Integrative Hydrologic Modeling Techniques for Sustainable Water Management regarding Global Environmental Changes in the Upper Danube River Basin

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ABSTRACT: The GLOWA-initiative (= *Glo*bal Change of the *Wat*er Cycle, www.glowa.org), funded by the German Ministry of Research and Education (BMBF), has been established to address the manifold consequences of Global Environmental Change on regional water resources in a variety of medium sized watersheds with different natural and cultural characteristics. In this framework, the Upper Danube watershed was selected as a representative mesoscale (A ~ 77.000 km²) testsite for mountain-foreland situations in the temperate mid-latitudes. The major goal of the GLOWA-Danube project is to develop and use new modelling and integration technologies to integrate natural and socio-economic sciences in order to develop new ways to aid sustainable water resources management on medium sized watersheds. A university-based distributed network of experts combining water-related competence in the fields of engineering, natural and social sciences develops and utilizes the Global Change Decision Support System DANUBIA to investigate the sustainability of future water resources management alternatives.

DANUBIA is developed on the basis of re-useable, refineable, and well-documented sub-models. It is object-oriented, spatially distributed and raster-based. For the first time in university based coordinated environmental research a standardized notation of parameters and functions and a platform-independent structure of computational methods and interfaces has been established using the Unified Modeling Language UML and the computer-language Java. The presented paper centres on the hydrology and water supply view on GLOWA-Danube, its approach of process model coupling and network based communication data exchange and object-oriented technology to simulate physical processes and interactions at the land surface. First results of the DANUBIA-prototype in the form of detailed simulations of the annual water balance of the Upper Danube watershed are presented. The Institute of Hydraulic Engineering, Universitaet Stuttgart, contributes a large-scale management model and a three-dimensional groundwater flow model to simulate both water supply structures and water allocation in Global Change scenarios.

1 INTRODUCTION

Water is basic to functioning matter cycles and hence for a clean, stable and sustainable environment. Water affects all economic, cultural, social and ecological aspects of daily life. A functional understanding of the processes related to the water cycle and their modification by human societies is crucial for the development of ways for its sustainable management. Since the related processes are strongly inter-related, sectoral science approaches, with their inevitably unilateral view of the world, are neither capable to understand the complex interactions between nature, water and man nor to develop methods for a sustainable water resource management under globally changing boundary conditions. A high level of transdisciplinary integration is required to provide a profound scientific knowledge base to extend the current paradigm of water management assuming inflexible "command and control" structures to watershed management decisions based on commonly formulated goals and taking into account continuously changing natural, social and technological boundary conditions known as Global Environmental Change. Proactive watershed management aiming at a sustainable use of the water resources thus heavily relies on the development of

scenarios of the future and on numerical models with predictive abilities. Until now no common accepted modelling approaches are available to integratively describe the complex interactions between natural and social processes. The lack of successful integration concepts results from the still large differences in the way the various disciplines formalize and describe their understanding of the respective processes. Consequently, the deviations in terms and concepts, comprehension and methodological approaches lead to sectoral approaches for solving separate parts of the task, and hence provide no reliable basis to simulate recursive and interacting scenarios of future development.

1.1 State-of-Art in water related Decision Support Systems

Increasing intensity of water use as well as water-related conflicting interactions between numerous stakeholders puts increasing pressures on the natural environment and ecology. Stakeholders represent governments, society, nature and industry. The European Water Resources Directive stresses the importance of decision support systems (DSSs) as tools for sustainable development based on participatory decision making. State-of-the-art DSSs are GIS-based expert systems that allow modeling and visualization of potential environmental impact of diverse uses on structure and dynamics of water-related issues. The European Union regulations on river basin management highlight many of these points and Decision Support Systems (DSS) seem to be one answer to the new management challenges. DSS try to combine both comprehensive modeling and support of the decision maker and stakeholders. Developing and using a DSS is expected to aid in the following tasks: structuring of problems, integration, information, analysis and learning. In this way a DSS can facilitate discussion between the parties involved in environmental and security management issues. A DSS provides an arena where short- and long-term impacts of proposed actions can be observed (in time and space) and where the feasibility of such actions can be investigated. To determine the sustainability of various management alternatives and to derive appropriate recommendations for public and commercial stakeholders it is necessary to accurately describe the complexity of water-related issues by an integrated approach. Therefore it is necessary to thoroughly identify the indicators that allow to isolate the driving forces of decision making. These indicators need to fulfill a number of basic requirements in order to simplify complex information to a reasonable degree of perceivability.

While these indicators need to be easy to communicate and cost effective, they must be based on good quality data, be scientifically valid, be sensitive to changes and be able to show temporal and spatial trends.

Many examples of Decision Support Systems can be found in literature and many projects in this regard have been carried out in the EU-DG12 Environment and Climate programme. These approaches usually deal with isolated water-related problems and little effort has gone into making this scientific material available as part of practical planning or management tools for public policy makers at the regional level. Some current examples shall be outlined that already cope with the transgression of these limitations and represent the current state of the art in water-related DSS: In a two-year project, MODULUS (Engelen 2000) developed generic spatial Decision Support System for integrated environmental policy-making at the regional level in which individual models from past or ongoing EU-projects, operating at very different temporal and geographical scales, were integrated. They represent the physical, economic and social aspects of land degradation and desertification in Northern Mediterranean watersheds. Another DSS is presently under development for the River Elbe Basin. It deals with the assessment and examination of effects of flood protection measures like dike shifting from an ecological and economic perspective (nature protection, agriculture, etc.) by means of providing access to objective information contained in a relational database (Becker (2003)). Other approaches are making extensive use of modern information and communication technologies such as the finish Web-HIPRE system (http://www.hipre.hut.fi/). It is based on value tree analysis and the collection of stakeholder information in web-meetings. Decision analysis interviews are applied to clarify the objectives of different stakeholders and to evaluate their attitudes towards different management strategies. The European project GREAT-ER (Geo-referenced Regional Exposure Assessment Tool for European Rivers, http://www.usf.uos.de/projects/GREAT-ER/) was launched and carried out as an international effort to develop a ArcView GIS-based DSS for the geo-referenced exposure assessment for discharged chemicals. The European funded project DAUFIN (http://www.dow.wau.nl/whh/daufin.html) is dedicated to improve the efficiency of water resources management by means of incorporating various types of data (in-situ-measurements and remote sensing) and consequently establishing an adjusted modelling framework, which will be

operated in catchments across various scales.

1.2 The GLOWA-Danube Project Setup

GLOWA-Danube comprises a university-based network of experts combining water-related competence in the fields of engineering, natural and social sciences. The project consists of the following disciplinary research groups, which cover the essential modules in GLOWA-Danube:

- *Coordination and GIS*, Dept. of Earth and Environmental Sciences, Chair for Geography and Remote Sensing, LMU Munich
- *Remote Sensing and Hydrology*, Dep. of Earth and Environmental Sciences, Chair for Geography and Remote Sensing, LMU Munich
- *Meteorology*, Institutes for Meteorology, LMU Universities of Munich and Mainz
- *Water Resources Management / Groundwater*, Institute for Water Resources, University of Stuttgart
- *Water Resources Management / Surface Waters*, Institute for Applied Water Resources, Ottobrunn
- *Plant Ecology*, Institute for Plant Ecology, University of Bayreuth
- *Environmental Psychology*, Scientific Centre for Environmental Research, University of Kassel
- *Environmental Economics*, IFO-Institute for Economic Reserach, Munich
- *Agricultural Economics*, Institute for Agricultural Economics, University of Hohenheim
- *Computer Sciences*, Institute for Informatics, LMU University of Munich
- *Glaciology*, Institute for Meteorology and Geophysics, University of Innsbruck and Bavarian Academy of Sciences, Munich
- *Remote Sensing and Meteorology*, Institute for Geography, University of Marburg
- *Tourism Research*, Institute for Geography, University of Regensburg

1.3 The Upper Danube Watershed

A watershed-area of 817.000 km², shared by 15 countries, makes the Danube the second largest river in Europe. GLOWA-Danube is limited to the analysis of the Upper Danube (A~77.000 km²) defined by the discharge gauge Achleiten near Passau in Germany. The Upper Danube is a mountainous catchment with altitudes ranging from 287 to 4049 m a.s.l.) and a large foreland. This introduces strong geographic, meteorological and socio-economic gradients (precipitation: 650 to >2000 mm/a, evaporation: 450-550 mm/a, discharge: 150-1600 mm/a, average annual temperature: -4.8 to +9 °C, sources of income changing from industry and services to agriculture and tourism). The highly fragmented land cover and land-use is mostly determined by human impacts. Forestry and agricultural use of different intensity (grassland, farmland) dominate, whereby climatic disfavours in terms of high precipitation and low temperatures limits the present agricultural potential in various parts of the catchment.

