

## **GLOWA-DANUBE: SUSTAINABLE WATER RESOURCES MANAGEMENT IN THE UPPER DANUBE RIVER BASIN UNDER CONDITIONS OF GLOBAL CHANGE**

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**Abstract:** The GLOWA-initiative (= Global Change of the Water Cycle), funded by the German Ministry of Research and Education (BMBF), has been established to address the manifold consequences of Global Change on regional water resources in a variety of catchment areas with different natural and cultural characteristics. Within this framework, the GLOWA-Danube project is dealing with the Upper Danube watershed as a representative mesoscale test site (~ 75.000 km<sub>2</sub>) for mountain-foreland regions in the temperate mid-latitudes. The principle objective is to identify, examine and develop new techniques of coupled distributed modelling for the integration of natural and socio-economic sciences. The transdisciplinary research in GLOWA-Danube develops an integrated Decision Support System, called DANUBIA, to investigate the sustainability of future water use. GLOWA-Danube, which is scheduled for a total run-time of eight years to operationally implement and establish DANUBIA, comprises a university-based network of experts with water-related competence in the fields of engineering, natural and social sciences. Co-operation with a network of stakeholders in water resources management of the Upper Danube catchment ensures that practical issues and future problems in the water sector of the region can be addressed.

In order to synthesize a common understanding between the project partners, a standardized notation of parameters and functions and a platform-independent structure of computational methods and interfaces has been established, by making use of the Unified Modeling Language (UML), an industry standard for the structuring and co-ordination of large projects in software development (Booch et al. 1999). DANUBIA is object-oriented, spatially distributed and raster-based at its core. It applies the concept of "proxels" (process pixels) as its basic objects, which have different dimensions depending on the viewing scale and connect to their environment through fluxes. The presented paper excerpts the hydrological view point of GLOWA-Danube, its approach of model coupling and network based communication, and object-oriented techniques to simulate physical processes and interactions at the land surface. The mechanisms and technologies applied to communicate data and model parameters across the typical discipline borders are demonstrated from the perspective of the *Landsurface* object. It comprises the capabilities of interdependent expert models for energy exchange at various surface types, snowmelt, soil water movement, runoff formation and plant growth in a distributed Java-based modelling environment using the Remote Method Invocation (RMI) (Pitt et al. 2001). The presented text summarizes the GLOWA-Danube concept and shows the state of an implemented DANUBIA prototype after completion of the first project-year (2001).

**Keywords:** GLOWA-Danube, DANUBIA, Decision Support System, web-based modelling, integration

## **1. Project Background**

Water affects all economic, cultural, social and ecological aspects of daily life and is a basic component in restoring and maintaining a clean and stable environment. While diverse research disciplines have set global aspects as the centre of their research interests, solitary sciences, 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 knowledge base to solve current and future problems and to answer evermore demanding questions in terms of Global Change Research. Nevertheless, until now no common modeling methods are available to integratively describe the 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 terminology and concepts, comprehension and methodological approaches lead to very specific solutions of disciplinary problems, but do not provide any reliable basis for the interdisciplinary simulation of interacting processes and scenarios of integrated future development.

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

Competition and interaction of numerous water-related stakeholders puts increasing pressure on the natural environment and ecology. Actors in this field are governments, industry, agriculture, scientists, society as a whole and, of course, nature itself. The EU Water Framework Directive (WFD) stresses the importance of Decision Support Systems (DSSs) as a tool in river basin management for sustainable development based on participatory decision making. State-of-the-art DSSs are GIS-based expert systems that allow for the visualization of the environmental impact of alternative measures to be taken in regional water resources management. The WFD highlights many of these issues, and Decision Support Systems seem to be a promising answer to the new management challenges. DSSs try to combine both comprehensive modelling and support of the decision maker and stakeholders. Structuring of problems, integration, information, analysis and learning are decisive steps to be taken in developing and using a DSS. In this process, a DSS facilitates discussion between the involved parties, which may have different views on environmental and security issues with respect to water resources management. A DSS provides an arena where participants can meet, where short- and long-term impacts of proposed actions can be observed in time and space and where the feasibility and sustainability of such actions can be investigated. In order to be able to derive appropriate recommendations for public and commercial stakeholders, it is crucial to accurately describe the complexity of water-related processes in an integrated approach. From such a process description, indicators have to be identified that can play a key role in 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, they must be based on high quality and scientifically valid data, that are sensitive to changes and able to reveal 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-FP4 Environment and Climate programme as well as the EU-FP5 research activity Energy, Environment and Sustainable Development (EESD). These approaches often 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 the framework of the EESD work programme, the project MULINO has been established to provide an operational Decision Support System for the multi-sectoral simulation of human activities, serving for the assessment and management of the sustainable use of water resources at the catchment scale. A GIS-based integration methodology of socio-economic and environmental modelling techniques is designed to support water management for various decisional cases

