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Modelling of hydrological and hydrochemical variability under environmental change impact

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ABSTRACT

Climate change inducing significant variations in the seasonal dynamics of the water cycle and hydrological extremes and land use change as one of the anthropogenic effects are among the major driving forces of global environmental change. Large and meso-scale river basins represent an appropriate unit to study global change impacts on water quality and quantity at the regional scale and to estimate water, material, and biogeochemical budgets. The Elbe river basin is used as test region for the application of the Nested Watershed Approach based on the Two-Domains-Modelling-Concept to test, modify, and validate models, parametrization schemes, and up- and downscaling techniques. In order to achieve the objectives of the project a Hydrological Modular Simulation System for catchment basin studies is developed, based on a Geographical Information System (GIS) and the Modular Modelling System (MMS). Within this system a number of hydrological and hydrochemical simulation models and model components are tested and modified with special attention to regional approaches for the analysis and modelling of hydrological, biogeochemical, and hydrochemical processes.

INTRODUCTION

Processes of the hydrological cycle (runoff, evapotranspiration, infiltration, etc.) depend strongly on climate characteristics, their seasonal variation, and long-term changes. Climate change may lead to significant variations in seasonal dynamics and spatial distribution of water resources, resulting in water scarcity or oversupply and surface water deterioration. On the other hand, it is well established that land use changes are among the major driving forces of global environmental change. Changes in land use influence evapotranspiration and mineralization of soil organic matter and river runoff, which have clear feedback effect on the climate.

Watersheds are important as integrators of many forces, including climate. Still knowledge about the dynamics of dominant processes in watersheds is rather limited. Large and meso-scale river basins with their natural boundaries and hierarchical structure represent an appropriate unit for the study of climate change impact at the regional scale. Our approach is to develop a modelling system for analysis and modelling of climate change impact on hydrology and water quality for meso-scale river basins. The German part of the Elbe river and some of its tributaries have been chosen for case studies.

Previous efforts in watershed modelling were concentrated mainly on developing either continuous-time spatially lumped models or single event spatially distributed models. The availability of GIS tools and more powerful computing facilities make it possible to develop distributed continuous time models, based on available regional information.

Our recent and previous research on water quality affected by nonpoint source pollution (NPS) has been focused either on agriculture nutrient (N,P) pollution causing eutrophication problems, or areas exposed to acid rain (Krysanova et al, 1989; Müller et al., 1993). Consideration of potential climate impacts is a new challenge for research on changes of fresh water supply.

Objectives of the Study

The project is focused on investigations of hydrological and hydrochemical processes and structures in catchments that are parts either of semi-natural not intensively used ecosystems or are embedded in forestry and agriculture landscapes. The project includes four main closely interlinked tasks:

(1) Analysis and modelling of hydrological processes, and their interaction with other processes (ecological, meteorological, etc.) at different scales,
(2) Analysis and modelling of biogeochemical and hydrochemical processes, determining fresh water quality,
(3) Development and test of up- and downscaling methods in the context of a nested multiscale watershed approach,
(4) Providing of tools for coupling the terrestrial water cycle with atmospheric circulation processes, taking into account existing feedback mechanisms,
(5) Development of a Hydrological Modular Simulation System HYDROSIM) (Fig.1) for regional and catchment basin studies of climate change impact.

DESCRIPTION OF THE STUDY AREA

Regions and Scales of Application

Protection of water resources requires international efforts, since usually rivers are not limited to any administrative boundaries. In the frame of the Global Energy and Water Cycle Experiment (GEWEX) the region of the BALTIC SEA with the drainage basins of all inflowing rivers, as well as the Elbe and Weser river basin, have been selected as the primary study area in Europe. This study is called BALTIC SEA EXPERIMENT (BALTEX). A mesoscale atmospheric model is intended to be developed for the BALTEX model area at the Max-Planck-Institute of Hydrology in Hamburg, using a regular grid of 15 to 20 km mesh size. This model will be run in a semi-coupled manner with the Hamburg General Circulation Model (GCM) ECHAM to provide information on present and potential future climate scenarios at a regional scale. The output of the model shall be used as input to the model of the Elbe river as part of the BALTEX study area.