Due to its size and its heterogeneous physiogeographic characteristics, the dominating factors of catchment hydrology are changing within the watershed and determined by numerous factors, which lead to a strong spatial and temporal differentiation of runoff behaviour. All discharge
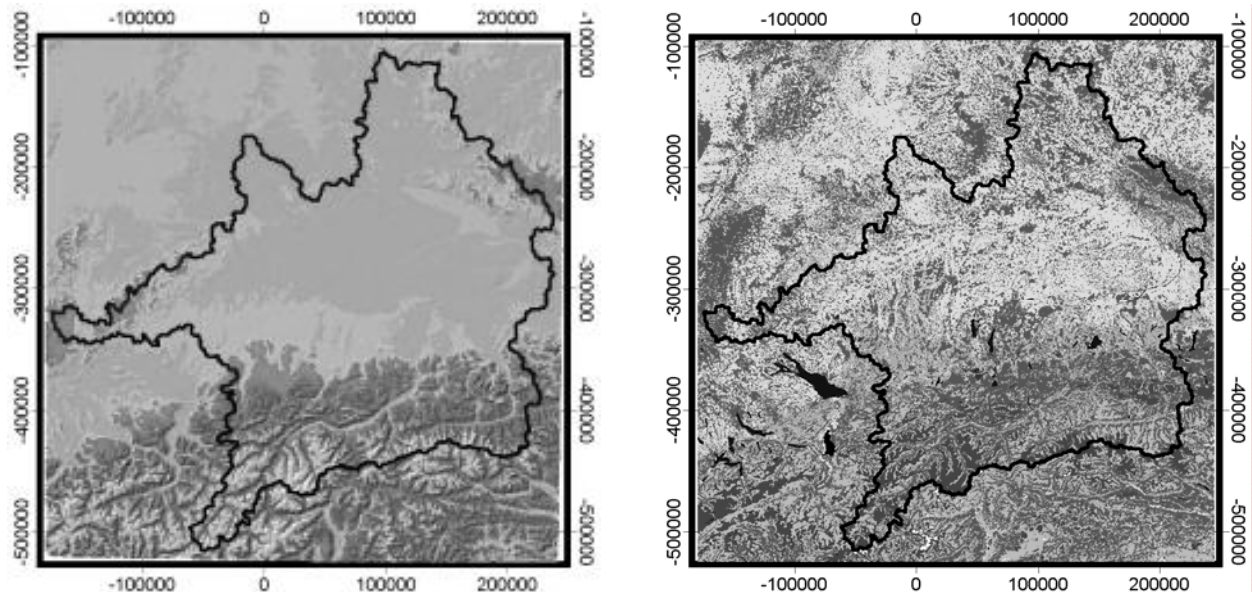

Fig.1: Topography (left, USGS) and land-use (CORINE) of the Upper Danube catchment (1 km resolution)

regimens from straight nival to pluvial occur. Floods occur frequently and produce large and increasing damage. Generally they are triggered regionally by convective summer rains in the alpine foreland and in the Alps. However, characteristic large-scale weather patterns combined with snowmelt activity also trigger floods, which have an impact upon the whole Upper Danube region and its tributaries (e.g. the 200-years Pentecost Flood of 1999).

The water resource management in the Upper Danube is complex and characterized by the different bordering countries: 73% of the Upper Danube is managed by the German states Bavaria and Baden-Württemberg, 24% by Austria and the rest by Switzerland, Italy and the Czech Republic. The Inn, as the most important alpine tributary, contributes up to 52% of the average discharge of 1420 m³/s.

The Upper Danube is densely populated with app. 8 Mio. inhabitants. A large part of the water for the water supply of the larger cities and industry originates in the pre-alpine region and the Alps. The most important industrial agglomeration areas are Munich (1.2 Mio inhabitants), Augsburg (260.000) and Ingolstadt (115.000) and the chemical triangle Burghausen.

For flood protection, energy production and water-resources-management purposes, the discharge of all important tributaries of the Upper Danube has been regulated through reservoirs an dams. To a large extent, their management is determined by the dynamics of the snow and ice storage in the Alps. Reservoir management at present is largely uncoordinated between the different administrative entities involved in power production. Therefore a large potential for optimisation of the management practices exists. Parts of the Upper Danube are navigable and are part of an important waterway that connects the Black Sea with the North Sea. This waterway is already used to export water from the catchment area of the Upper Danube into the catchment of the River Rhine. Increasing demand for water during the course of a more intense and more coordinated water use in Europe will put increasing pressure on the export of water from the catchment area of the Upper Danube. Withal, the ecological and socio-economic effects as well as the environmentally sound capacity of the water resources are still largely unexplored.

1.4 Why a Decision Support System for the Upper Danube ?

The Upper Danube is a catchment of definite water surplus. Hence the relevance for Global Change Research in this area is characterized less by a lack of water quantity then by a lack of substantiated definitions of the various existing conflicts and especially the Upper Danube possible future functions in a regional management of the water resources.

Due to the strong natural and socio-economic gradients in the catchment, the Upper Danuba qualifies as a prototype for Global Change Research in numerous ways. A complex and diverse administrative structure, consisting of 3 countries and 2 German states, currently employs very different strategies in mediating water use conflicts and is characterized by a lack of coordination between the specific economic and political interests in terms of water resource management.

The strong utilization of all natural resources related with water through various and intense economic activities within the catchment area, triggers strong present and foreseeable conflicts in water use, an export of water to other catchments as well as a strong import/export of virtual water, which is both imported through agricultural products and industrial goods and used/exported during the production of industrial goods. At present, the strongest conflicts are not water quantity related. Severe quality conflicts exist between agriculture (entry of fertilizers and pesticides to stabilize and raise yields) and water supply (maintenance of sufficient water quantities at high-quality standards). This may change in the future based both on a foreseeable change in climate and on an also foreseeable change in agricultural and water supply infrastructure. In the course of the future catchment related water management of the European Water Resources, present water supply structures (e.g. currently more than 1000 communal water suppliers in the watershed) will undergo a radical centralization, although no common strategy has yet been developed among the involved parties.

Further strong conflicts of use also exist in the Upper Danube area between tourism and environmental protection. Southern Bavaria is the centre of tourism in Germany. Tourism is a decisive and employing factor in Bavarian economy. Agriculture, forestry, tourism and environmental protection compete in shaping the landscape and the industrial structure of the alpine forelands and in the Alps.

