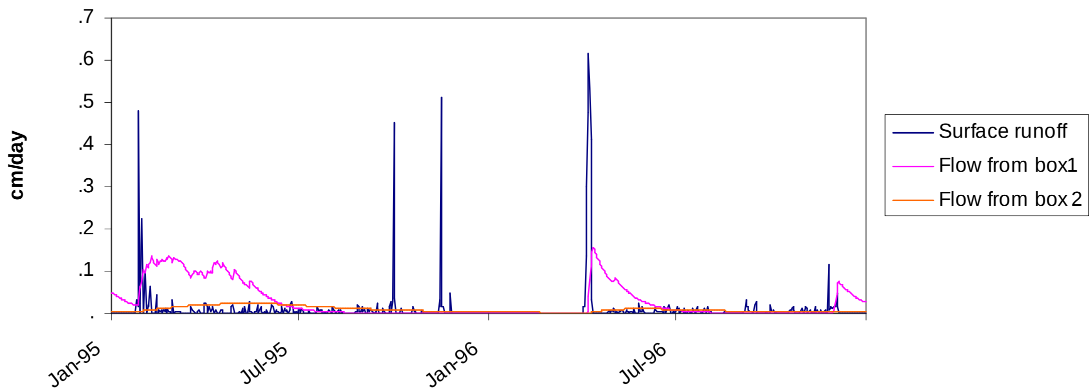


Figure 8. The predicted daily contribution to streamflow from surface runoff and groundwater box 1 and 2 and the total streamflow, 1995-1996.

4.2 IMPACT OF THE CURVE NUMBER ON NUTRIENT SOURCE APPORTIONMENT

The model was run with different choices of curve numbers according to Approach A and B. The curve numbers are presented in table 3.

Table 3. The two sets of curve numbers used

Land Use	Curve number	
	Approach A	Approach B
Artificial surfaces	100	100
Cultivated land	80	70
Herbaceous land	80	70
Lichens and wetlands	80	70
Coniferous forest	80	60
Mixed forest	80	60
Deciduous forest	80	60
Water	100	100

Figure 9 illustrates the impact of the curve number on the distribution of total nitrogen loads from different land uses. The total nitrogen load includes surface runoff and erosion from each land use. Water surfaces and cultivated land are the main contributors. With approach A cultivated land makes up most of the nutrient loads (71 %) and water surfaces make up 23 %. With approach B the relative impact of water surfaces is enlarged and makes up 54 % of the total load while the relative impact of cultivated land is lessened (46 %). The impact of forested land is smaller for approach B than for approach A since the curve number is the same for forested land and cultivated land in approach A, but smaller for forested land than for cultivated land in approach B. The phosphorus source apportionment is not displayed since the model fails to predict phosphorus loads.

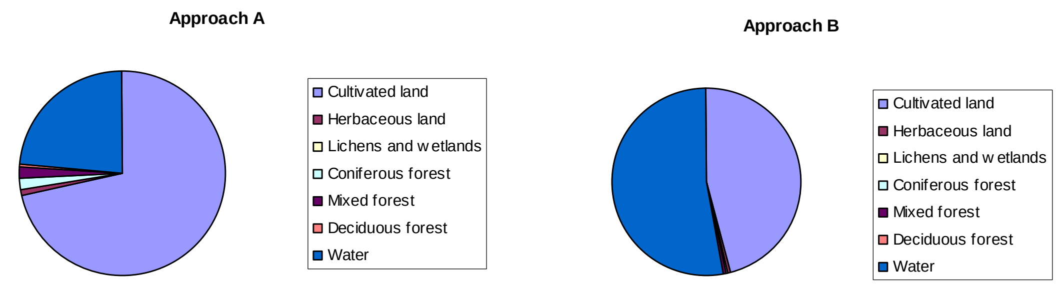


Figure 9. The relative contribution to nitrogen loads from each land use with different methods for choosing the curve number.

4.3 SENSITIVITY ANALYSIS

The result of the sensitivity analysis is presented in figure 10. The nitrogen concentration in groundwater box 1, $C1_gN$, is the one of the analysed parameters whose value has the greatest impact on the nutrient load. A change of this value by 50 % will change the nitrogen load by 27 %. The variable that has the least impact on the nitrogen load is the recession coefficient for box 2, r2. A change of the value of this coefficient by 50 % will change the nitrogen load by less than 1 %. It should be noted that the change in nutrient load will be directly proportional to the change in the nitrogen concentration in box 1 and 2 due to the linearity of the model equations that determine nutrient loads from the groundwater.

