# NUTRIENT TRANSPORT SCENARIOS IN A CHANGING STOCKHOLM AND MÄLAREN VALLEY REGION

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## ABSTRACT

Norrström catchment, west of Stockholm, covers most of the Mälaren valley. Provision of drinking water from Lake Mälaren is an absolute precondition for continued growth in the region. Stockholm County's population is expected to increase by 600 000 people before 2030. Current climate change predictions anticipate significant temperature and precipitation increases. We implement the PolFlow model embedded in PCRaster for quantifying water and substances fluxes on the catchment scale over a 30-year time horizon. We formulate scenarios for changes in water quality and quantity due to dimate change and population development. Results indicate a mild impact from climate change on surface flow rates but substantial effects on sub-surface residence times. Population development slightly affects nutrients loads. Using source apportionment and sensitivity analysis, we identify a number of critical parameters/processes to be further studied, in order for future results to be more reliable and usable in a water resources management context.

**Keywords: Water basin management, eutrophication, GIS , climate change, population growth**

## INTRODUCTION

### Nutrient pollution and eutrophication in the Baltic Sea region

Today, water quality management within drainage basins and in associated coastal and marine waters is one of the main environmental concerns in the Baltic Sea Region (BSR). The Agenda 21 for the Baltic Sea Region (Baltic 21, 1996) and the Helsinki Commission (HELCOM, Baltic Marine Environment Protection Commission, 2000) support international cooperation in the region. Within the listed Hot Spots in Sweden, reducing nutrient inputs from agriculture remains a major long-term challenge5. The Swedish local Agenda 21 recommends6 that "the measures to reduce discharge and leakage of manure and fertilisers from drainage basins should consist in a reduction of fertilisers use, an improved nitrogen removal in wastewater treatment plants, a better dissemination of urine separation systems and more effective management of manure from the stables and construction of wetlands", with the latter acting as nutrients traps.

### The Norrström basin, Sweden

The Norrström basin (see Figure 1) is, in Sweden, one of the most important in terms of population (over 1.7 millions) and land area (22 000 km$^2$)7. The suburbs of Stockholm and its region of influence have spread to more than 100 km from the city and many industries have settled around the Lake Mälaren. The water quality of the Lake is at stake for the regional supply of fresh water and for water resources management in the drainage basin of the BSR. However, parts of the basin are covered by heavily exploited agricultural areas, which is considered a main reason why eutrophication has remained a serious problem in many inland and coastal Swedish waters8. The central farmed plains of Sweden have today the most eutrophic lakes and streams, namely the Lakes Mälaren and Hjälmaren with a Phosphorus content above 25 µg/l.

### *Objectives*

With regard to the considerable stakes in the region and additional pressures from climate change and population development, the project presented here aimed to: 1) assess qualitative and quantitative impacts from climate change on surface and sub-surface water fluxes and Nitrogen and Phosphorus transport; 2) estimate the potential effects on Nitrogen and Phosphorus emissions and coastal loads, from scenarios picturing development of population and modifications in life style in a 30-year horizon; and 3) identify critical parameters/processes to be further investigated in order to improve knowledge, reliability and relevance of use in a water resources management context.

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5 Hot Spots listed by HELCOM, http://www.helcom.fi/environment/pollution/hotspots.html
6 Agenda 21 in Sweden, http://www.agenda21forum.org/rapporter/slutbetankande/del2.html
7 Hannerz (2002)
8 Eutrophication of soil and water, http://www.environ.se