in representative European catchments. In a two-year project, MODULUS (Engelen 2000, [http://www.riks.nl/RiksGeo/proj\\_mod.htm](http://www.riks.nl/RiksGeo/proj_mod.htm)) developed a generic spatial Decision Support System for integrated environmental policy-making at the regional level in which individual models from past or ongoing EU-funded projects, operating at very different temporal and geographical scales, were integrated to represent the physical, economic and social aspects of land degradation and desertification in Northern Mediterranean watersheds. Another such 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. Other approaches are making extensive use of modern information and communication technologies such as the Finnish 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 furtheron 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 GIS-based DSS for the geo-referenced exposure assessment for discharged chemicals. The European funded project DAUFIN (<http://www.dow.wau.nl/whh/research/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. The introduced GLOWA-Danube project is thoroughly analysing these and other ongoing initiatives to build up on the elements which are feasible to contribute to the projects efforts.

## 1.2. Project Setup

In order to constructively reply to complex questions regarding the sustainability of water resource management and to cover a wide range of water-related issues in integrated Global Change Research (Fig. 1), GLOWA-Danube comprises a university-based network of experts with water-related competence in the fields of engineering, natural and social sciences. The project consists of a number of core groups (representing the scientific disciplines Hydrology, Remote Sensing / GIS, Meteorology, Water Resources Management – Groundwater, Water Resources Management – Surface Waters, Plant Ecology, Environmental Psychology, Environmental Economy, Agricultural Economics and Computer Science), which develop and run the essential modules in DANUBIA, and several bridge groups (representing the scientific disciplines Glaciology, Remote Sensing in Meteorology and Tourism Research), which operate specific interfaces in the model framework (Mauser and Ludwig 2002):

Fig. 1: Issues of an integrated Global Change Research in alpine watersheds.

While being scheduled for a total project-runtime of eight years, the complete development process of DANUBIA is subdivided in three consecutive phases, of which the first is currently implemented. Each stage is characterized by specific milestones:

Phase 1: Methodological Functionality (2001 – 2004):

DANUBIA quantitatively describes the interactions of the different disciplines concerned with water fluxes. It covers simple scenarios about the future developments and their influence upon water quantity and quality in the Upper Danube catchment. At present, a first executable prototype has been developed, which already represents the crucial building blocks of the DANUBIA system (see chapter 4)

Phase 2: Complex Scenarios (2005 – 2006):

Procedures are developed in cooperation with stakeholders and are applied for the common evaluation of the sustainability of the various complex scenarios of the future global and regional changes.

Phase 3: Practical Application (2005 – 2006):

DANUBIA is prepared for practical application. It will then, on demand, integratively model the "lead-substances", such as water, carbon, nitrogen, phosphorus, capital and human migration based on approved scenarios and will provide management alternatives for manifold water related problems.

### 1.3 The Upper Danube Watershed

Covering an area of 817.000 km<sub>2</sub>, shared by 15 countries, makes the Danube the second largest river in Europe. GLOWA-Danube is limited to the analysis of the Upper Danube (~77.000 km<sub>2</sub>), defined by the discharge gauge Achleiten near Passau., situated briefly downstream the inflow of the river Inn. The catchment area is characterized by a strong relief energy (altitudes range from 287 m near Passau to Piz Bernina at 4049 m asl), introducing strong physiogeographic and meteorological gradients (precipitation: 650 - >2000 mm/a, evaporation: 450 - 550 mm/a, discharge: 150 - 1600 mm/a, average annual temperature: -4.8–+9 °C). Landuse and the resulting land cover pattern shows a high spatial variability and small-scale changes, due to the dominant human impact. Forestry and agricultural use of different intensity (grassland, farmland) dominate, whereby climatic disfavor in terms of high precipitation and low temperatures limits the present agricultural potential in various parts of the catchment area.