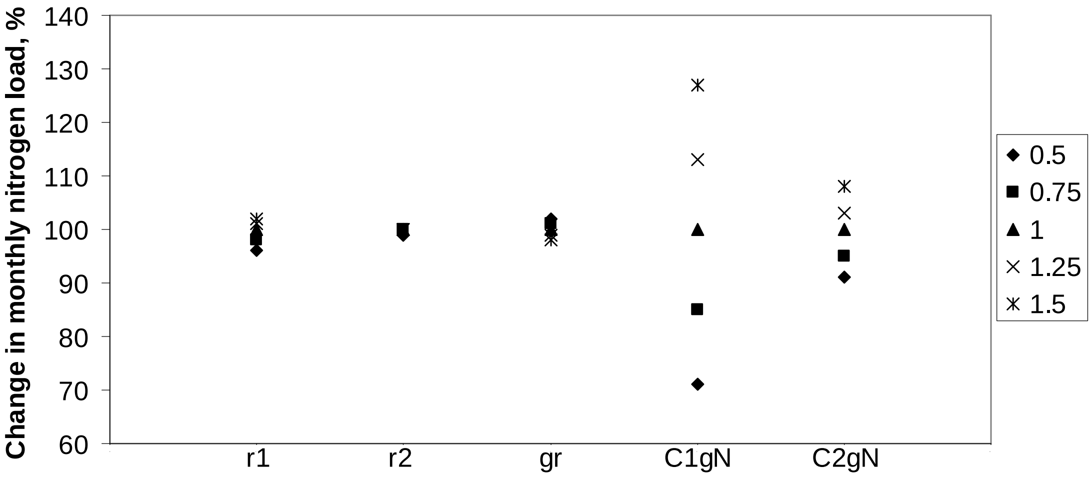


Figure 10. Result of the sensitivity analysis. On the x-axis are the analysed parameters. The y-axis shows the average change in monthly nitrogen load over 10 years when the parameter values have been multiplied by the factors 0.5, 0.75, 1, 1.25 and 1.5, respectively.

5. DISCUSSION

The aim of the model is to predict long-term nutrient loads from a watershed. The model predicts yearly nitrogen loads from the Daugava basin quite well. The mean absolute percentage error of estimations of yearly nitrogen loads during the years 1993-1999 is 18 %, and the corresponding R^2-value is 0.78. Considering the simplicity of the model and the defectiveness of input data this can be considered a quite good result. During the 1980's (validation period) the model underestimates nitrogen loads by approximately 30 % even though streamflow is quite well predicted during this period. A reason for this may be that the surface runoff and groundwater nitrogen concentrations were higher during the 1980's than during the 1990's. This is probable since the use of fertilisers, especially in the Latvian part of the basin, dropped dramatically in the beginning of the 1990's due to the collapse of the Soviet Union. There has been a negative trend in nitrogen loads from the Daugava during the years 1987-1998 (Stålnacke et al., 2003). Since the nutrient concentration in the GWLF model is constant, the model can never predict trends in nutrient concentration due to changes in the groundwater or surface runoff concentrations. In that sense the model is static and not suitable for long-term nutrient load predictions.

The GWLF model, as implemented, fails to predict phosphorus loads. The modelled phosphorus loads are about 90 % less than reported loads. One reason could be that phosphorus concentrations in surface runoff and groundwater used were too low. However, in order to reach the observed levels, the input concentrations in surface runoff and groundwater needed to be increased almost by a magnitude, which does not seem reasonable. A possible cause to this discrepancy could instead be an underestimation of phosphorus loads from erosion. The erosion factor, the rainfall erosivity and the sediment delivery ratio are dependent on parameters such as agricultural management practices and crop coverage. Since no such data were available the chosen value is a very rough approximation. The value of rainfall erosivity is likewise an approximation and the sediment delivery ratio is an extrapolation since values were not given for watersheds as large as the Daugava basin. All together, the predicted erosion may be considerably erroneous. Never the less, a more probable explanation for the underestimation of phosphorus loads is that the reported values of point source phosphorus loads in the basin are a lot less than the actual value and that phosphorus from septic systems, which are not included in the modelling, contributes substantially to the total load. According to HELCOM (2004b), about 70 % of diffuse phosphorus loads to the Gulf of Riga origin from other sources than agriculture and forestry, for instance from septic systems. Looking at Daugava the figure is probably something similar since water from the Daugava is the main contributor to the Gulf of Riga. Gren et al. (1997) state that the lack of sewage treatment in the Gulf of Riga region contributes to very large input of phosphorus to the sea. Since agriculture and forestry are the main sources of phosphorus according to the model and since septic systems are not included it is therefore not surprising that the model fails to predict phosphorus loads.

An indication of point source phosphorus pollution is that concentrations are higher at lower flows and lower at higher flows. In figure 11 the observed phosphorus concentration and streamflow are displayed.