The second international programme the project is closely related to is the International Geosphere-Biosphere Programme, especially its core project "Biospheric Aspects of the Hydrological Cycle (BAHC)".

Early facing of problems affecting river systems led to the establishment of a number of international commissions. One of them is most important for our case study: The International Commission for the Protection of the Elbe / Labe river.

Furthermore, the project is related to the research priority programme of the Deutsche Forschungsgemeinschaft (DFG) on "Regionalization in Hydrology". Collaboration with this programme concerns a number of aspects including GIS tools and data exchange.

Within the Elbe river basin smaller subbasins are selected for finer scale studies. One such subbasin is the Stör river basin north of Hamburg, for which the Ecosystem Research Center of the Kiel University has provided the data required for modelling. It is also planned to collaborate with ZALF, Müncheberg in the North-East Study Area, which covers the north-eastern part of the Elbe river basin, i.e. the upper Havel basin.

The Elbe river drainage basin and environmental problems

The Elbe River is one of the longest rivers in Europe (1092 km), with a drainage basin of 148268 km^2 and 24,9 million inhabitants. About 2/3 of the drainage basin belong to Germany and 1/3 to the Czech Republic. Since large parts of the river systems are located in regions of not more than 1500 m elevation, the river discharge is characterized by winter and spring high water periods. The upper, mainly Czech part of the river is dominated by weirs and dams, whereas the middle part can be considered as a semi-natural river system. Its final 142 km are effected by tide processes. Potential erosion increases downstream in glacially formed landscapes of the north German lowland. The combination of these natural factors with river management actions caused a depletion of low level water tables in the lower parts of the river during the last decades (Simon, 1993).

Compared to the discharge behaviour of the Rhine valley it is obvious, that in the Elbe natural upstream buffer storages of glacial snow packages against both flood discharge and low flow are missing due to the lack of high mountain regions. Thus the span between monthly low flow and high flow in the Elbe is 1:21 as compared to 1:1,75 in the Rhine valley.

Agriculture areas that cover about 56 % of the total area of the drainage basin represent one of the most important sources of pollution (Simon, 1993). The Elbe and its tributaries are intensively used for fresh water supply (drinking water, irrigation and industrial process water).

Due to ineffective sewage water treatment from municipal and industrial sources, and lack of nonpoint source pollution control (especially in the Eastern part of Germany and the Czech Republic), fresh water supply is severely limited and requires extensive waste water treatment. Dominant pollutants are heavy metals, nutrients, chlorinated hydrocarbons, and other organic pollutants.

Though efforts to reduce pollutant loadings to the Elbe river during the last four years have been quite successful, the Elbe is still one of the most heavily contaminated water courses in Europe (Mobs, 1993; Reincke, 1993). On the other hand, the river system and its riparian areas include unique biotopes for various plant and animal species that are threatened of extinction. Many large Czech and German nature preserves belong to the Elbe drainage area. The UNESCO-biosphere preserve "Middle Elbe" has been established to protect one of the largest continuous alluvial forests in Central Europe.

Hydrological temporal variability and spatial changes

What are expected changes in hydrological characteristics in time and space for the Elbe basin? First of all, it is clear that critical situations can be caused by the increasing probabilities of floods and drought, and increase of water demand in a warmer climate. Climate change may influence hydrological extremes, affecting all their parameters - intensity, magnitude, frequency. For example, increased winter precipitation can cause winter floods, whereas increased evapotranspiration in summer can cause soil moisture deficits and negative consequences for agroecosystems.

Changes of air and soil temperature may lead to changes in both snow cover, evapotranspiration (ET), atmospheric circulation, and sea water levels. The direction of some of the consequences can not be estimated: e.g. an increase of ET may lead to an increase of cloudiness, subsequently causing an ET reduction. In addition, not all the quantitative aspects of the effects are yet known.