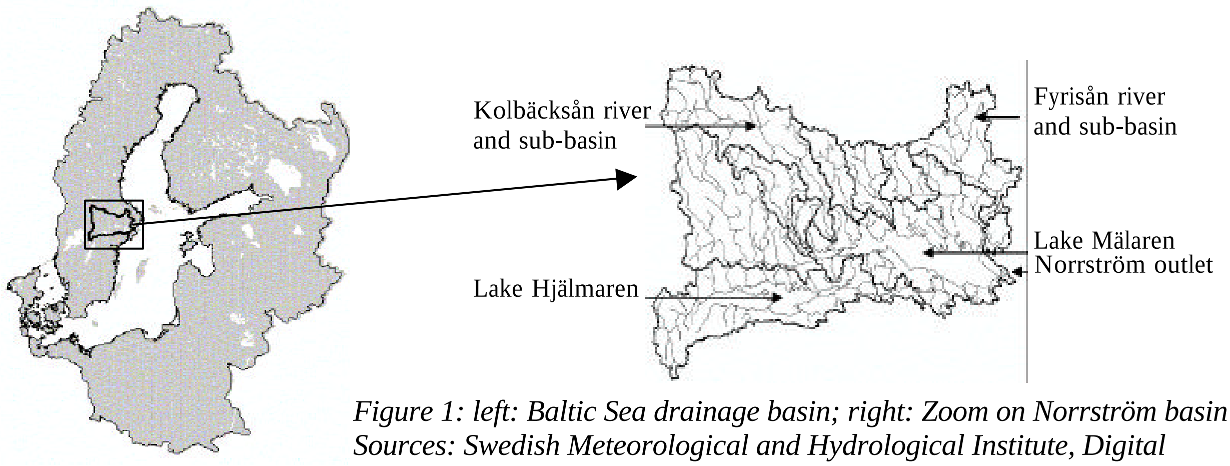

*Figure 1: left: Baltic Sea drainage basin; right: Zoom on Norrström basin*
*Sources: Swedish Meteorological and Hydrological Institute, Digital Chart of the World, Hydro1K dataset*

## METHODS

### Modelling water fluxes and nutrients transport in Norrström basin

GIS-based PolFlow model

The method is based on the PolFlow model (De Wit, 1999). It was first implemented at the Norrström basin by Greffe (2003), who used it to describe water, Nitrogen and Phosphorus discharges in the basin, for the five-year period 1995-1999. The PolFlow model is embedded in PCRaster, a raster-based GIS modelling tool[9]. The water flow module of PolFlow is based on three determinant factors: 1) the long-term average total runoff or precipitation surplus $Q$ (mm.year$^{-1}$): $Q=(P-Ea)$ where $P$ is the long term average precipitation (mm. year$^{-1}$) and $Ea$ is the long term average actual evapo-transpiration (mm.year$^{-1}$) -“long term” always referring to an annual average made over several years (here ten years)-; 2) the groundwater recharge index $Qgw/Q$ where $Qgw$ is the long term average total groundwater recharge (mm.year$^{-1}$); and 3) the groundwater residence time $RTgw$ (year). Nutrients are assumed to follow water flow paths and the results from the water model therefore build the basis for the nutrient transport module of PolFlow. Total Nitrogen and Phosphorus quantities in soils, rocks and water are considered. The nutrient transport model works on a five-year time step. Paths of circulation for nutrients are described and evaluated at the surface of the soil and through the soil and groundwater. Paths can be vertical (upward and downward) as well as horizontal (see Figure 2). Runoff, recharge and residence times are obtained from the water model.

Model validation for the Norrström basin

The modelled water fluxes factors were validated by monthly measurements of river discharge at 25 stations in the Norrström basin, with a high correlation for the discharge term (Figure3a). Deep and total groundwater recharge indexes could not be validated because of poor data availability.

Modelled values were found to be in accordance with De Wit (1999) results for the Elbe and Rhine basins. Residence times in shallow and deep groundwater were in the range 0-5 years and 0-200 years, respectively, with lower times for the western hilly part of the catchment (see Figure 3a, b, c). Modelled Nitrogen and Phosphorus loads compared very well to observed values derived from concentration measurements at 62 monitoring stations (Figure 3d). Test of the robustness in time further reinforced reliance in the model and in the relevance of its use for future studies in Norrström basin.

### Scenarios building

Building scenarios for the future

The current context and state of the environment in the Norrström basin imply that attempts to assess future tendencies and their water quality effects are highly relevant. In our study, scenarios are both qualitative and quantitative impact assessments, which aim at being instructive, rather than reflect the likelihood of underlying assumptions. The scenarios are of the exploratory or descriptive type, referred as “those that begin in the present and explore trends for the future” (Alcamo, 2001).