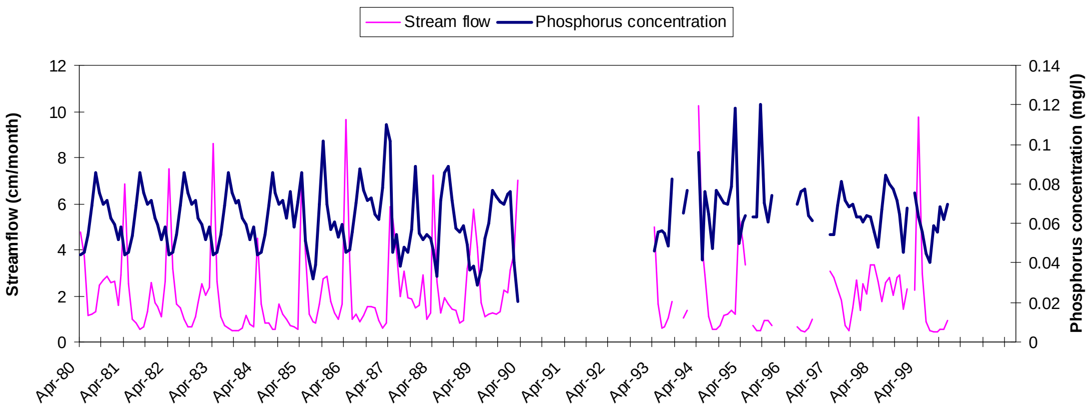


Figure 11. Reported streamflow and phosphorus concentration, 1980-2000.

It seems like the peaks in phosphorus concentration occur at low flows which could be an indication of point sources of phosphorus, but in order to say something definitely one would need to conduct a statistical analysis of the two time series.

Of the parameters used in the sensitivity analysis the nitrogen concentration in groundwater box 1 is the one that affects average loads the most. This is not surprising since streamflow mainly consists of water from groundwater box 1. It is therefore important to calibrate this parameter carefully. The impact of the recession coefficients and the coefficient determining flow between the two groundwater boxes appears to be very small, looking at the result of the sensitivity analysis. The reason for this is the small difference between the nitrogen concentration in the two boxes (1 and 1.3 mg/l, respectively). With a more pronounced difference in concentration between the boxes the impact on the nitrogen load of the recession coefficients and the coefficient determining flow between the two boxes would have been greater.

The choice of curve numbers that determine surface runoff has a great impact on the nutrient source apportionment. Since no data were available on site specific nutrient contributions from different land uses, it was not possible to calibrate the curve numbers in order to fit observed apportionments. The values suggested in the manual for the original GWLF (Dai et al., 2001) are developed for North American conditions and it is difficult to say much about their relevance in this area. It is important to be consistent when choosing curve numbers in the rest of the Baltic Sea basin and to bear in mind that the source apportionment from different land uses contains substantial uncertainties.

When looking at the source apportionment it should be remembered that only surface runoff and erosion is included; nutrient contributions from the groundwater flow is not considered. Due to nitrogen leakage a substantial part of nitrogen in agricultural soils will be transported down to the groundwater and thus result in increased nitrogen concentrations. The total nitrogen load is thus largely affected by nitrogen from the groundwater. Thus, the actual contribution from agricultural land is greater than what is suggested by the source apportionment analysis.

In a drainage basin as large as Daugava the amount of nitrogen that is lost on the way to the sea is substantial, but nitrogen retention is not included in the model. The retention affects the model calibration in such a way that the calibrated groundwater nitrogen concentrations are lower than they would have been, had retention not existed. The groundwater nitrogen concentration in the model is thus probably lower than in reality. The inability of the model to estimate nitrogen retention might affect the usefulness of the model for scenario analysis. For example, the construction of wetlands may help decrease nitrogen loads from water passing through the wetland since nitrogen is lost by denitrification. In this way, wetlands can help decrease nitrogen loads from for instance agricultural lands. But in the GWLF the nitrogen load from agriculture will not be affected by the increase in wetland areas. Also, since retention is not included in the model, the impact of land anywhere in the basin will have the same impact, a situation that is unlikely to occur in reality.

The quality of data is of major importance for the result of any modelling. In the Daugava basin it is difficult to find reliable data. The reported streamflow and nutrient loads can also be questioned. Little information is given regarding what reported data are observed and what are calculated. In order for modelling results of nutrient flows from the entire Baltic Sea basin to be trustworthy more reliable data are therefore needed. It is of utmost importance that such data are easily accessed and homogenous in order to support sustainable water management in the Baltic Sea Region (Hannerz et al. 2005).

In order to use the GWLF for long-term prediction of nutrient loads, modifications of the model are suggested. For instance, nutrient concentrations should be variable with time. For simulations over short time periods it is probable that the groundwater concentration remains more or less the same. However, considering long time spans or periods with sudden changes in management, like for instance the collapse of the Soviet Union and its agricultural policy, it is not likely that the groundwater concentration will be constant. As stated above, it must be remembered that the model is static in this sense. Another change that could be made is to divide the existing land cover categories into several subcategories depending on more site-specific land use. As an example, presently it would be impossible to handle a future scenario where a certain fraction of all cultivated land will have winter crops. In order to simulate such a scenario it would be necessary to divide cultivated land into two categories; cultivated land with winter crops and cultivated land without winter crops. This way it would be easier to handle scenarios where new agricultural policies affect management practices.