The natural environment in the Upper Danube is very sensitive to climate change. Especially the alpine area of the Upper Danube is being increasingly limited in its development due to spontaneous mud flows and avalanches. A combination of the factors water, land-use changes as well as the settlement dynamics in the valleys of

the Alps plays an essential role in both cases. A steady decrease in the groundwater levels in the alpine foreland has also been observed for almost 30 years. The causes for the decline and its significance with respect to a sustainable water resources management are still largely unclear. It is to be expected, that climate changes will lead to strong water- and land-use changes. However, these changes are also affected by other factors, that are not related to climate change. Among these are the creation of cultivated plants with a higher resistance to cold, precipitation, and parasites and their changed yield structure, changes in the vegetation growth and the water use efficiency due to increased CO_2 concentrations, especially at higher altitudes changes in agricultural production goals (quality vs. quantity) and the structure of agricultural industry in Germany. Possible changes of the role of the Upper Danube basin within the EU may also be triggered by a conspicuous deterioration of the prerequisites for agricultural production in the Mediterranean area due to a strongly decreased precipitation. As a result, the Bavarian alpine foreland may have to be more strongly used to maintain the European food production. The ecological, economical, and societal effects of this bundle of foreseeable changes have not yet been assessed. There are also no strategies available for sustainable environmental management under such dynamic changing boundary conditions.

2 DESIGN AND IMPLEMENTATION OF THE DECISION SUPPORT SYSTEM DANUBIA

2.1 The Integration Concept

The methodology used to develop DANUBIA is characterized by applying integrative numerical, network based model development methods and integrative monitoring through remote sensing (Ludwig (2003b). In the area of integrative numerical modelling, the necessity of improving the optimisation of the industrial production cycle across all areas of the production processes has led to two new methodologies in computer sciences during the last years. These serve as the basis for developing a new approach for integration of the disciplines in GLOWA-DANUBE:

A formal language is used, which enables the involved disciplines to model sub-models of very complex systems as well as their interactions in a common way. This meta-modelling language describes the essence of the modelling in a way that is independent of the respective discipline. It is thus very well suited to formulate the interaction and communication between the various processes and to check for completeness and functionality. The

Unified Modelling Language (UML; Booch et al., 1999) has developed within a few years to the de facto industry standard and is used in the project as the common meta-modelling language for all groups. UML allows to formulate diagrammatically model-structures and routines across disciplines, which can then automatically can be transformed into object-oriented code of Java or C++.

Fig 2: Connections and dependencies between the main model components.

Networked communication of distributed objects
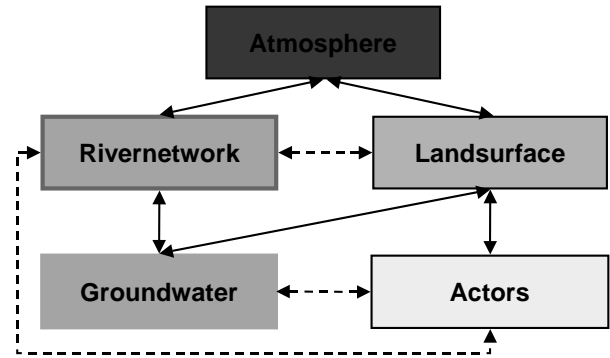
(i.e. independent, self-contained parts of a model compound) is used to enable the various elements of the whole model or model compounds (further called objects) to run in a network on different computers in different locations. The communication consists of an exchange of data and methods and in the synchronization of the various model elements. Furthermore, the possibility to subdivide complex and voluminous applications onto a large number of different networked computers theoretically enables an almost inexhaustible and very cost-effective computer capacity. The standardized computing and communication infrastructure was implemented using Java as platform-independent language based on UML-diagram. A prerequisite for this is that only selected, standardized communication procedures are used by all groups, such as the Java-based Remote Method Invocation (RMI). On this basis, DANUBIA is developed as a synchronized system that consists of distributed networked objects, which can communicate through RMI on the net.

Each discipline contributes its part of the complex model compound as an object. In this respect, an object is an encapsulated unit, which completes a distinct function in the Decision-Support-System and carries out the data exchange and the synchronization through defined interfaces. Hereby, the object can be implemented in any desired language. This selected concept of a network-based, distributed model compound for integrative modeling in environmental sciences is new.

2.2 The Modelling Concept

Beyond the use of information technology industry standards, the following characteristics and concepts make certain that the set-up of DANUBIA is feasible: As shown schematically in Fig. 3, DANUBIA is *raster based* at its core. Although this may not be the optimal spatial representation for all use cases, it simplifies the interdisciplinary description of the interactions between the considered processes. The spatially distributed, raster based modelling of the core processes (run-off generation, evaporation, plant growth, economics, human behaviour through agents) are expanded at first by one-dimensional modelling of the processes in flumes and water bodies with regards to quantity, matter turnover, and management.
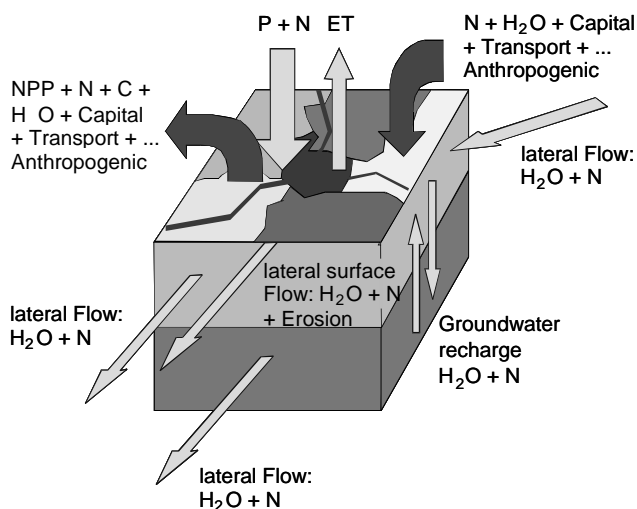

Fig. 3: Schematic raster based modelling in DANUBIA on the proxel basis.

DANUBIA uses the concept of *"proxels (process pixels)"*. Proxels are the basic building blocks of DANUBIA and consist of a pixel (picture element) in the form of a cube, in which processes occur (Tenhunen et.al., (1999), Mauser et al. (2000)). This cube, which can have different dimensions depending on the respective viewing scale, connects to its environment (other proxels) through fluxes. In DANUBIA, a proxel-area of 1 km² is used for the mesoscale modelling of land surface processes as well as for the key socio-economic processes in the entire catchment area of the Upper Danube (A ~ 80.000 km²) and 1/10 to 1 ha for the on-going detail studies of characteristic sub-catchment areas of the Upper Danube (A ~ 1000 km²). A basic proxel in the DANUBIA architecture supplies to all disciplinary users all basic functionality for geographic referencing and spatial managing of the necessary parameters within the object as well as data imports and exports via defined and standardized interfaces. An object in DANUBIA is an extension of a basic proxel, which inherits all the properties of the basic proxel. It can thus be e.g. a surface proxel, that describes the water flow on the surface, through vegetation and in the ground water. Socio-economic processes (migration, behaviour, market situation, perception, etc.) are also described on the basis of proxels. In socio-economics, DANUBIA uses the concept of agent based modelling *(Suleiman 2000)* on proxels. The core idea of an agent model is that every single agent involved is modelled in a domain of individuals. This procedure differs fundamentally from all summative modelling approaches, in which the input-output-functions of a whole system are described. Agent based modelling can be subdivided into shallow and deep models. Shallow models specify the input and output connections of the behaviour of single agents in a descriptive way with little or no theoretical assumptions. This can be implemented through straight forward mathematics or through neuronal networks. Deep models generate the behaviour from a theory about the agents and enable semantically meaningful statements about the motives of the agent. Methods used here are e.g. symbolic modelling, in which decision making is described as a sequence of rules. Agent models can be used successfully, if a meaningful standardization of the agents can be carried out. Modelling of the agents enables not only a detailed extrapolation of behaviour (which is important in the case of DANUBIA, with respect to the agent types as well as the spatial distribution), but is also easily expanded and refined. A deep model enables mapping and interpretation of the dynamic phenomena of adaptation, learning, and interaction. Initially, shallow agent models are used for all actors in DANUBIA. Currently DANUBIA represents economy, agricultural economy, private water users, water suppliers and tourists as shallow actors. In the second project phase, they will be extended to deep actors.