Climate change scenario

Despite persistent uncertainties about regional responses to global greenhouse warming, the strong interactions within the hydrological cycle of rainfall, runoff and evaporation motivate the need for “improved regional climate models with sufficient spatial resolution […] that can be coupled with hydrologic models for better quantitative prediction of ecosystem effects”, as expressed in the Report of the Second International Conference on Climate and Water[10] (1998). SWECLIM, the Swedish Regional Climate Modelling Programme, focuses on climate change and its consequences in Nordic area, especially Sweden. Transferring results from Global Climate Models, SWECLIM has built future regional climate

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[9] Introduction to PCRaster, http://www.geog.uu.nl/pcraster/tekst.html, Faculty of Geographical Sciences of Utrecht University, Netherlands

[10] Report of the Second International Conference on Climate and Water, http://www.water.hut.fi/wr/caw2/report.html

scenarios[11] that can be used to estimate impact on water fluxes. Climate change was then implemented into the present water flux model through changes in average annual temperature, winter temperature and annual average precipitation, with a 30-year time horizon. Values (see Table 1) were interpolated linearly from SWECLIM prognoses (Mattson, 1998).

***Table 1: Climate change scenario variables***

| Variable for climate change | SWECLIM prognoses | 5-year increase |
|---|---|---|
| Average annual temperature | +2.5 ºC up to 2050 | 0.21 ºC |
| Winter temperature | +0.5 ºC per decade | 0.25 ºC |
| Annual average precipitation | 9% from 1990 | 0.75% |

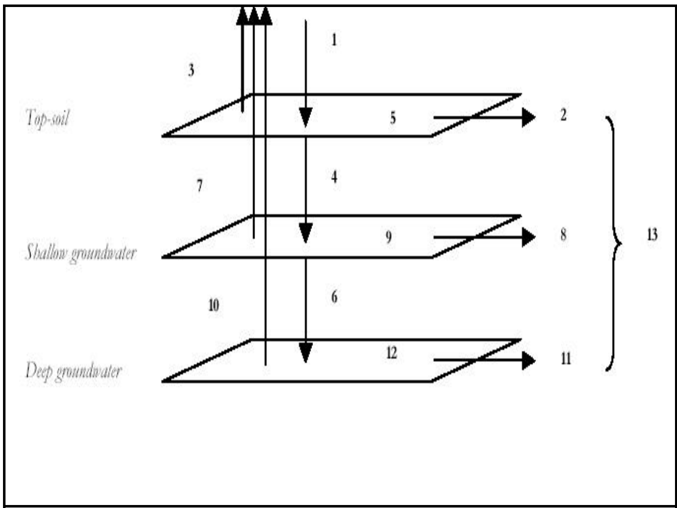

*Figure 2 (a) Underlying principles of the transport model (after De Wit, 2001). (a) Division into three sub-systems.,Numbering refers to the processes involved in the transport of nutrients from soil into surface waters.*
*1. addition of diffuse emissions to the nutrient content of soil, 2. Surface runoff and erosion, 3. denitrification in soil, 4. leaching from suface to shallow groundwater. 5. New nutrient content for the soil input for next time step. 6.leaching from shallow to deep groundwater. 7. denitrification in shallow groundwater, 8.shallow groundwater runoff to surface water, 9. New nutrient content in shallow groundwater, input for next time step, 10.denitrification in deep groundwater, 11.deep groundwater runoff to surface water 12.new nutrient content in deep groundwater, input to next step, 13.total input to surface waters via surface and groundwater runoff*

