THE IMPACT OF GLOBAL CHANGE DYNAMICS ON THE WATER AND MATTER CYCLE ON A REGIONAL SCALE - A MODELLING CONCEPT

by G. H. Schmitz and F. Lennartz

Institute of Hydrology and Meteorology, Dresden University of Technology, Germany

Abstract

Political decisions concerning the environment on a regional scale have to consider the potentialities of a "global change" which incorporates climatic change as well as changes in landuse, socio-economical factors, industrial structure and/or migration processes. This task requires a decision support system (DSS) which allows to quantify the dynamic impact of global change on the water/matter cycle and ecosystem as strongly interdependent phenomena. In order to account for a change of the hydrological system itself and to permit applications to other regions with similar hydrological characteristics the proposed research concept employs physically based models with physical, chemical or biological parameters. The exploitation of any relevant (also qualitative) information, an objective parameter identification as well as the development of new upscaling techniques are additional focus points. The organisational structure of the proposed model system is formed by several layers. 1. The natural input layer, 2. The geo- hydrological kernel, 3. The water quality layer, 4. The water management layer, 5. The socio-economical layer. Each model layer represents an interdisciplinary working group and consists of various submodules describing strongly interconnected processes between related disciplines. The different layers as well as the submodules within one layer are interconnected by a dynamic coupling technique which provides exchange of information between the model components at process-adequate, floating time intervals. The coupling still includes any significant feedback between interconnected processes by an iterative procedure.

General

Quantifying the impact of global change on the water/matter cycle with all the interactions and consequences to the natural, economic and social environment necessitates multidisciplinary new modelling techniques. The envisaged study domain is the pre-mountainous upper catchment of the Elbe River which covers an area of about 75000km². In this area a very pronounced 'global change' in the form of dramatic sociological, economical and landuse changes has taken place over the last 10 years which makes the area ideally suited for such investigations.

Research Strategy

A nested approach is proposed for providing the possibility of evaluating the upscaling technique and of testing the integrated model as well as the interaction between model components at different scales. The "small scale" refers to the upper catchment of the Mulde (an Elbe tributary, ~600km²) and, the second step, after upscaling, covers the whole catchment (~ 6000 km²). The third step finally leads to the above defined overall study area of about 75000km². A decentralised meta-databank accounts for adequate handling of the data together with facilitating the preprocessing of the output data of the various submodules of the system.

Contrary to common approaches, the climatic aspect of a global change not only requires characterising the long term behaviour of hydrologic processes by their mean values but also by their variance (extreme events) because in many cases, changes in the variance affect the biospheric part of the water and matter cycle much more than a change in the mean values only. In this context the variance has a basic significance for defining regional aspects of a global change. This is addressed by a dynamic time and space discretisation within the model system for including typical extreme events of relatively short periods and limited spatial extent. Characterising the long term behaviour of hydrologic systems by introducing a stochastic term to deterministic process descriptions by perturbation analysis is envisaged. Modelling global change includes a change of the system itself which determines the methodology which, for potential applications to similar regions, aims towards a rather general problem description: Instead of relying on the classical empirical/conceptual models with model parameters from historic time series, we focus on physically based models using process parameters with physical, chemical or biological significance whenever required. The possibility of benefiting also from qualitative information as well as an objective parameter identification are additional focus points.

Outline of Research Strategy and Methods

The organisational structure of the model system (Fig. 1) is formed by several layers. Each layer represents an interdisciplinary working group and consists of various submodules describing the strongly interconnected processes between related disciplines. The layers as well as the submodules within one layer are interconnected by a dynamic coupling technique which provides exchange of information between the model components at process-adequate floating time intervals. The coupling cares for significant feedback (interconnected processes) between different submodules and/or model layers by an iterative procedure.