Due to its size and its heterogeneous physiogeographic characteristics, catchment hydrology is determined by numerous factors, which lead to a strong spatial and temporal differentiation of runoff behaviour. All discharge regimes from straight nival through to pluvial occur. Floods also occur frequently. Generally they are caused regionally by convective summer rains in the alpine foreland and in the Alps. However, characteristic large-scale weather patterns (e.g. a Vb situation) combined with snowmelt activity also trigger floods, which have an impact upon the whole Upper Danube region and its tributaries (e.g. the Pentecost Flood of 1999).

The water resources management in the Upper Danube is complex and characterized by the different bordering countries: 73 % of the Upper Danube is managed by the German federal states of Bavaria and Baden-Württemberg, 24 % by Austria and the remaining 3 % by Switzerland, Italy and the Czech Republic. The Inn, as the most important "tributary", contributes up to 52 % of the average discharge of 1420 m<sup>3</sup>/s to the discharge measured at gauge Achleiten downstream of Passau.

With approx. 8 Mio. inhabitants the catchment area of the Upper Danube has a high density of population of more than 100 inhabitants / km<sub>2</sub>. The major part of the water for the supply of the larger cities and the industry originates in the pre-alpine region and the Alps. The most important industrial agglomerations are Munich (1.2 Mio. inhabitants), Augsburg (260'000) and Ingolstadt (115'000) and the "chemical triangle" Burghausen.

For flood protection, hydropower generation and water resources management purposes, the discharge of all important tributaries of the Upper Danube has been regulated through reservoirs. To a large extent, their management is determined by the dynamics of the snow and ice storage in the Alps. At present, reservoir management is separately coordinated by the different administrative entities involved in hydropower production. Hence a high potential to optimize the current management practice does exist. Several kilometres of the Upper Danube are navigable and are part of an important international waterway connecting the Black Sea with the North Sea. This waterway is already used to export water out of the catchment area of the Upper Danube into the Rhine-Main region and beyond. Increasing demand for water in the future due to a more intensive and more coordinated water use throughout Europe will put increasing pressure on the export of water out of the catchment area of the Upper Danube. However, neither the ecological and socio-economic effects of such perspectives nor the environmentally sound volume for such a transfer of water resources has been determined so far.

Fig. 2: Landuse (derived from CORINE) and topography of the Upper Danube catchment area (1 km spatial resolution).

### 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 than by a lack of substantial definition and analyses of the various existing conflicts, especially in terms of the Danube's possible future functions.

Due to the strong natural and socio-economic gradients in the catchment area, the Upper Danube qualifies as a prototype for Global Change Research in numerous ways. A complex and diverse administrative structure, consisting of three countries and two German federal states, currently employs very different strategies in mediating water use conflicts and lacks coordination between the specific economic and political interests in terms of water resources management.

The strong usage of all natural resources connected 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 used in the production of goods. At present, the strongest 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). In the course of the future catchment related water management of the European water resources, present water supply structures (e.g. currently 2200 water suppliers in Bavaria) will undergo a radical centralization, although no common strategy has yet been developed among the involved parties.

Further strong conflicts of use also exist 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 against each other 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 possibilities due to natural hazards, such as 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 this case. A steady decrease in the groundwater levels in the alpine foreland has also been observed for almost 30 years. The causes and the 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 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<sub>2</sub> concentrations, especially at higher altitudes changes in agricultural production goals (quality vs. quantity) and the structure of agricultural industry in Germany, and the conspicuous deterioration of the prerequisites for agricultural production in the Mediterranean area due to decreased precipitation. As a result, the Bavarian alpine foreland may 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 circumstances.