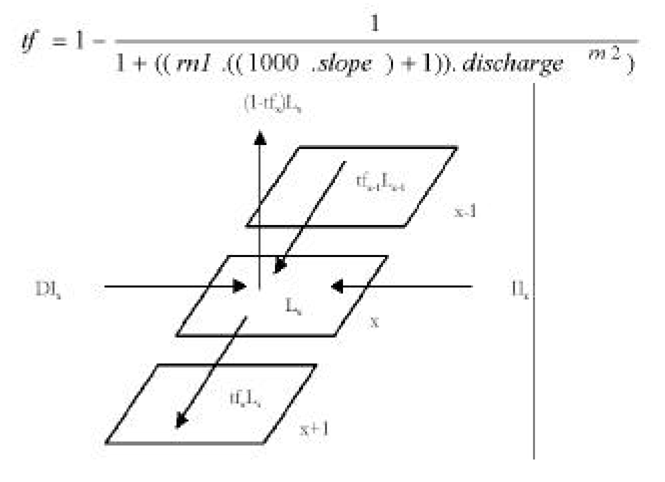

*Figure 2(b) Transport form cell to cell in the river network. Using the local drainage direction to route the nutrients through the river system, each cell is connected to its lowest neighbour, all the way down to the basin outlet (De Wit, 1999) tf is the fraction of nutrients transported from one cell t the next one downstream, (1-tf) is the retention loss and decay in the river. Parameter m1 quantifies the basic loss in a segment of the river network and the dependence of tf on the slope, m2 quantifies the change of the avlue of the transport fraction through the river system, Lx is the nutrient load in the cell, x. Dix stands for the direct emissions and IIx, for the indirect emissions from surface and groundwater runoff.*

### Population and life-style scenarios

The regional socio-economic system, where population growth and economic development are major driving forces, is a further source of pressures to water resources. During the last 30 years, national population has increased by less than 10% whereas population in Stockholm County has increased by more than 23%[12]. Through consumption and pollution, population development affects land-use, food production, fresh water demand, air and water pollution etc. Scenarios for population change were derived here from prognoses on Swedish population development at county level, as reported by the County Council (Landstingsförbundet, 2000). Three population change scenarios and a no-change scenario were modelled with a time horizon of 30 years from year 2000, and a time step of five years. The Trend-scenario continues last years' population tendencies until 2030. The Base-scenario follows national population prognoses from Statistics Sweden and is considered as the most realistic scenario. The Positive-scenario represents required population increase for positive socio-economic development. In addition to population variation, life-style scenarios were modelled, using as parameters the relative parts of urban and rural populations in the basin's municipalities. Two life-style scenarios, plus a no-change-in-life-style baseline, were considered: the urban attraction scenario and the rural attraction scenario. For implementation, climate change was set as a background to all population and life-style scenarios. Per capita indexes were then used to relate changes in population to resulting changes in nutrients emissions (see Table 2).

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[11] SWECLIM Introduction to latest climate scenarios result year 2002, http://www.smhi.se/sweclim
[12] Sttistika Centralbyrån, Statistics Sweden, http://www.scb.se/databaser

**Table 2: Changes in nutrients emissions**

| Nutrients emissions from | Changing mode |
|---|---|
| Waste water treatment plants | Per capita indexes |
| Industries | No change in emissions |
| Agriculture | Proportional to total population change by 2/3 |
| Deposition on lakes | Proportional to total population change by 1/3 |
| Private or absent sewage system | Per capita indexes |
| Urban wash-off | Per capita indexes |
| Clear cuts | Proportional to total population change by 1/3 |