Each participating group is developing an object (derived from the basic proxel) based on their available disciplinary model approach and knowledge. The objects communicate through a standardized mechanism, which ensures that for every time step in the model calculations, the spatial data (e.g. temperature, radiation, biomass, income, etc.) and parameters (e.g. water-import, suggested subsidy of corn, etc.) required by a partner-object are provided. This mechanism is thus comparable with a market place, in which data are offered and exchanged. An object can simultaneously be the supplier and receiver of data. The "Market-Place-

concept" was developed and refined through intensive discussions within all participating project groups. A cut-out of the DANUBIA market place is shown in Fig. 4.
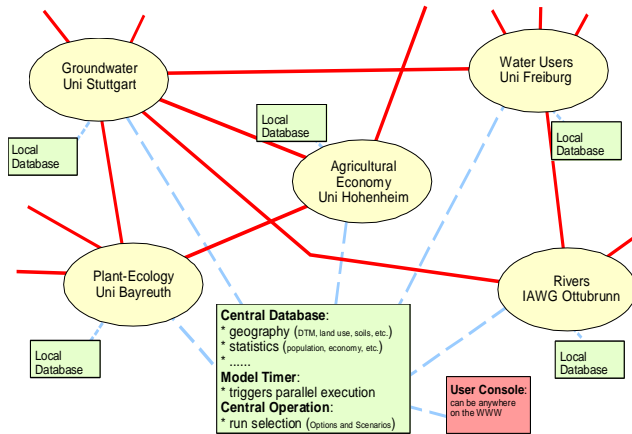

Fig. 4: Cut-Out of the Market Place Concept of Networking of the Participating Groups in the Project. Ellipses show groups, which exchange (offer and receive) dynamic data through solid lines and are supplied with static data from a Central Data Base

Different processes need data update from neighbours in different time steps. Meteorological data are exchanged between the atmosphere object (offers air temperature, wind, incoming radiation, precipitation, etc.) and the land surface object (offers outgoing radiation, evapo-transpiration, etc.) hourly whereas planting choices are exchanged between agricultural economy and plant physiology yearly. Mutual synchronization of the objects is therefore a central task. It is formulated with UML independently from the disciplines involved and leads to a universal time controller, which synchronizes the different objects of DANUBIA.

A prototype of DANUBIA was implemented on a LINUX-cluster containing 26 nodes consisting of off-the-shelf Intel-based computers with 2 CPUs and 1 GB of core memory each, connected through a LAN, which is built-up of conventional Ethernet switches. The prototype contains all basic characteristics of the web-based final system. Vvalidation, refinement, and application of the created objects and interfaces is carried out.

3 WATER BALANCE SIMULATION WITH DANUBIA

As a first step of the validation of DANUBIA the long term water balance of the Upper Danube was simulated for one hydrologic year. For this purpose the following objects were synchronized:

- Atmosphere from interpolated data measured by the German meteorological service (DWD)

- Land surface energy balance, which models the radiative transfer of vegetation canopies and evaporation of the land surface
- Vegetation ecology, which models the physiology of vegetation CO_2- and water-exchange (transpiration) as well as plant growth
- Soil hydraulics, which models the water and nutrient flow in the unsaturated zone
- Groundwater flow in the Upper danube aquifers

The modelling approach is described in more detail by Ludwig (2003), Mauser (1998) and Schneider (2000). No calibration of the different sub-models was carried out in order not to loose predictive ability, which is essential to examine changes in the water balance induced by different future changes in the boundary conditions of the watershed.

The calculations were carried out on an hourly basis. Fig 6 shows an example of a snap-shot of three layers, which were synchronously calculated by three communicating objects on three different computers for March 10, 2000 at 14:00. It shows precipitation, snow accumulation and subsurface runoff (interflow) in the Upper Danube. As can be seen clearly strong precipitation (right) at the edge of the Eastern Alps creates extensive subsurface runoff (right) and is not converted into snow cover due to temperatures above zero degrees in this part of the mountains and in the forelands. This detailed simulation of the water flows in the watershed is carried out for each time step in the hydrologic year.

The layers are accumulated to form the water balance of the whole year. Fig.6 shows the result for the year 1999.

For each 1x1 km proxel the hourly water flows in and out of the proxel were accumulated over the year 1999. Precipitation is shown in the map to the left. It was produced from station data taking into account the influence of the topography in the watershed. Increasing precipitation in the mountain regions can be seen clearly as darker shades. Evapotranspiration in the middle shows a very complex spatial pattern, which is, beyond climate parameters, mainly depending on the land use. The influence of decreasing temperatures in the mountains and their negative influence on evapotranspiration can be seen. The accumulation of this proxel discharges over a total watershed results in a discharge of 694 mm/year. This compares well with a measured discharge 1999 of 674 mm/year at the outlet of the watershed.

Fig.5 shows the simulated water balance for one selected 1x1 km proxel in the Upper Danube watershed, which is situated in the Bavarian Alpine foreland. The dominant land use with 50% fractional cover is pasture. 24 % of the proxel area is covered

with deciduous forest, 14 % with arable land and 12 % with built-up area.

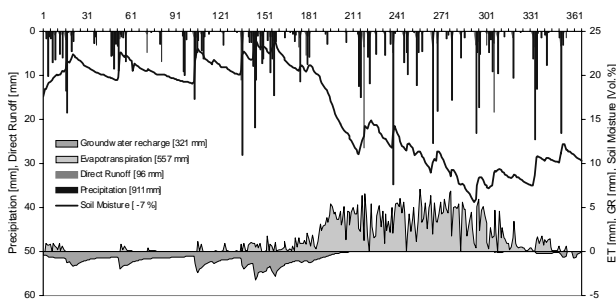In Fig.5 the course of precipitation, evapotranspiration, ground water recharge, direct surface runoff and soil moisture over the year 1999 are shown. As can be seen, soil moisture depletes during the summer and increases again towards autumn and winter, when ground water recharge sets in again. Evapotranspiration of the developing plant cover is the main consumer of the water stored in the soil. During spring, when soil-moisture content is high, groundwater recharge reacts directly to precipitation. During this period evapotranspiration is generally low and restricted to very short periods, when evaporation occurs from rainfall interception. As soon as vegetation starts leaf expansion and assimilation transpiration also increases and groundwater recharge stops. Especially the dry period after day 180 together with the large water consumption by the growing vegetation sharply decreases the soil moisture storage. Surface runoff of 90 mm/year, which does not infiltrate and which is directly transferred to the river network, is solely produced by built-up areas (12 % of the proxel area).
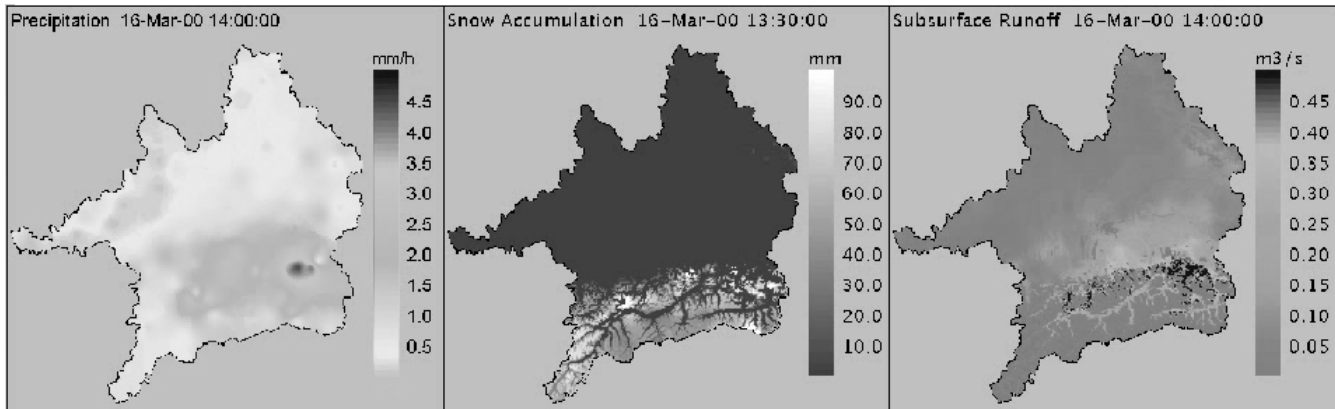