Figure 1

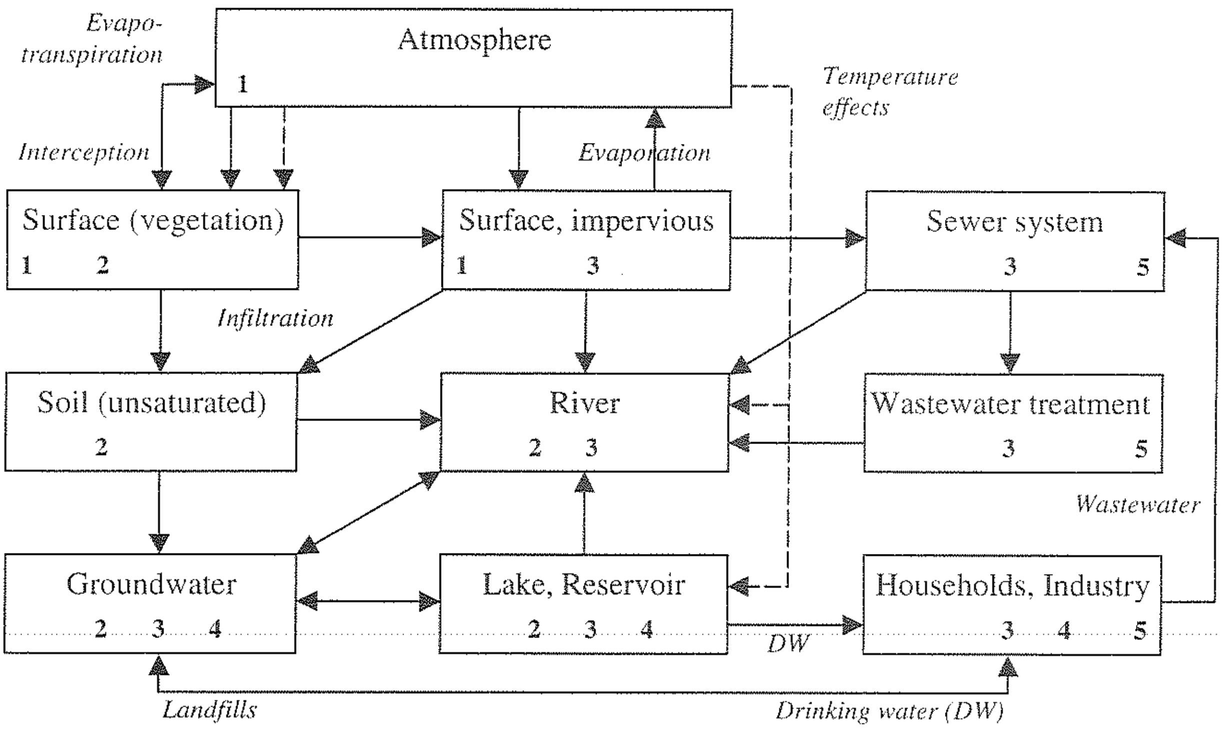

Figure 1 Flow chart of water and crucial temperature influence (---). The numbers in the boxes refer to the layers introduced in the text, i.e. 1) natural input layer, 2) geo-hydrological kernel, 3) water quality layer, 4) water management layer, 5) socio-economic layer.

1 NATURAL INPUT LAYER

1.1 Atmosphere

The atmospheric part of the hydrological cycle controls the water input to the terrestrial part of the cycle and links it to the other components of the climate system. It is coupled via physical and biological feedback, both in the short term (diurnal and annual cycles) as in the long term (changes in land use and global circulation patterns). Society triggers global change through social and economical developments and is in turn affected by global change.

Climate Scenarios and Atmospheric Input: Progress in applying Global Circulation Models (GCM), allows to derive space and time characteristics of climate variables under global change conditions. In co-operation with climate research centres and meteorological institutions, climate forecasts (e.g. current and doubled CO_2 concentrations) will provide precipitation and radiation patterns in adequate space (10x10 km²) and time (hourly) resolution. Statistical techniques are applied for down-scaling of atmospheric variables.

Precipitation and Surface Fluxes- Model Input, Validation and Downscaling: The variability in precipitation patterns and in surface energy exchange (temporal and spatial) for current CO_2 concentrations will be derived using long-term meteorological remotely sensed data. The inferred patterns will be used as input data for the 'geo-hydrological kernel' for limited episodes (months) to explain discrepancies emerging from global climate model results. In co-operation with the GPCC (Global Precipitation Climatology Center) and the WMO ISCCP (Satellite Cloud Climatology Project) a data base will cover the complete watershed.