One should be aware of the possibilities that the spatial and temporal patterns of precipitation events may change, rather than just the mean values, and that stable periods of either heavy rain fall or drought may increase, leading to a rise of seasonal extremes of water availability. Further more, runoff amounts may stay on the same level as a result of a combined increase in precipitation and evapotranspiration.

Significant hydrological vulnerability in the Elbe region, especially in its north-eastern part, is due to intensive water use all along the river and comparatively low yearly amounts of precipitation (between 450 - 500 mm/yr.), causing severe problems both to agriculture (irrigation) and for stability of drinking water supply. These problems are particularly severe around Berlin (about 4 Mio. inhabitants) since this area is heavily depending on fresh water supply from Elbe tributaries. It has been stated several times, that the water table in the region of Havel and Spree may not fall below a certain threshold to insure about 60 % of the water supply as well as energy production for more than 4 Mio. people in and around the metropolis.

In addition, the area has been effected by open cut mining during the last decades leading to 3300 km2 of groundwater depletion. During the last 3 years mining activity has been reduced causing that less ground water from deep aquifers has been spilled into the water courses. It has been estimated, that groundwater deficits in this region amounts to about 13 billion m^3.

The period from 1989 to 1992 has been the second driest in this century (Simon, 1993) with respect to mean values of yearly discharge during the century, and 1991 is on the fourth place of dry single years in the Elbe during the last 90 years. During those years runoff was about 60 % of the mean yearly values at most of the international gauge stations. In spring 1994 the north eastern parts of Germany suffered from an extensive rainfall period leading to flooding events in various parts of the Elbe basin lowland, which caused huge damages to agriculture and housing. Assessment of this latest events may include satellite pictures taken by the environmental mission shuttle "Endeavor".

In addition to meteorological fluctuations leading to river runoff change, changes in land use and agriculture practices are of great importance for water quality. The nitrate load of the Elbe steadily increased during the period 1970 to 1990. Reduction of agricultural land use - after the German unification - caused by economic restrictions and restructuration in the former German Democratic Republic was primarily focused on the less productive soils. While the oxygen concentration in the Elbe has increased, inorganic nitrogen increased as well, due to the time delay between nitrogen application and release from soils to tributaries (Meissner and Rupp, 1993).

METHODOLOGY

Nested multiscale watershed approach

River networks represent a useful organizing concept in subdividing land surfaces into subunits, i.e. drainage basins of tributaries, where all water flows are integrated over the entire basin area. This is the key of the watershed approach, which can be applied in a nested way and used to test available models and parametrization schemes at different scales, as well as up- and down-scaling techniques for landscapes differing in their degree of heterogeneity.

The nested watershed approach takes into account the natural integrating behaviour of river basins for all surface and sub-surface water flows and related waterborne transports (sediments, nutrients, heavy metals, etc.). This approach will allow to test, modify, and validate hydrological models for land surface processes at different scales, for areas where data availability is clearly differing. It is especially important for nonpoint pollution modelling, as data availability for hydrochemical processes modelling is usually very scarce, and extrapolation from small representative sub-watersheds to the whole drainage basin is the only possibility to overcome these difficulties. This would allow to estimate water, material and biogeochemical budgets for watersheds of any size, where water and constituent discharge is measured at the closing river cross-section. These budgets can be used for basin related tests of the applied hydrological and hydrochemical models.

It is intended to model in sequence several subbasins of different size in the Elbe river basin with scale specific or scale-adapted hydrological models, starting from very small study areas, where detailed information on important processes and controlling geocharacteristics is available (catchment areas of a few km2) to ever larger watersheds, e.g.

- upper Stör and its tributaries,
- Spree and some of its tributaries,
- Elbe river basin downstream of Dresden,
- whole Elbe basin, including the Czech part.

Linkages to General Circulation Models and to regional atmospheric models will be provided.