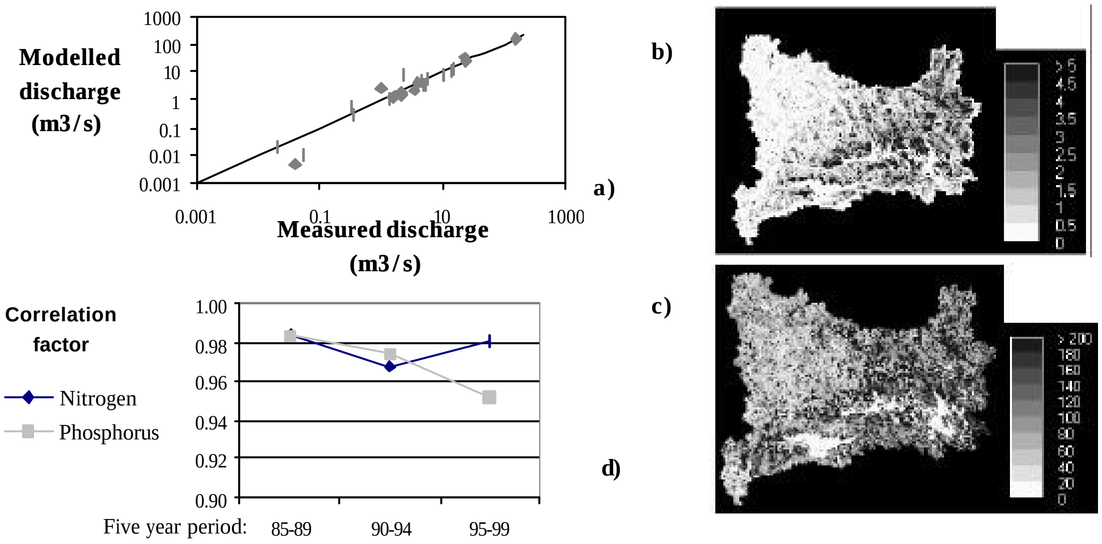

*Figure 3: Validation of the water flux and nutrient transport models, after Greffe (2003)*
*a) Modelled vs. measured annual average discharge ($m^3.s^{-1}$), in logarithmic scale*
*b) Residence time in shallow groundwater (year), over the basin*
*c) Residence time in deep groundwater (year) over the basin*
*d) Correlation factor between modelled and observed Nitrogen and Phosphorus loads, at 62 monitoring stations in the Norrström basin, from 1985 to 1999.*

## SOURCE OF DATA

Table 3 lists all the used model input data for the original model by Greffe (2003) and for its development into the scenario analysis reported here.

**Table 3: Sources of input data (all raster maps were used with a spatial resolution of 1km$^2$)**

| Module | Input data | References |
|---|---|---|
| Water fluxes | Average annual precipitation | Swedish Meteorological and Hydrological Institute (SMHI) |
| | Average annual temperature | SMHI |
| | Hydrogeological data | Geological Survey of Sweden (SGU) |
| | Elevation map | GTOPO30/HYDRO1K, US Geological Survey |
| | Slope | Derived from the elevation map |
| | River network | Digital Chart of the World; SMHI Water Systems in Sweden |
| | Land cover | BALANS data set from the Baltic Drainage Basin Project |
| | Soil map | SGU |
| | Water discharge data | SMHI |
| Nutrient transport | Nutrient point and diffuse emissions | TRK project, Swedish University of Agricultural Sciences (SLU) |
| | Water nutrients concentration data | SLU, Institution for Environmental Analysis |
| Climate change scenario | Prognoses for temperature and precipitation by 2050 | SWECLIM climate research program (Mattson, 1998) |
| Population scenarios | Current population data | Statistics Sweden (SCB) |
| | Population development scenarios | County Council (Landstingsförbundet, 2000) |

## RESULTS AND DISCUSSION

### Results from climate change scenario

The climate change scenario had relatively limited impact on the determinant factors for water fluxes (see Table 4). The annual evapo-transpiration exhibited the most noticeable response with 6% increase. Residence times globally decreased. We differentiated the western from the eastern part of the basin, due to differences in slope and land-use. Climate change hardly affected the final Phosphorus (0.04% increase due to climate change) and Nitrogen (0.05% increase due to climate change) 2030-loads at the outlet of the basin.

***Table 4: Effects from climate change on water fluxes***

| Parameter | Evolution |
|---|---|
| Long term average runoff ($m^3/s$) | + 0.5% West; - 0.2% East |
| Evapo-transpiration (mm/year) | + 6% |
| Total groundwater discharge ($m^3/s$) | + 0.5% West; - 0.2% East |
| Deep ground water discharge ($m^3/s$) | + 0.5% West; + 5% East |
| Shallow groundwater residence time (year) | - 5% |
| Deep groundwater residence time (year) | - 0.5% West; - 5% East |

Shorter residence times imply higher travel velocity of nutrients through the basin, reducing the time shift between pollution emission and discharge into the recipient. Yet the rise of evapo-transpiration with air temperature may counteract the rise in precipitation and produce reduced runoffs and hence smaller impacts on nutrient loads (Frederik, 1997).