1.2 Landuse and Landcover

This data complex will be provided by a raster database in accordance with the requirements of hydrologic modelling. Whilst landuse as a functional attribute is mainly affected by the socio-economic and political environment as well as by long-term variations of the physical environment, landcover also partly reacts on seasonal and local medium-range weather conditions (e.g. agricultural land). An efficient data compilation concept integrates existing landuse information from state-, federal- and European Union- databases and updates from satellite imagery in multi-annual cycles together with model based information to account for the high frequency variations of landcover and, to a certain extent, also of landuse. Combining remote sensing and ground truth provides spatial and temporal data on radiation, turbulent fluxes (like evapotranspiration), precipitation, landuse and landcover that feeds into the 'geo-hydrological kernel' and serves as a validation for current atmospheric conditions and current landuse at a high spatial resolution e.g., some km^2 (Bernhofer et al., 1998).

2 GEO-HYDROLOGICAL KERNEL

The processes driving the regional water cycle guide the setup of this inner model layer. They are described the hydrologic phenomena on a physical basis within their geographical and geomorphologic context. The geohydrological 'kernel model' is built by submodules for interception, evapotranspiration, surface runoff and interflow, infiltration, water in the unsatu- rated zone, groundwater and open channel flow with direct link to the water quantity module.

2.1 Soil

In order to answer the question 'which amount of precipitation contributes either to runoff, evapotranspiration, or recharge?' the classic physically based modelling for water transport in the vadose using the Richards equation does not seem to be adequate for the considered scale. Instead of applying the governing laws (Darcy and mass conservation) as idealised balances solely at one point in the porous media, we apply these laws to finite domains adapted to the layer structure of the soil. Thus, our recently developed method of 'finite compartments', which satisfies the Richards equation in an integral form, still includes the soil specific behaviour of preferential flow and characterises our strategy of vertical upscaling (Schmitz et al., 1999). For upscaling with respect to the area, we apply a newly developed theory of similarity of the hydraulic soil characteristics, also allowing the inclusion of qualitative data by using an expert system within hydraulically similar soil layers (Lennartz et al.,1999) Such data is obtained from soil classification maps, topographical maps and remote sensing data.

2.2 Vegetation

Changes in water availability affect vegetation and biosphere. In turn, the biosphere influences the hydrological cycle. Our strategy accounts for interactions of energy, water and vegetation.

Interaction vegetation-atmosphere: The tool for the simulation of vegetation-atmosphere feedback is based on the vegetation coupled planetary boundary layer model HIRVAC (High Resolution Vegetation Atmosphere Coupler; Frühauf et. al., 1997) which covers important landuse effects like radiation exchange, transpiration, interception, carbon sequestration and deposition. The model includes a photosynthesis module that allows to study carbon-water feedback effects. Due to its physical basis HIRVAC can serve as a submodule for evapo-transpiration in atmospherically coupled 3D-models also under "global change conditions".

Interaction climate-vegetation (biodiversity, landuse, landcover): Water availability has a major impact on the competitive status of co-existing tree species and thus on species composition and biodiversity. In this context, the probability of occurrence, magnitude and duration of extremes like floods and droughts are of special importance. Additionally, a rising CO_2 concentration in the atmosphere will influence assimilation with possible feedback on evapotranspiration. In order to incorporate these effects and to link the driving abiotic factors and biological reactions, plant physiological models (e.g. FOREST-BGC) will be applied. Ecophysiological studies on leaf and tree level yield the necessary parameters. The results will be trends for forest species composition and assimilation in a changing climate.

2.3 Surface Runoff

This process is described in both urban and catchment hydrology submodules by a hydrodynamic analytic model (Schmitz et al., 1999). According to the process characteristics (low Froude numbers) it is modelled as a sheet flow and based on the solution of the hydrodynamic equations with zero-inertia (St. Venant equations - neglecting the inertia terms).