Fig.5: Water Balance Components 1999 of a 1x1 km Proxel in the Bavarian Alpine Foreland as Simulated with DANUBIA

Fig. 6: Example of precipitation [mm/h], snow accumulation [mm] and subsurface runoff [m³/sec] for March 10, 2000 as simulated by DANUBIA

Precipitation	Evapotranspiration	Discharge
1224 mm	530 mm	694 mm

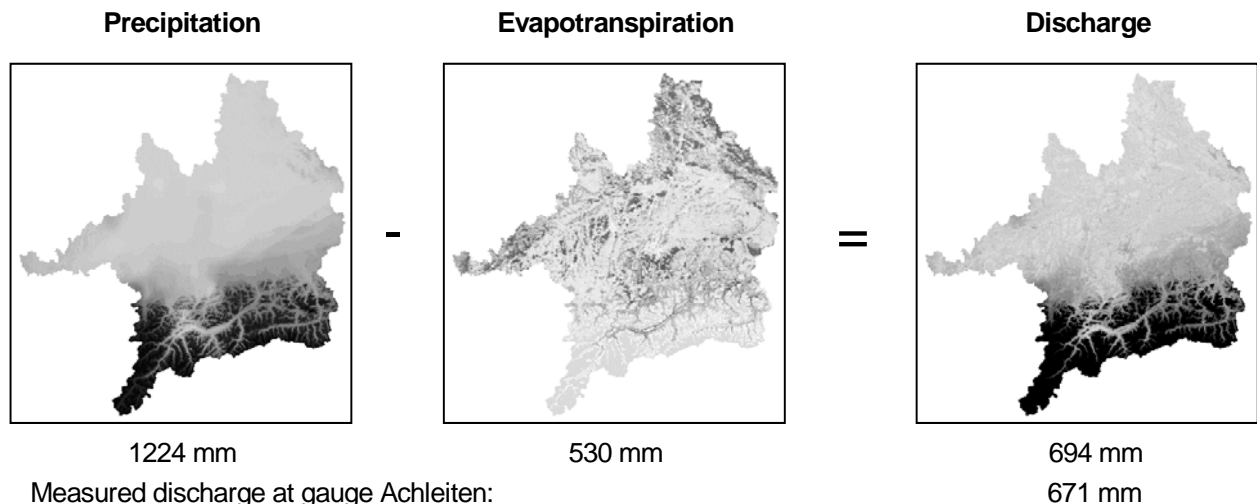Measured discharge at gauge Achleiten: 671 mm

Fig. 7: Simulated Water Balance of the Upper Danube Catchment Using the DANUBIA Decision Support System for the year 1999

4 THE GROUNDWATER COMPONENT

The previous chapter described the DANUBIA approach to treat the physical processes that dominate the hydrological cycle at or above the land surface or in the shallow subsurface. It is self-evident that a full and adequate description of all relevant aspects, including human activity and atmospheric processes, would require much more attention than is possible in this GLOWA-Danube overview. Therefore it was decided to add the description of just one more model component: the numerical treatment of groundwater flow as an example for another physically based process that is at the same time strongly linked to the aforementioned landsurface processes. Since groundwater is the main drinking water resource in the Danube basin accounting for up to 95% of the water supply, a brief description of another model component, the "WaterSupply" model is given to give an outlook on the non-physically based or partly physically based Actors models (see fig. 2).

4.1 Groundwater: Overview

The main aim of the groundwater model is to assess and forecast quantity and quality of the groundwater resources together with the other physically based models under conditions of global change. Upon completion, the groundwater flow and transport model currently being developed will be the largest multi-purpose numerical groundwater model ever created in Germany with respect to area and complexity. The construction of a conceptual hydrogeological model for such an enormous area is a task which requires not only the collection of extremely large quantities of field data but also the use of advanced data managing and evaluation tools. Additionally, interpolation methods capable of considering the different degrees of confidence of the values and the existence of discontinuities such as geological boundaries are utilised.

In accordance with the size of the model area and the PROXEL-based DANUBIA approach (fig. 3), a finite-difference model approach (MODFLOW; McDonald & Harbaugh, 1988) was chosen. In a second stage, a transport model simulating nitrogen transport will be added. A case study, currently under preparation, seems to prove that the intended use of a finite difference transport modelling approach (e.g. MT3D; Zheng, 1990) might not lead to the desired results because of the pre-eminent effects of numerical dispersion. Special attention will therefore have to be paid to the upscaling of the governing parameters (dispersion coefficients). MODFLOW was chosen because of the robustness

of the model which has been proven over many years. World-wide it is one of the most commonly used models. Its modular aspect makes the modification of its code a relatively easy task.

The main focus of research in the first two years of the project has been on the development of the conceptual hydrogeological model of the catchment. The gathering and processing of data for a drainage area of this magnitude has been and remains one of the major tasks. For areas that are not yet or only poorly investigated, geostatistical methods are utilised and if necessary enhanced to describe the subsurface.

A particular challenge lies in the modelling of groundwater flow and substance transport for a very coarse grid fixed to 1x1 km and in the constant exchange of input and output data with the other research groups (parallel calculations). The proxel architecture of DANUBIA, necessary to ensure communication between the different disciplines, requires the development of new upscaling methods to reproduce soil heterogeneity and geo-hydraulic boundary conditions in order to simulate groundwater flow and substance transport without readjusting the grid.

The connection between "Groundwater" and "Rivernetwork" is defined by means of infiltration and exfiltration rates between the aquifer and the surface water body. The hydraulic connection is a function of the water level of the surface water body (averaged over one cell), the piezometric head in the hydraulically connected layer in the groundwater model and a parameter signifying the hydraulic conductivity of the layer separating the two water bodies. The connection between "Groundwater" and "Landsurface" is defined by the computation of recharge rates into the groundwater and of evapotranspiration rates occurring through capillary rise from the groundwater.

4.2 The conceptual hydrogeological model

Over the course of the first project year it became apparent that the data situation in the basin is highly differing. Geological data of satisfactory coverage and quality which is required for the geometrical description of the aquifers is available for most areas of the catchment. However, only a small part of this data is available in digital format. Data in printed format had first to be compiled from various sources and subsequently digitised and processed. In contrast, data on the hydraulic properties of the subsurface is infrequent or not accessible. Other important data, e.g. the leakage properties of rivers, do only exist for a small number of selected locations (e.g. Maloszewski & Trimborn, 1997). The

latter therefore can only be estimated by calibration. For the hydraulic conductivity, data exists mainly for the quaternary aquifers (e.g. Seiler & Neumaier, 1980). Fewer measurements are available for the carstic and tertiary formations. Considering the size of the model area and the heterogeneity of the geological conditions, the availability of hydraulic parameters is poor, even if the area is relatively well investigated. The hydraulic conductivity as a crucial property in groundwater modelling should normally be based on as many field observations as possible.

Regardless of the evident importance of a correct representation of the hydraulic parameters in a groundwater model, the appropriate definition of the model geometry (layer top and bottom) has proven to be the critical and dominating factor for the model conduct. More details will be provided on the next pages. The calibration of hydraulic conductivities can be considered to be "fine-tuning" if one deals with such large and coarse models.