Two domains modelling concept

The Nested Watershed Approach includes the application of the Two-Domains-Modelling-Concept (introduced by Becker and Nemec in 1987), which allows to decouple and model separately the "vertical fluxes domain" (all vertical water, energy, and other fluxes at the land surface - atmosphere interface) and the "lateral flows domain" (all lateral water flows and chemical matter transports across a reference area, e.g. a river drainage basin). This concept allows to apply different space resolutions and spatial discretization schemes in both domains and to directly couple the vertical fluxes domain model with atmospheric models. This means, while a high resolution scheme may be appropriate in modelling the vertical fluxes domain to assess land surface heterogeneity, much larger areal resolutions can be applied for modelling the lateral flows in river basins. In this context a major research subject will be to identify those hydrological model components (modules) and spatial discretization schemes which are best suited for regional impact studies.

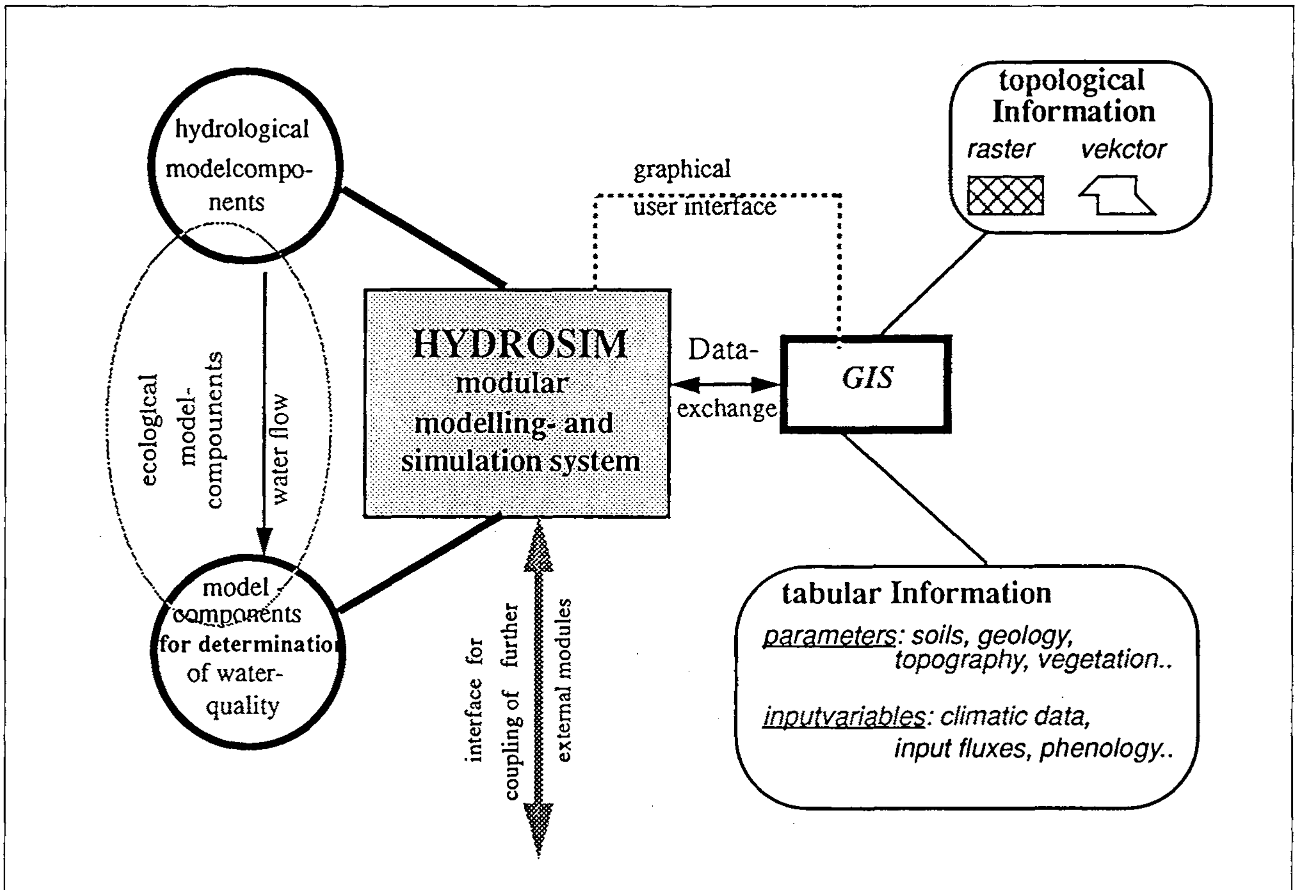
Downscaling from GCM

A classical scale of hydrological analysis refers to a moderately steep and homogeneous catchment in a certain climate. Downscaling from GCM models which is necessary to make use of GCMs for hydrological study, is a very serious computational problem, as the resolution of GCM models is too crude. Nevertheless, it is possible to couple them with hydrological models to use the output from GCM model as the input to watershed model. Some methods are being developed for this purpose.

In this context, the coupling of atmospheric and improved land-surface hydrological models is receiving increasing attention. Especially on the mesoscale level remarkable progress is expected from the coupling of atmospheric models with complex hydrological models for river basins. To contribute to this development is an important aim of our work.

Upscaling for estimation of NPS pollution

Nonpoint source pollution (NPS) is the most difficult problem in the water quality studies for large areas. Basing on our previous experience, we suggest to solve it through upscaling: physically-based balance simulation models at the micro-scale can give a possibility to assess Unit Area Loads (UAL) as dependent from a num-



ber of relevant driving parameters, like hydrological regime, soil structure, and agriculture practices. This can give a possibility to apply the UAL estimations at a higher watershed scale. In that sense, a regional approach provides an interface between the global scale with systems oriented goals and micro-scale with disciplinary oriented goals.

Models and Tools