2.4 Groundwater

Measurements (natural tracers) show that groundwater accounts for a significantly higher part of the event flow as generally assumed in commonly used rainfall- runoff models. This indicates that the natural processes are not described adequately enough to reflect reality. In mountainous regions, a description of groundwater flow through carstic or fissured rock aquifer systems and its parameterisation at catchment scale seems to impossible. Nevertheless, dealing with global change effects on a regional scale, the source areas, transit times and flow paths of groundwater and matter flow need to be determined, which will be performed by a physically based geohydraulic approach built using geohydraulic similarity data from a classification of the hydraulic property of geologic units more than 140 mountainous watersheds with an area of more than 40.000 km² which allows for an objective parameter identification for the various geological units (Schwarze et al., 1997). This has already been successfully tested in the experimental sites in the larger surroundings of Dresden. Furthermore, the methodology employs watershed and streamflow hydrograph analyses as well as hydrological isotope analyses together with a recently developed, closed form analytical solution of the 2D Laplace equation (Schmitz et al., 1999). The latter describes saturated hillslope flow and thus will be used for the geohydraulic process description as well as for modelling the hydraulic interdependency between river and aquifer. The description of groundwater flow in alluvial aquifer systems uses a hybrid approach distinguishing between sensitive and non sensitive regions. Sensitive regions are characterized by strong transient changes in groundwater flow and matter transport, as e.g. in the vicinity of landfills, production wells and urban areas. Transport in these regions will be calculated using MODFLOW and a problem oriented time/space discretisation. Non-sensitive regions with more steady flow conditions will be described by the Bousinessq equation allowing for a larger grid spacing. Both submodules are coupled by a flexible iterative procedure.

2.5 River Flow

Erosion, transport and deposition of solid particles in rivers and reservoirs have an important influence on aquatic life, water quality, environment and, ultimately, on the entire ecosystem. Human activities exert a profound impact on these processes. Sediment particles have become an increasing concern as carriers and storage agents of nitrogen, phosphorus, heavy metals, organic compounds and other substances. Our model system incorporates hydrodynamics, sediment transport (suspended and bed load) in combination with water quality (see 3.2).

3 WATER QUALITY LAYER

The 'water quality layer' is directly connected to the geohydrological 'kernel model'. It comprises the water and matter transport to and from sewage treatment plants and considers the load on water quality resulting from industrial water pollution, discharge of cooling water, pharmaceutical waste, outflow from waste disposal and other contaminated sites and includes the most nefarious diffusive impact on water quality from agriculture. Besides the investigation of the origins of pollution and its course through the terrestrial water cycle which will be supported by adequate measurement strategies (hydrochemical and ecotoxicological), the evaluation of the ecological impact of pollution will also be carried out in this model layer. Because water quality is controlled by external and internal factors and their transformation in the aquatic ecosystem, identification of these transformation processes is a must for predicting water quality. This (quality) layer is closely interconnected with the water management layer.

3.1 Urban Water Systems

Urban water systems are not evenly distributed over a catchment and must thus be treated as point sinks/sources. They turn over a significant percentage of the water cycle and contribute to a major part to the pollutant load (nutrients, heavy metals). The impact of change in rainfall characteristics and change in water consumption will be investigated,. The results are water and compound fluxes via sewer overflows and wastewater treatment plant effluents to the river system. This requires a model that integrates water supply management and quality processes in the distribution system, urban hydrology, hydraulics and transport processes of particulate and dissolved matter in the sewer system (Krebs et al., 1999), and the degradation processes in wastewater treatment plants. Acute effects in the receiving waters are analysed by extreme value statistics whilst accumulative effects are described by long term simulations. Scenario analysis will include alternative system approaches and operation strategies.

3.2 Water quality development in the surface water system

The description of water quality in running waters employs a water quality model (Müller et al., 1997) developed by the German Federal Institute of Hydrology (BfG). It includes various modules for simulating physical, chemical and biological processes, e.g. zooplankton, carbon dioxide concentration, planktonic algae groups; green algae and diatoms; oxygen production and demand by benthic algae and macrophytes; chemical and biological oxygen demand; nitrification process including ammonium and nitrate concentration etc.