6. CONCLUSIONS

The main conclusions that can be drawn from the study are:

- Yearly nitrogen loads are fairly well estimated by the model during the calibration period, but since the loads during the validation period generally were higher than during the calibration period it was not possible to validate the ability of the model to predict nitrogen loads.
- The model significantly underestimates phosphorus loads. Possible reasons for this are that septic systems, which were not included in the model, are a main contributor to phosphorus loads and that reported point sources are underestimated.
- Modifications of the model need to be done in order to use the model for long-term predictions. As an example it should be possible to vary the groundwater nutrient concentration with time.
- The lack of good quality data makes it difficult to model nutrient loads in parts of the Baltic Sea basin. It should be of high priority to make data more readily available and to create more homogeneous databases for the region. In order to do this successfully cooperation between all the countries in the region is needed.

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Appendix A. Input data and parameters used by the GWLF model

Description of parameter/input	Name	Unit	Initial value	Calibrated Value	Reference
Recession coefficient box 1	R1	day^{-1}	0.0025	0.03	Mörth, 2004
Recession coefficient box 2	R2	day^{-1}	0.001	0.01	Mörth, 2004
Groundwater transfer from box 1 to box 2	gr	day^{-1}	0.001	0.01	Mörth, 2004
Seepage coefficient	s	day^{-1}	0		
Initial unsaturated storage	U(0)	cm	0		
Initial saturated storage box 1	S1(0)	cm	18.6	2.7	Average predicted value in March
Initial saturated storage box 2	S2(0)	cm	23.6	1.7	Average predicted value in March
Initial snow cover		cm	20	1.5	Average predicted value in March
Sediment delivery ratio	DR		0.009		Dai et al., 2000
Unsaturated water capacity	U*	cm	0		Mörth, 2004
ET cover coefficient, oct-apr	CVt		0.3	0.35	Dai et al., 2000
ET cover coefficient may-sept	CVt		1	0.83	Dai et al., 2000
Day length APRIL	Ht	H	13.82		Orchid culture
Day length MAY	Ht	h	15.87		
Day length JUNE	Ht	h	17.06		
Day length JULY	Ht	h	16.57		
Day length AUG	Ht	h	14.74		
Day length SEPT	Ht	h	12.43		
Day length OCT	Ht	h	10.15		
Day length NOV	Ht	h	8.05		
Day length DEC	Ht	h	6.93		
Day length JAN	Ht	h	7.5		

Description of parameter/input	Name	Unit	Initial value	Calibrated Value	Reference
Day length FEB	Ht	h	9.37		
Day length MAR	Ht	h	11.46		
Growing season (average daily temp. > 10 °C)			May-Sept		BALTEX Hydrological Data Centre data base
Erosivity coefficient growing season	a		0.25		Dai et al., 2000
Erosivity coefficient no growing season	a		0.06		
<u>Area of each land use type</u>	AR_k	ha			Hannerz and Destouni, 2005
Artificial surfaces (urban)			50819		
Bare areas (rural)			0		
Cultivated areas (rural)			4409294		
Herbaceous+shrub (rural)			510356		
Wetland (rural)			44831		
Snow and ice (rural)			0		
Coniferous (rural)			1482044		
Mixed forest (rural)			1429719		
Deciduous forest (rural)			509744		
Water (rural)			148463		
<u>Curve number</u>	$CN2_k$				Löfgren, 2004
Artificial surfaces			100		
Bare areas			75	80	
Cultivated areas			75	80	
Herbaceous+shrub			75	80	
Wetland			75	80	
Snow and ice			100		
Coniferous forest			75	80	

Description of parameter/input	Name	Unit	Initial value	Calibrated Value	Reference
Mixed forest			75	80	
Deciduous forest			75	80	
Water			100		
Soil erodibility factor	K_k		0.25		Dai et al., 2000
<u>Topographic factor</u>	$(LS)_k$				Hannerz and Destouni, 2005
Artificial surfaces			2.233		
Bare areas					
Cultivated areas			5.594		
Herbaceous+shrub			3.680		
Wetland			2.094		
Snow and ice					
Coniferous			3.862		
Mixed forest			4.325		
Deciduous forest			3.587		
Water			2.388		
<u>Cover and management factor</u>	C_k				Dai et al., 2000
Bare areas			0		
Cultivated areas			0.01		
Herbaceous+shrub			0.01		
Wetland			0.01		
Snow and ice			0		
Coniferous			0.001		
Mixed forest			0.001		
Deciduous forest			0.001		