Based on the data currently available for the catchment area, a first conceptual hydrogeological model has been conceived as a prerequisite for the development of the numerical model.
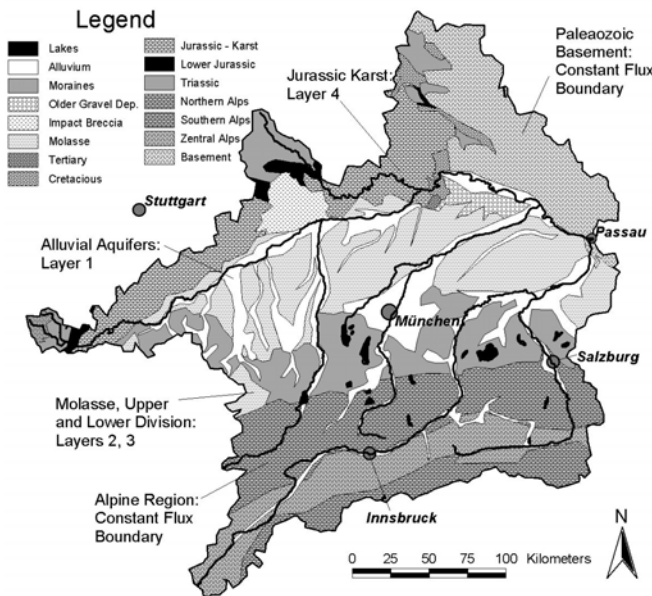

Fig. 7: Schematic geological map of the upper Danube basin.

The conceptual model consists of four layers, comprising the strata "Malm Karst", "upper Tertiary Molasse", "lower Tertiary Molasse" and "Quaternary". The units "upper" and "lower" Molasse are for the most part synthetically defined and only then oriented on the lithostratigraphic units where this is stringently required by the geological situation. The upper Tertiary unit is an approximately 50m thick layer, within which the important local structures can be modelled independent of the properties of the subjacent Molasse. The Quaternary layer is mainly defined by small and thin local structures of high permeability (valley aquifers, alluvial gravel plains, figs. 7 and 9). This uppermost layer is most important for short and medium term groundwater flow. It's importance in DANUBIA is obvious, because it represents the interface to the other models. Unfortunately the complicated geometry of the Quaternary layer makes it the most difficult to model. Importance and complicacy of the layer brought it into the centre of research activities. Some details on these issues are given on the next pages.
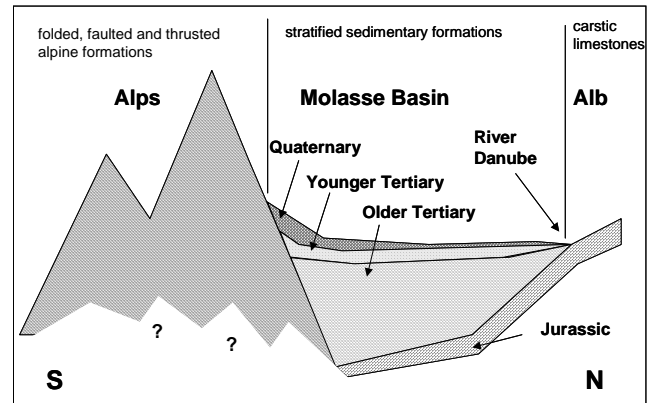

Fig. 8: Schematic geological cross section of the upper Danube basin showing the four model layers. See figs. 7 and 9 for the horizontal distribution of model zones.

The hydro-stratigraphical units subjacent to the Malm are not considered explicitly, as here groundwater exchange takes place, which is negligible for GLOWA. Therefore the base of the "Jura" aquifer constitutes the model basis (fig. 8).

In the Palaeozoic Basement in Northeast Bavaria, local hydraulically unconnected aquifers predominate. Since they are too small to be modelled on the predefined grid size, these areas are excluded from the groundwater model. Instead, a boundary allowing temporally variable inflows will be drawn along these sections. The task of quantifying such boundary inflows into the model area is still under investigation.

The alpine section of the model area is a subject of particular concern. On the one hand, the alpine regions, covering approximately 30% of the catchment area and contributing about 40% of the total precipitation, evidently play an outstanding role in the water cycle of the region. On the other hand, it is not possible to treat the extremely faulted, folded, and thrusted stratigraphic units of the Alps as ordinary quasi-horizontal layers as they are usually expected in the MODFLOW concept. Karstification, which plays an important role in certain parts of the Northern Alps, adds to the difficulties in this area (see also next chapter).

4.3 The numerical groundwater flow model

The task of developing a three-dimensional (3D) groundwater flow and transport model of this size has been divided into the following manageable sub-steps to allow for the simultaneous, painstaking process of data acquisition:
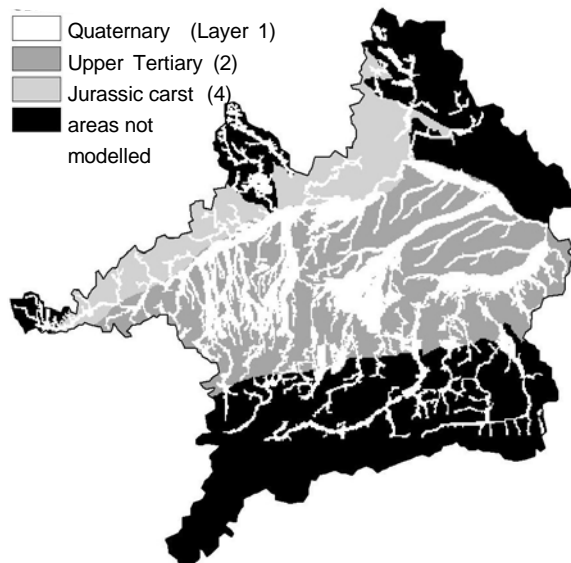

Fig 9: Horizontal distribution of the uppermost active layer of the groundwater model.

1. Creation of a two-dimensional steady-state model using the simplest assumptions concerning aquifer geometry, boundary conditions and model parameters. Only the alluvial aquifers (figs. 4 and 6) are modelled explicitly, whereas others are neglected or, where necessary, taken in account as boundary conditions. The Alps and the Palaeozoic Basement are excluded from the model area and are represented by constant flux boundary conditions (fig. 9). The purpose of step one is mainly to set parameters and boundary conditions as a first approximation. It is based on the assumption that the alluvial aquifers are the most important for the processes that are recognised in the DANUBIA scale (space and time). The model calibration is primarily done by trying to achieve "reasonable" results, e.g. the minimisation of flooded areas.
2. Successive refinement and adjustment of the model from step one, replacement of estimated parameters by measured values where available, and the use of field observations for the model calibration. The model area is still reduced to the core part of the catchment, excluding the highlands and mountain areas.
3. Expansion of the two-dimensional model to 3D by adding the lower three layers.

4. Calibration and validation of the model for steady-state and transient conditions.
5. Detailed modelling of the mountainous areas using a conceptual hydrological approach.
6. Calibration and validation of the full 3D model for steady-state and transient conditions.

Currently (December 2003) the project group has completed steps 1-4 and is mainly concerned with step 5 & 6.

4.4 Integration of MODFLOW in Danubia - Adaptation of the proxel concept

Parallel to the development of the flow and transport model, the integration of this model in the structure of DANUBIA is being pursued. The finite-difference models MODFLOW and MT3D, for flow and transport respectively, were chosen mainly because of the cell-based approach that matches the proxel concept of DANUBIA in a nearly ideal way (see fig. 10). 1:1 Data exchange with other models is possible without elaborate post-processing of the model output. Although the block-central flow approach used by MODFLOW has numerous advantages (simplicity, robustness, perfect integration in DANUBIA), it also has clear disadvantages, particularly with regard to the implementation of boundary conditions and the representation of complex geometrical features.