In order to achieve the objectives of the project powerful tools and software systems are needed. The Geographical Information systems ARC/INFO and GRASS are widely used for spatial data processing, preparation of input data, analysis and graphical presentation of spatially distributed data (soil types, land use, vegetation cover, ground water level, etc.). In our study we intend to combine the existing tools and new submodels with the Modular Modelling System (MMS, Restrepo, 1993). For this purpose a number of hydrological and hydrochemical simulation models are tested and modified with special attention to regional approaches:

Hydrological Models

•Semi-distributed conceptual hydrological model EGMO ("Einzugsgebietsmodell - catchment modelling system" , Becker and Pfützner 1987)
•Distributed hydrological model MIKE - SHE ("System Hydrologique European", Danish Hydraulic Institute, 1993)
•Topography-based model "TOPMODEL" (Beven and Kirkby 1979)

Hydrochemical Models:

- Nonpoint source pollution model for field scale OPUS (Smith, 1993)
- Water quality model for agricultural mesoscale watersheds MATSALU (Krysanova et al., 1989; Krysanova, Luik, 1989)
- Integrated hydrology-water-quality models SWRRB (Arnold et al. 1990) and SWAT (Srinivasan and Arnold 1993)

These models and model components (resulting from our own research or received from other research groups) are tested and modified to choose the appropriate modules to be incorporated into comprehensive modelling systems for regions or river basins. In a first phase, only the hydrological and hydrochemical processes are studied. Later on, ecological submodels and socio-economic submodels (representing driving forces of land and water resources use change) will be developed and included into the simulation systems. On a long term basis, the development of a comprehensive simulation system is envisaged, which can be used for different impact studies in any region with different data availability.

CONCLUSIONS

The area of the German part of the Elbe drainage basin has been affected by both changes in discharge and hydrochemical loads during the last years, and nested watershed modelling can be useful for the prediction of hydrological variability and changes in hydrochemical flows. The development of a nested watershed modelling approach and a comprehensive simulation system for meso-scale watersheds can be useful for different regional impact studies, which are most appropriate for decision makers, as

- such a modelling system can help to bridge the gap between the large and small scale modelling,
- coupling GCMs with hydrological models can improve GCM predictions at the regional scale,
- focus on critical situations may improve estimation of probabilities of extreme hydrological events under global environmental change,
- the nested watershed approach could be the only possibility to evaluate water quality, namely nutrient and pollutant flows with surface and subsurface runoff.

An improvement in the description and modelling of the global environmental change may not be limited to climate change but has to take into consideration various anthropogenic effects, particularly in densely populated regions like Central Europe.

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