Description of parameter/input	Name	Unit	Initial value	Calibrated Value	Reference
Water			0		
Supporting practice factor	P_k		0		Dai et al., 2000
Sediment N concentration	Cs	mg/kg	2800		Mörth, 2004
Sediment P concentration	C_s	mg/kg	1276		Mörth, 2004
N concentration groundwater box 1	C1gN	mg/l	3	1.3	Löfgren, 2004
N concentration groundwater box 2	C2gN	mg/l	1	1	Löfgren, 2004
P concentration groundwater box 1	C1gP	mg/l	0.005		Löfgren, 2004
P concentration groundwater box 2	C2gP	mg/l	0.002		Löfgren, 2004
Number of manured land uses			0		
<u>N concentration in runoff</u>	Cd_k	mg/l			Löfgren, 2004
Bare areas			1.6		
Cultivated areas			6.5		
Lichens and wetland			1		
Snow and ice			0		
Coniferous			0.5		
Mixed forest			0.5		
Deciduous forest			0.5		
Water			1.6		
<u>P concentration in runoff</u>	Cd_k	mg/l			Löfgren, 2004
Artificial surfaces			0		
Bare areas			0.01		
Cultivated land			0.17		
Herbaceous land			0.01		

Description of parameter/input	Name	Unit	Initial value	Calibrated Value	Reference
Lichens and wetlands			0.02		
Snow and ice			0		
Coniferous forest			0.009		
Mixed forest			0.009		
Deciduous forest			0.01		
Water			0.01		
Artificial surfaces					
N build-up rate on artificial surfaces	n_k	kg/ha/day	0.101		Dai et al., 2000
P build-up rate on artificial surfaces	n_k	kg/ha/day	0.0112		Dai et al., 2001
Point sources					
Point N	DP_m	kg/month	91000		Latvian Environment Agency, 2002
Point P	DP_m	kg/month	17000		Latvian Environment Agency, 2002

Appendix B. Determination of surface runoff

Surface runoff is computed from weather data by the U.S. Soil Conservation Service's Curve Number Equation (equation B1) (Dai et al., 2001).

$$Q_{kt} = \frac{(R_t + M_t - 0.2 \cdot DS_{kt})^2}{R_t + M_t + 0.8 \cdot DS_{kt}} \qquad \text{(B1)}$$

where
Q_{kt} = surface runoff from land use k on day t [cm]
R_t = rainfall on day t [cm]
M_t = snowmelt on day t [cm]
DS_{kt}= detention parameter for land use k on day t [cm]

Precipitation is assumed to be rain when the daily mean air temperature is more than 0 °C.
If there is a snow cover, snowmelt is computed by a degree-day equation:

$$M_t = TC \cdot T_t \qquad \text{for } T_t > 0\ °\text{C} \qquad \text{(B2)}$$

where
TC = temperature coefficient for snowmelt [cm/°C]
T_t = mean air temperature on day t [°C]

The detention parameter DS_{kt} is determined from a curve number CN_{kt}:

$$DS_{kt} = \frac{2540}{CN_{kt}} - 25.4 \qquad \text{(B3)}$$

Curve numbers are determined from a function of antecedent moisture as shown in figure B1. Curve numbers for antecedent moisture conditions 1 (driest), 2 (average) and 3 (wettest) are $CN1_k$, $CN2_k$ and $CN3_k$ respectively.

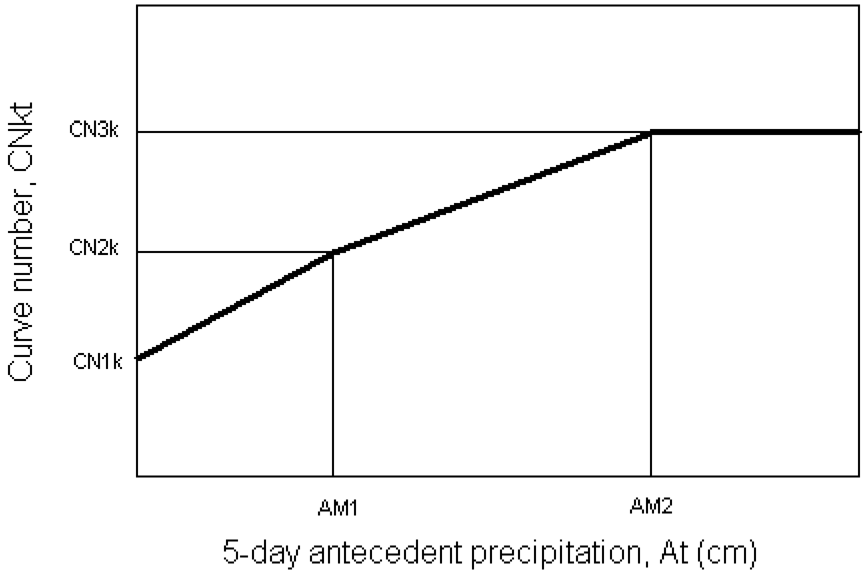

Figure B1. Selection of curve number as a function of antecedent moisture.