The following input data are calculated by the models named in parenthesis: river level (River Network), nitrogen in surface water (River Network), groundwater recharge (Landsurface), nitrogen in percolating water (Landsurface), groundwater withdrawal (WaterSupplyActor). Likewise, the following output data are required by the models stated in parenthesis: groundwater level (Landsurface), nitrogen in groundwater (Landsurface, RiverNetwork, WaterSupplyActor), infiltration and exfiltration between groundwater and surface water (RiverNetwork). The transfer parameters were implemented in UML-diagrams, which in turn were used to create a Java code which can be integrated in the overall structure of DANUBIA.

4.5 Special issues of the large scale groundwater model

While procuring data with the necessary spatial resolution, a second challenge must be addressed, namely the upscaling of local, heterogeneous structures such as line and point data sources to fit the square kilometre grid. Many of the features in nature that play an important role in the water cycle

show heterogeneity on a scale much smaller than the 1km grid. Prime examples for this problem are the river valleys crossing the catchment from the bordering Alps with courses aligned from South to North or Southwest to Northeast (fig. 11). While these alluvial river valleys have small cross sections (less than 500m in many places), they are at the same time significant aquifers due to their deposit's coarse grain size, their thickness and the valley's steep gradients. Particularly when such structures run diagonally to the grid, their discretisation presents a great challenge. Rojanschi (2001) pursued

these and other similar questions extensively and tested various methods for modelling the differences in hydraulic conductivity between a highly permeable Quaternary aquifer and the surrounding Molasse based on the proxel size (1km²). His research showed that in many cases the upscaling methods currently in use yield unsatisfying results. Hence, the second major research emphasis of the research group "Groundwater" is in the development of new scaling procedures.
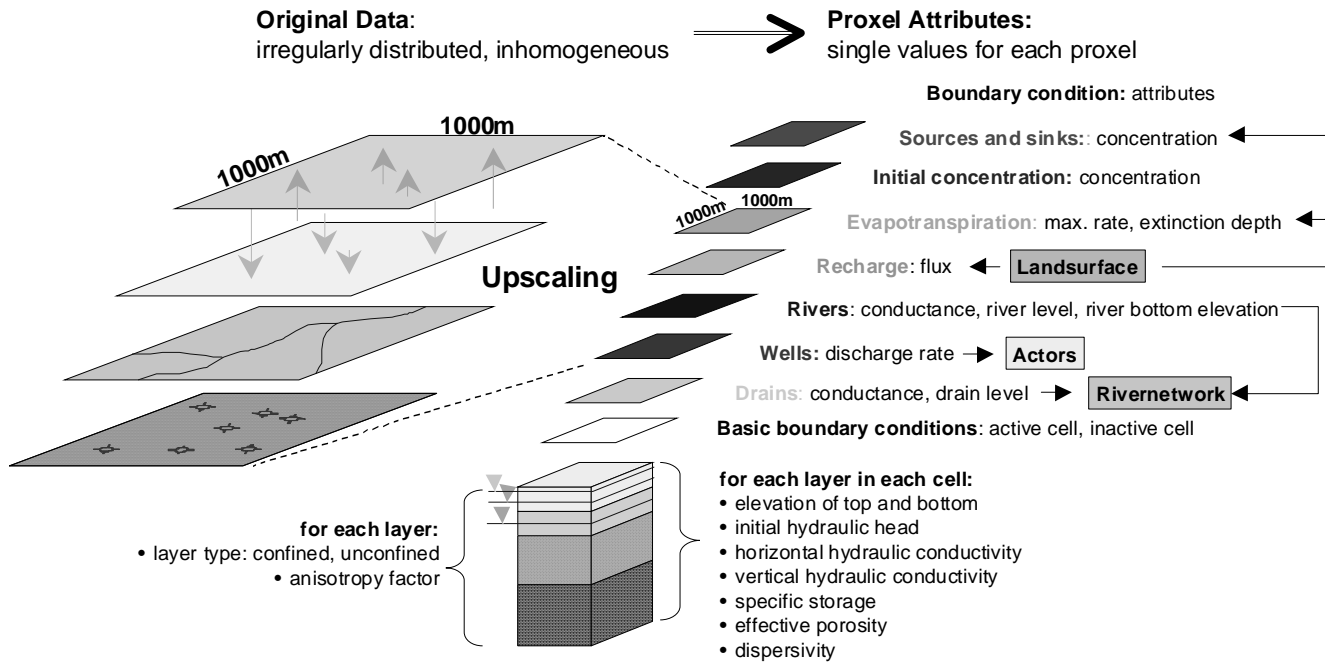

Fig. 10: The groundwater proxel concept, its representation in MODFLOW and MT3D and its interaction with other DANUBIA objects. The groundwater "proxel" (see fig. 3) consists of several layers and the corresponding boundary conditions.
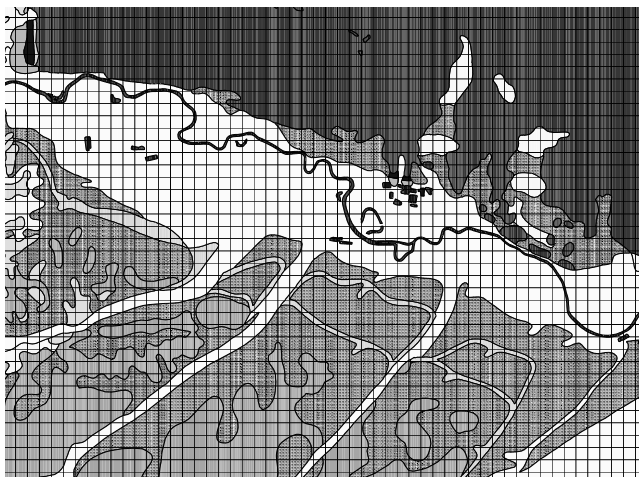

Fig. 11: Cut-out of the hydrogeological map of the upper Danube catchment. White areas: High permeability alluvial aquifers (quaternary deposits) in river valleys (model layer 1).

As shown in Rojanschi (2001) the difficulties are related mainly to the upscaling of layer parameters,

such as hydraulic conductivity, and of point and linear boundary conditions, such as wells and rivers. The main aim of upscaling is to minimise the errors resulting from modelling on a coarse scale as compared to a theoretically correct but unmanageable fine grid model.

Scaling issues affect not only the hydraulic parameters but also the model geometry itself. As mentioned before, the correct and appropriate representation of the model geometry has a very high importance and influence on the conduct and performance of the model. The difficulties arise mainly from the fact that the uppermost, partly saturated (unconfined) quaternary layer is a) of very complex geometry and b) very thin (0 to 50m, average 10m) compared to the grid cell size.

Moreover, the finite difference method usually allows only one specific flow path through such structures (perpendicular to the cell faces). Therefore it has to be guaranteed that the bottom and top of the

cells upstream and downstream and the possible positions of the hydraulic heads in such cells allow a continuous flow through the structure. Otherwise the smallest changes in recharge, extraction by wells or generally every change in hydraulic head anywhere can cause the most dramatic effects starting from the flooding of large areas to the drying up of cells. Wolf et al. (2003) describe this problem and some solutions to it in detail.

Two additional problems have proven to be decisive in the attempt to successfully model the groundwater flow dynamics of a coarse regional groundwater model with complex geological conditions:

1) Sub-domains within the model area, which cannot be modelled as a layered aquifer system: Such sub-domains are represented by the mountainous areas at the model boundaries, namely the Alps in the south and a crystalline region in the northeast of the basin. In such regions, only small, disconnected saturated zones exist. Groundwater flow is restricted to fracture zones or carstic systems, which under the given constraints and, because of missing data, cannot be included in a regional model. To overcome this problem, a combined deterministic-conceptual approach was used. Flow from those mountainous regions is calculated on the basis of a simplified hydrologic model (linear storage), which is coupled to the groundwater flow model. The interface is represented by a flux boundary condition.