Reservoirs, are another important part of the surface water system which contributes significantly to river flow and quality. Water quality development in the reservoirs is fundamentally different from the rivers. The model SALMO (Benndorf et al., 1985), approved in multiple applications, is used to incorporate this important aspect into the model system. SALMO is oriented to deep stratified waters (reservoirs) and also enables investigation of the impact of higher trophic levels (zooplankton, fish) on water quality.

3.3 Effect monitoring of water quality

Combining chemical and physical data with effect-related biological and ecotoxicological data (effect-monitoring) shall allow for a regionalisation of model parameters. For developing a more ecology-oriented approach of water quality monitoring Compounds are selected on ecotoxicological requirements and indicator-compounds and changes of water quality are to be determined as a consequence of the socio-economic development. We aim to develop a methodology allowing the use-related evaluation of water quality based on available data and indicator compounds. Indicator compounds are identified for different types of land use also.

3.4 Impact of land fills and waste sites

Numerous land fills and industrial waste sites contaminate ground and surface water. A first step towards incorporating these point sources into the model system is a concept that classifies land fills and industrial waste sites by various characteristics, e.g. size and chemical components. In a second step, numerical experiments of water flow through the site as well as the connection to ground and surface water investigate the impact of various soil and geological formations on the pollution potential. These investigations are accompanied by an appropriate measurement concept providing the model parameters. Together with the classification concept, the results form the basis of an expert system that allows for the quantification of pollution potential and the forecast of future large scale behaviour.

4. WATER MANAGEMENT LAYER

4.1 Water Quantity Management

Socio-economical factors strongly control water allocation and development. Ground- and surface water is used to satisfy the water demand of the different facets of water consumption. A existing water management model will be employed and expanded with multipurpose optimisation techniques. This model will be linked to the water quality aspects.

4.2 Water Quality Management

Water quality has an increasing economical importance. The ultimate goal of any water quality management and the choice of water treatment technologies is obviously 'clean water'. However, the multiobjective optimisation requires the inclusion of many aspects which will be elaborated in co-operation with the DVGW-Technology Center, Karlsruhe.

Water quality is the result of both ecosystem-external factors (energy, organic matter, nutrients, toxic substances) as well as the transformation of these factors through complex interactions within the aquatic ecosystem. These transformation processes are largely controlled by the food web structure within running and standing waters. Due to recent findings it is not possible to simply add the internal measures of water quality improvement (food web optimization) to the „classical" strategy of reducing the external load of substances. On the contrary, the internal processes of food-web structuring depend also on external factors. This dependency is characterized by abrupt changes in the internal processes after relatively small changes in the external factors, if these changes take place in sensitive transient situations. For an integrated water quality management on catchment scale an the ecotechnological approach needs identifying such transient states in relation to potential changes in climate and socio-economic conditions (water temperature, discharge, organic matters, nutrients). We will elaborate'Optimum' food web structures which are able to improve the elimination of substances released from the catchment area (Benndorf, 1995).

5 THE SOCIO-ECONOMIC LAYER

Socio-economic factors dictate most of the water use and have a significant influence on water quality (Wiesmeth, 1994). Socio-economic and climatic scenarios form an input layer within the model system. In order to elaborate meaningful scenarios with respect to the potential future development of other East European countries we follow a step by step approach which exploits data and experiences collected before, during and after the political change in East Germany. The first step is to analyse sociological factors, e.g. demographic change, changes in either private behaviour including responses to rising water price levels or to de-industrialisation and changes in land-use, trends towards re-forestation or tourism. In the second step we address the economic drawbacks with respect to global change. Sociological factors and the economic system represent interdependent feedback systems, whereby a change in one of the systems causes an amplifying 'domino' effect (either positive or negative) upon the status quo of the partner system, e.g. at high unemployment levels. Appropriate methods for the analysis of such feedback patterns and the underlying causal mechanisms cannot be described only by statistics, e.g. migration or average family income. Network analysis is still needed for including the dynamics of these feedback processes.

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