Recommended values of the break points AM1 and AM2 have been used (Dai et al, 2000). The 5-day antecedent precipitation is computed as follows:

$$A_t = \sum_{n=t-5}^{t-1}(R_n + M_n) \qquad \text{(B4)}$$

$CN2_k$ values for different land uses are given in the BasinSim 1.0 User's Guide (Dai et al, 2000).Values of $CN1_k$ and $CN3_k$ are computed from $CN2_k$:

$$CN1_k = \frac{CN2_k}{2.334 - 0{,}01334 \cdot CN2_k} \qquad \text{(B5)}$$

$$CN3_k = \frac{CN2_k}{0.4036 - 0.0059 \cdot CN2_k} \qquad \text{(B6)}$$

Appendix C. Determination of potential evapotranspiration

Potential evapotranspiration is given by the following equation (Dai et al., 2001):

$$PE_t = \frac{0.021 \cdot H_t \cdot e_t}{T_t + 273} \qquad \text{(C1)}$$

where
H_t = number of daylight hours per day during the month containing day t
e_t = saturated water vapour pressure on day t [mbar]
T_t = daily mean air temperature, average value for entire basin [°C]

The saturated water vapour pressure is estimated from daily mean air temperature:

$$e_t = 33.8639\left[(0,00738 \cdot T_t + 0.8072)^8 - 0.000019(1.8 \cdot T_t + 48) + 0.001316\right], T_t \geq 0 \quad \text{(C2)}$$

Appendix D. Determination of monthly sediment yield

The monthly watershed sediment yield in the GWLF is determined from a model that is based on three assumptions:

(i) Sediment originates from sheet and rill erosion (gully and stream bank erosion are neglected)

(ii) Sediment transport capacity is proportional to runoff to the 5/3 power

(iii) Sediment yields are produced from soil which erodes in the current year (no carryover of sediment supply from one year to the next)

Accordingly, the sediment yield in a certain month will consist of contributions from all other months during that year. The contribution from each month will be equal to the sediment yield for that month multiplied by the fraction of total transport capacity in that month (Dai et al., 2001).

The total watershed sediment supply generated in month j is:

$$X_j = DR \sum_k \sum_{t=1}^{d_j} X_{kt} \quad \text{(D1)}$$

where

DR = watershed sediment delivery ratio

X_{kt} = erosion from land use k on day t [Mg]

d_j = number of days in month j

Erosion from land use k on day t is given by:

$$X_{kt} = 0.132 \cdot RE_t \cdot K_k \cdot (LS)_k \cdot C_k \cdot P_k \cdot AR_k \quad \text{(D2)}$$

where

RE_t = rainfall erosivity on day t [(MJ*mm)/(ha/h)]

K_k = soil erodibility factor

$(LS)_k$ = topographic factor

C_k = cover and management factor

P_k = supporting practice factor

The product K*LS*C*P is called the erosion factor. Standard values for K, C and P for different land uses and soil types can be found in tables in the BasinSim User's Guide (Dai et al., 2000). LS is determined from data on topography. Rainfall erosivity is estimated by the following empirical equation:

$$RE_t = 64.6 \cdot a_t \cdot R_t^{1.81} \quad \text{(D3)}$$

where
a_t = rainfall erosivity coefficient
R_t = rainfall on day t

The rainfall erosivity coefficient varies with season and geographic location.

In order to determine the transport of sediments in each month, a transport factor is defined as:

$$TR_j = \sum_{t=1}^{d_j} Q_t^{5/3} \tag{D4}$$

The sediment produced in month j will be allocated to months j, j+1, …12 in proportion to the transport capacity of each month. The total transport capacity for months j, j+1, …12 is proportional to the sum of the transport factors during these months, defined as B_j.

$$B_j = \sum_{h=j}^{12} TR_h \tag{D5}$$

For each month, the fraction of available sediment X_j which contributes to Y_m, is TR_m/B_j. The total monthly yield is the sum of all contributions from preceding months:

$$Y_m = TR_m \sum_{j=1}^{m} (X_j / B_j) \tag{D6}$$

Appendix E. Determination of urban runoff nutrient loads

Urban surfaces are assumed to be impermeable. Nutrients accumulate on urban surfaces over time and are washed off by runoff events. The accumulation rate during dry periods is:

$$\frac{dN_k}{dt} = n_k - \beta \cdot N_k \tag{E1}$$

where
$N_k(t)$= accumulated nutrient load on land use k on day t [kg/ha]
n_k = constant accumulation rate [kg/(ha*day)]
β = depletion rate constant [day^{-1}]

By solving equation E1 we obtain:

$$N_k(t) = N_{k0} e^{-\beta t} + (n_k / \beta)(1 - e^{-\beta t}) \tag{E2}$$

where
$N_{k0} = N_k(0)$

With increasing time, equation E2 approaches an asymptotic value as the depletion rate approaches the accumulation rate:

$$N_{k,\max} = \lim_{t\to\infty} N_k(t) = n_k / \beta \qquad \text{(E3)}$$

Assuming that $N_k(t)$ reaches 90 % of its maximum value in 20 days, the equations can be solved for β. The result is β = 0.12, which is the value that is used here.