2) Sub-domains that are characterized by very deep regional groundwater tables, or deep confined aquifers respectively: In such areas, local, perched aquifers, which cannot be modelled in a regional model, predominate in the uppermost part of the subsurface (0-200m). On the regional scale, perched aquifers have to be treated as part of the unsaturated zone. Horizontal flow leads to discharge of percolating water in springs and small tributaries. It has proven to be extremely difficult to determine the actual recharge to the deep groundwater system, in particular because data to describe this deep partly saturated zone does not exist. The approach to tackle this problem is to regionalize the factors that determine the amount of horizontal discharge and the deep percolation rates of the deep unsaturated zone, and use them to parameterize the corresponding transfer functions.

The investigation of the two latter aspects in the context of GLOWA-Danube showed that there is a great need of further detailed research on a smaller scale especially in the field of coupled surface water - subsurface water processes in the deeper unsaturated and partly saturated zone. A research proposal concerned with these problems in a sub-catchment of the Upper Danube Basin is therefore underway.

4.6 Results

The current working version of the groundwater model has been successfully run and tested within the DANUBIA environment. In a local test environment promising results were yielded after careful adaptation of the model geometry, parameter upscaling and calibration for both steady state and transient conditions. In fig. 12 the calculated proxel values of a steady state run are plotted against the corresponding measured (annual mean) values of 1371 observation wells. This results are preliminary and need to be discussed and enhanced. However, they prove that even with such a coarse grid, a meaningful representation of the piezometric heads is possible.
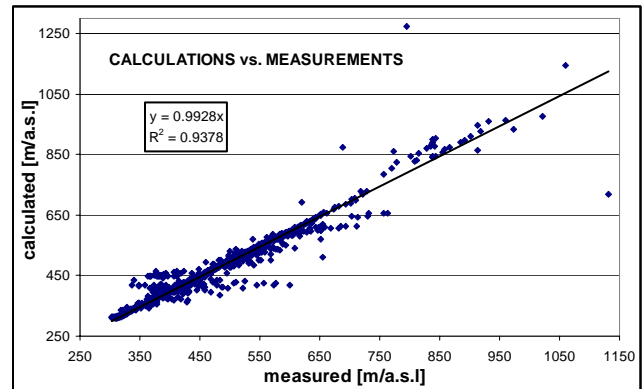

Fig.12: Calculated versus measured piezometric heads for 1371 observation wells in the catchment (steady state, averaged heads)

5 THE WATER SUPPLY COMPONENT

5.1 Overview

The model "Water Supply" provides a link between the Actor objects on the one hand and the engineering and natural science models on the other. It obtains information about available water resources, aggregates the water demands of the different Actors (HouseholdActor, Economy, TouristActor, and Farming), develops a supply strategy, decides which water resources to use in order to meet the demands and informs the objects Groundwater and Rivernetwork accordingly.

The specific aim of the Water Supply model is not only to simulate the present day system of water extraction, treatment and distribution but also its development and change with time. As most changes to the system are brought about by decisions made by relevant actors in the field of water management or their behaviour (in response to political and economic boundary conditions,

changes in water demand or water quality, advances in technology etc.), the use of agent-based modelling was chosen, whereby an agent is seen as a computer system (in our case representing a human or group of humans) which is aware of its environment, has defined objectives and is able to act independently in order to meet these objectives (Ferber, 1999). Whereas agent-based modelling has received much attention over the past decades, the use of this type of modelling for water supply systems is something very new (Tillman et al., 1999).

5.2 Model concept and development

Initially a conceptual water supply model was developed using UML and JAVA, in which both the model boundaries and area of expertise as well as parameters to be exchanged between the Water Supply model and other models were defined. Following the object oriented philosophy of JAVA, the water supply system was broken down to a small number of main classes that represent the hierarchy typical for the water supply - consumer relation in Germany. Sub-classes that inherit properties of their parents are used to categorize the main objects. Decisions are based on sets of rules that are defined according to the sub-class membership. A catalogue of decision-making rules will be prepared as a basis for discussion and will be debated with the relevant stakeholders. These rules provide the basis for decision-making algorithms which allow model agents to respond to their environment, communicate with one anther and behave in a goal-oriented manner to bring about change in the water supply system in response to changing conditions with regard to the climate, water quality, political and social boundary conditions, and changing demand.

The required data is only partly available from the authorities, common interest organisations or in the public statistics. In order to gain access to more specific information regarding individual water supply companies, the Water Supply group has carried out a wide-spread questionnaire addressed to all water supply companies in the GLOWA-Danube model area – well over 1000 in total in Bavaria, Baden-Wuerttemberg. The questionnaire contains questions pertaining to the two distinct fields "economics and pricing" and "technical aspects", and aims at gathering information regarding the present day situation of the water supply system, the developments over the past 10 years as well as planned developments for the immediate future. A return of more than 150 questionnaires (~10%) provides a good basis for statistical analysis, categorisation, definition of types and regionalisation.

5.1 Integration of the model WaterSupply in Danubia

Data on the potential water resources (quantity and quality) for each proxel is obtained from the Groundwater and Rivernetwork objects at each time step. This data is used as input for the model calculations performed in the model *WaterSupply*. The cost for water treatment for the respective raw water qualities and the costs for transportation and distribution are determined based on data obtained from statistical surveys and from water suppliers. The model aggregates the water demand of the Actors, which is exchanged within the DANUBIA network. If the supply meets the demand, the model determines the economically and ecologically best possible source of water and conveys the necessary extraction rates to the resources models. Should the supply side not be able to meet the demand, the model uses priority rules..

The DANUBIA concept allows to represent the various and far-ranging aspects and implications of water supply in the technical and socio-economic field as well as the close relation of water supply and natural resources. An example of a typical problem that reaches beyond the boundaries of the individual disciplinary model, is the interdependency of groundwater and water supply in the question of available groundwater quantity (and quality) at a certain location (proxel) at a certain time step. An exchange parameter calculated by the groundwater model, the "maximumGroundwaterWithdrawal", was defined. This parameter cannot be determined independently for one proxel due to horizontal flow in the groundwater model. It is therefore a function of the water demand and the actual withdrawal that takes place in the neighbouring proxels. The maximum possible withdrawal can therefore only be calculated iteratively using an optimizing algorithm. Various constraints influence the results. It should be mentioned that the maximum withdrawal from a well is not only limited by the hydraulic conditions but can also be restricted because of legal, economical or environmental aspects.

6 OUTLOOK

Using a network-based approach and the discipline-independent diagrammatic modelling language UML, the natural-science basis of the decision support system DANUBIA was designed and implemented. It considers all hydrologic processes related to the water cycle. To evaluate impacts of changing boundary conditions the predictive ability of the models used have to be high. Therefore no model calibration was carried out and model parameter were taken solely from literature review.

It was possible to show, that a realistic simulation of plant growth and water balance can be achieved with the selected approach. On the basis of the results of the water balance calculations as a first step the impacts of different future land uses and climates on the water balance as well as on snow cover and plant growth will be evaluated. For this purpose DANUBIA is being combined with the mesoscale atmospheric model MM5 (Grell, 1994) to model the effect of changing atmospheric composition and external large scale climate forcing on the regional climate and hydrology in the Upper Danube basin. At the same time socio-economic models for the demographic and agricultural development as well as for water supply, household, tourist and industry water use are being developed.

The results of the simulations will be presented to the interested stakeholders. Among them are members of the water management authorities of the different political-administrative entities, the agricultural management authorities, the power industry, the tourist boards. Appropriate scenarios for further simulation runs will be developed in cooperation with them.

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8 ACKNOWLEDGEMENT