### Results from population and life-style development scenarios

Results from population and life-style scenarios are presented in Figure 4, exhibiting only small differences between different scenarios. The positive scenario had the worse nutrient load consequences because it includes population increase in all municipalities within the Norrström basin. The effects from the most probable scenario -the Base scenario- on nutrients' loads range from 2,2% for Phosphorus to less than 5% for Nitrogen. The effects from life-style scenarios are mostly visible in connection with the Positive population scenario. For the Trend and Base scenarios, no major differences appear due to counterbalances between negative and positive population growth municipalities over the basin.

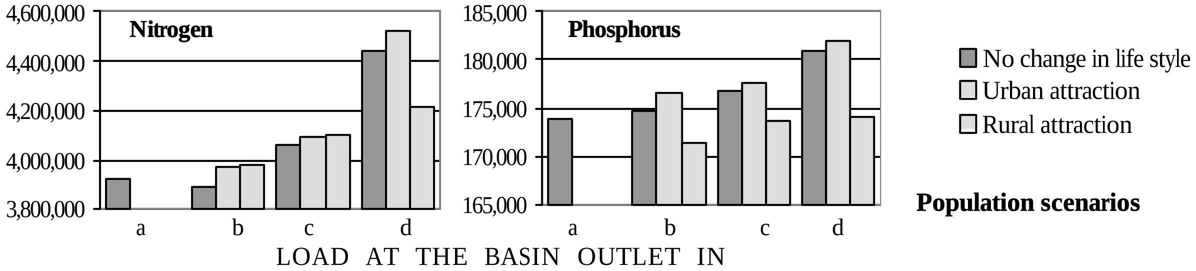

*Figure 4: Population and life-style scenarios' impact on nutrients loads (kg/year). a) No change in population; b) Trend scenario; c) Base scenario; d) Positive scenario*

### Discussion

The population and life-style scenarios consisted in modifying anthropogenic nutrients inputs from the base year (2000). A source apportionment analysis on the contribution to the final inputs to surface water, however, indicated that nutrients loads were mostly governed by the already existing nutrient content in soil and aquifers. This existing content, which we called semi-natural, includes a natural yield and an accumulation from past human activities; the source apportionment was verified for every five-year period from 1945 to 1999; after 2000, we assume constant source apportionment, even though Figure 5a shows a slightly increasing anthropogenic trend for Nitrogen. The major contribution from semi-natural sources might explain the small effects on nutrients loads from population and life-style changes; in particular the response of Phosphorus load to the different scenarios was noticeably low, with semi-natural sources contributing, nearly constantly between 1945 and 1999, to more than 85% of total Phosphorus inputs to surface water. The source apportionment analysis further revealed an increase of the contribution from the total diffuse sources (semi-natural plus anthropogenic inputs) between 1945 and 1999. It appears therefore of primary interest to be able to quantify as correctly as possible surface water, sediment and groundwater accumulation and exchange processes for correct estimation of the important input from the semi-natural background. Figure 5b displays the evolution from 1945 to 1999 of the contribution to inputs to surface water from different sub-systems' flows: surface water, and shallow and deep groundwater runoffs. Surface runoff appears then to dominate nutrients inputs to surface water. For Phosphorus especially, surface runoff (erosion) is also commonly considered the major pathway for the loss of P to river network (De Wit, 1999). An increasing trend for the contribution from shallow groundwater, however, was observed for the Nitrogen transport.