Equation E2 can be written for a time interval of one day, which is the form that is used by the GWLF model:

$$N_{k,t+1} = N_{kt}e^{-0.12} + (n_k / 0.12)(1 - e^{-0.12}) \qquad \text{(E4)}$$

By adding a negative term to the right hand side of this equation, the effect of wash off is included:

$$N_{k,t+1} = N_{kt}e^{-0.12} + (n_k / 0.12)(1 - e^{-0.12}) - W_{kt} \qquad \text{(E5)}$$

where
W_{kt} = runoff load from land use k on day t [kg/ha]

The runoff nutrient load at a wash off event is a function of the amount of accumulated nutrients at the time and the runoff flow:

$$W_{kt} = w_{kt}[N_{kt}e^{-0.12} + (n_k / 0.12)(1 - e^{-0.12})] \qquad \text{(E6)}$$

where

$$w_{kt} = 1 - e^{-1.81Q_{kt}} \qquad \text{(E7)}$$

Equation E7 is based on the assumption that 1.27 cm of runoff will wash off 90 % of accumulated pollutants.

Monthly runoff loads of urban nutrients are thus given by:

$$SU_m = \sum_k \sum_{t=1}^{dm} \left(W_{kt} \cdot AR_k\right) \qquad \text{(E8)}$$

Appendix F. Regression lines of reported and modelled monthly and yearly values

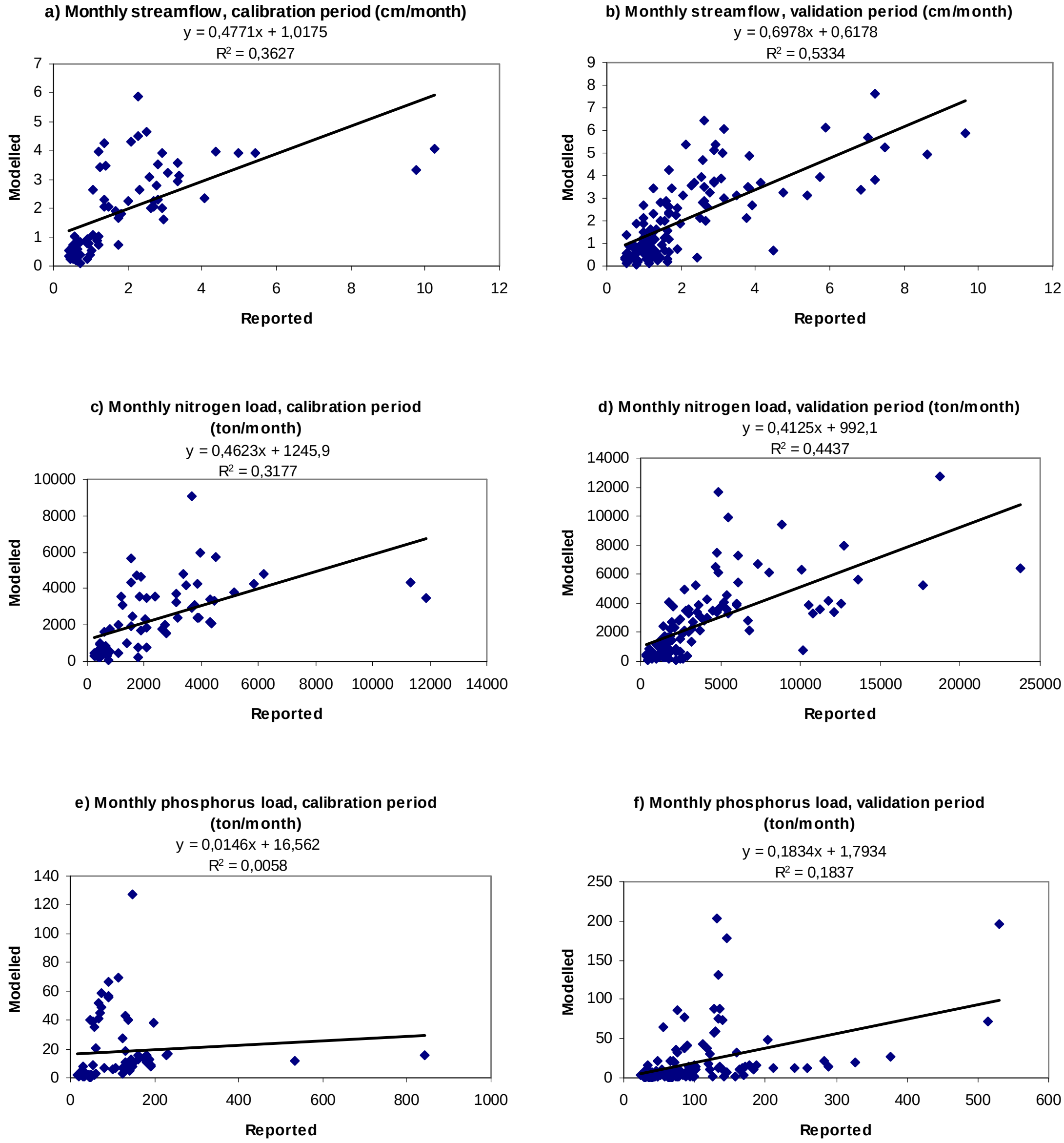

Figure F1. Regressions of monthly reported and modelled values of streamflow, nitrogen load and phosphorus loads for calibration period and validation period respectively.

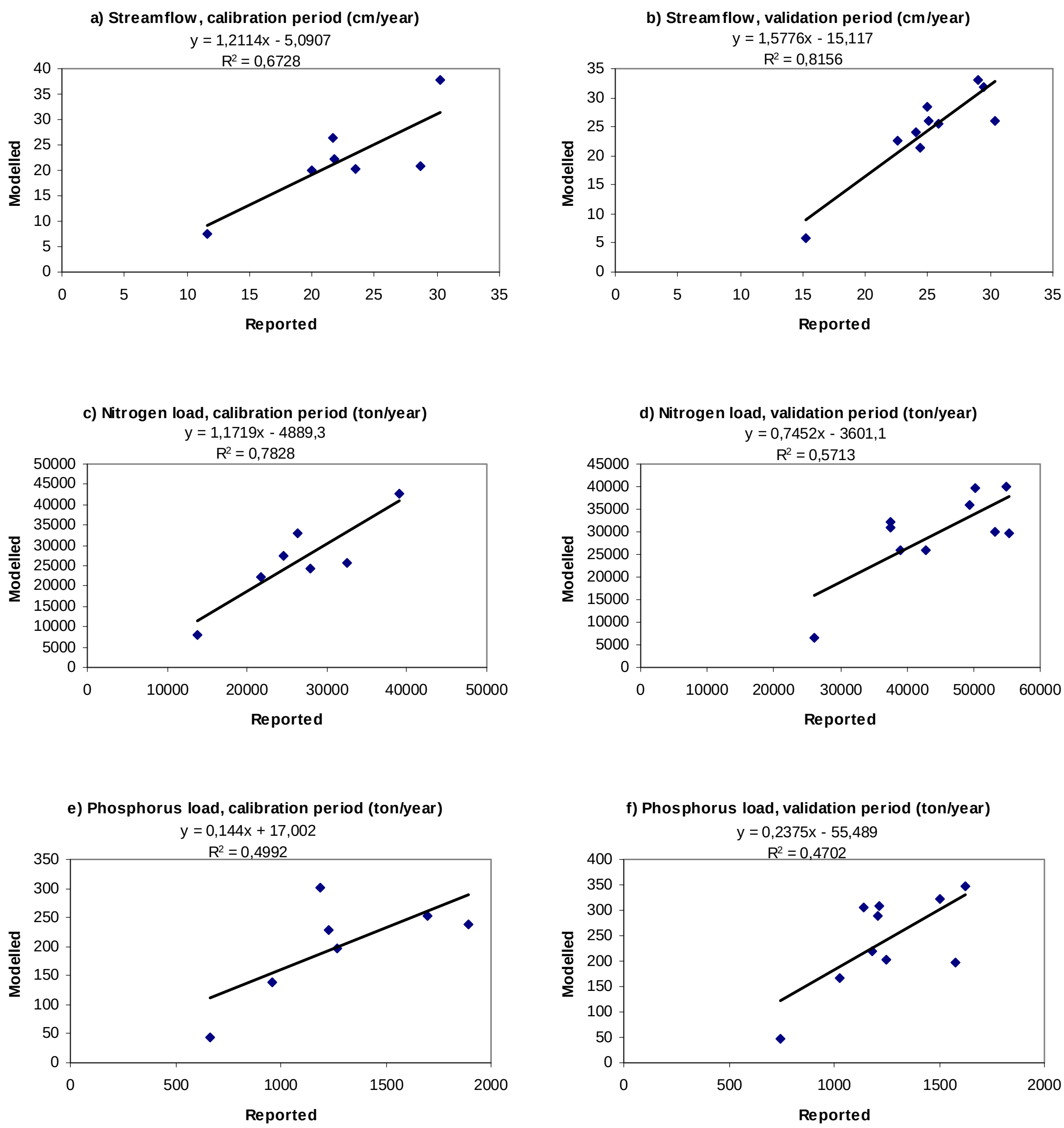

Figure F2. Regressions of yearly reported and modelled values of streamflow, nitrogen load and phosphorus loads for calibration period and validation period respectively.