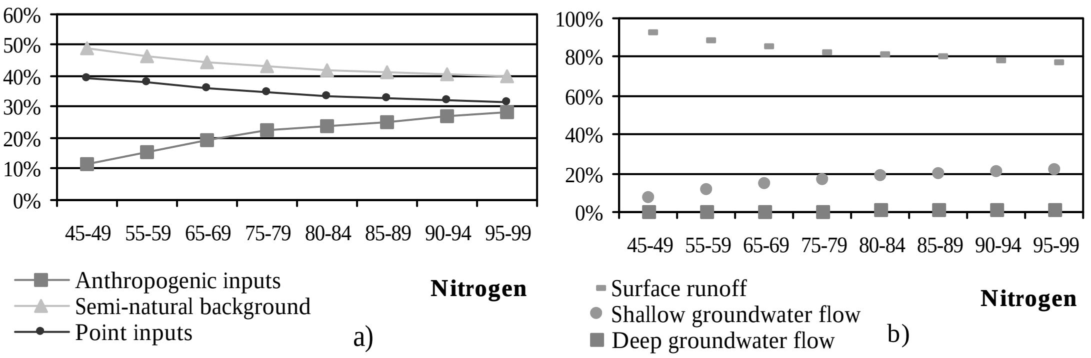

*Figure 5: Source apportionment on the inputs to surface water for Nitrogen between 1945 and 2000 a) between point and diffuse sources -Diffuse sources consist in anthropogenic inputs and inputs from a "semi-natural" background-; b) between different sub-systems' flows - surface, shallow and deep groundwater runoffs.*

*Note: The source apportionment for Phosphorus led to constant results for 1945-2000. Therefore only Nitrogen results are displayed. The apportionment showed that 88% of the total inputs to surface water originate from the semi-natural background (4% from anthropogenic sources and 8% from points sources) and that 99.9% of the total runoff flows from the surface.*

We further carried out a parameter sensitivity analysis to relate these obtained results to the processes and parameters involved in the PolFlow model (Figure 6). Following Rankinen (2002) the sensitivity was assessed via the MAROV Index, which is particularly relevant for classification purposes. The final nutrient loads at the basin outlet were mostly affected by the model's loss/attenuation parameters (*rn1* and *rn2* determining *tf*, the nutrient transport fraction from one cell to the nearest neighbour). In particular, the MAROV index relating *rn1* and the load was >1, which indicates an "over reaction" of the Nitrogen load to the parameter's variations (related to the large spreading of lakes over the basin). In addition, the parameter *sr* determining the effect of surface runoff and erosion also had a major effect on the nutrients loads.

Furthermore, based on a sensitivity analysis, we concluded that both nutrient leaching from the surface to the groundwater and groundwater flows (Table 5), and to a smaller but substantial extent also nutrient load at the outlet (Figure 6), are sensitive to the parameter *pms*, which quantifies the nutrients storage capacity of the soil. The parameter *gr*, which weights the effect of groundwater recharge on the leaching-to-groundwater amount, seemed also essential in quantifying sub-systems' processes and therefore determining with greater accuracy and reliability the inputs from anthropogenic and semi-natural sources.

***Table 5: MAROV Indexes***

| | **Leaching to groundwater** | | **Soil surface runoff** | | **Shallow groundwater flow** | | **Deep groundwater flow** | |
|---|---|---|---|---|---|---|---|---|
| | N | P | N | P | N | P | N | P |
| sr | 0.0073 | 0.0072 | 0.9655 | 0.9655 | 0.0072 | 0.007 | 0.0049 | 0.0049 |
| gr | 1.4203 | 1.4285 | 0.0041 | 0 | 1.4207 | 1.4285 | 1.4237 | 1.4285 |
| pms | 1.478 | 0.999 | 0.006 | 0.006 | 1.48 | 1.48 | 1.488 | 1.488 |

## CONCLUSIONS

We formulated scenarios for changes in water quality and quantity due to climate change and population development in the basin. The main findings were: 1) a substantial impact of climate change on sub-surface residence times, particularly for the eastern part of the basin, close to the Baltic Sea; 2) a relatively mild impact on surface flow rates and nutrients loads, the increase of precipitation being possibly balanced by the considerable increase in evapo-transpiration; 3) a rather small effect on nutrients loads from population development and differences according to life-style changes. These results provide a first assessment and we recognise the considerable uncertainties with regard to nutrient transport extended over the next 30 years, both related to forecasted emissions and process parameters. A source apportionment and sensitivity analysis thus helped us to identify a number of critical parameters/processes. The "semi-natural" nutrient pool, including natural nutrient content and the accumulation from anthropogenic past activities, appeared to be a major diffuse source of nutrients to surface water. The soil storage capacity, the effect of surface runoff and erosion, as well as the effect of groundwater recharge to the leaching process were found to be critical factors for understanding and improving knowledge, reliability of the results and relevance of use in a water resources management context.

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