## **2. The Decision Support System DANUBIA**

The major objective of GLOWA-Danube is to develop and validate integration techniques, integrated models, and integrated monitoring procedures and to implement them in the network-based Decision-Support-System DANUBIA. DANUBIA contains the essential physical and socio-economic processes that are required for realistic modeling of water fluxes in mountain-foreland situations. Above all, the lateral flow, the relationships between the upper and lower river sections, the meteorological gradients as well as the specific consideration of sensitive boundary areas will be taken into account. It will be regionally transferable and thus applicable for a wide range of catchments. Within the DANUBIA system, a decision-making component has to be established that decides a change in land use and land cover, and decides a change in water use. Figure 3 illustrates various

pressures that could be produced by the model's components. They are gathered in so-called containers, where the actual decision-making process takes place. The exact definition of this process is still under discussion; in a first version, it will comprise a hierarchical decision-making according to pre-defined rules by the project partners. These rules rank the occurring pressures according to given weights. Later on, more intelligent and flexible rules will be adopted, in close collaboration with the project's stakeholders. Cost-benefit analysis can provide decision rules where rational decisions are to be taken with the objective of utility maximisation. Fuzzy logic techniques might prove to be more suitable, if no precise weighting is possible. Multi-criteria analysis and decision aid are discussed as a possible solution for complex scenarios, when interacting decisions have to be made.

Fig. 3: Scenario generation and decision making in DANUBIA

DANUBIA delivers the basis to evaluate management alternatives concerning a foresighted water management and sustainable development of the fluxes of water and matter at regional scales under consideration of global eco-systematic connections and socio-economic boundary conditions (Mauser and Ludwig 2002). Finally, DANUBIA will be made available to all parties concerned with water-resources-management (policy and administration, planning agencies, non-governmental organisations (NGOs), science and economy) as a planning and management tool. GLOWA-Danube's long-term objective is to provide a decisive contribution to developing a globally applicable tool for the simulation and comparison of sustainable development alternatives for a wide range of environmental conditions.

Skrytý text

## **2.1 The Integration Concept**

The methodology used to develop DANUBIA applies integrative numerical, network based models, integrative analyses of complex scenarios and integrative monitoring (e.g. by means of remote sensing). In the area of integrative numerical modelling, the necessity to improve 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 served as the basis to develop a new approach for integration of formerly remote disciplines in GLOWA-Danube:

### **2.1.1 The Unified Modelling Language (UML)**

Firstly, a formal language is used, which enables the involved disciplines to commonly model very complex processes and interactions in an integrated system. This Meta-Modelling language describes the abstract essence of the modelling in a way that is independent of the respective discipline. In software engineering, the Unified Modelling Language UML has been established as a quasi standard for large projects with heterogeneous partners (Booch et al. 1999; Hennicker and Koch, 2001). In the GLOWA-Danube project, UML has been used for the design of the model framework of the DANUBIA system. It was used to formulate the interaction and communication between the natural and socio-economic processes and to check for completeness and functionality, as well as for the definition of all interfaces between the model components. With the common commitment to designed interfaces, a clear and unambiguous basis for the exchange of parameters and variables between the core models could be established. The first major task was to clarify the mutual dependencies between the participating disciplines by identifying the kinds of informations to be exchanged between the different simulation models. Each single model plays two roles, acting as a supplier and also as a user of informations. After a careful (partnerwise) analysis of requested and supplied informations a set of interfaces between GLOWA-Danube models has been identified and graphically documented with the UML. Figure 4 shows the form of interface diagrams in the case of three participating models A, B and C which exchange informations through the interfaces AToB, AToC, BToA and CToB. Circles in the upper right corner indicate interfaces and operations of the form getX() describe services that an interface offers. The model which implements an interface (connected to the interface by a dashed line with a solid triangular arrowhead) is responsible to provide the interface informations which can be used by the client model.

Fig. 4: Interfacing models using UML

In GLOWA-Danube many different models are involved and diagrams of the above form soon become too complex. To overcome this problem five major components have been identified (*Atmosphere*, *Landsurface*, *Rivernetwork*, *Groundwater* and *Actors*) (Figure 5) which group logically related models together. Each component is equipped with a component controller which handles the exchange of informations with other components.

Fig. 5: A simplified UML class diagram of the DANUBIA system

The circles in Figure 5 represent the interfaces between individual model components, over which data and parameters are either imported or exported. Each model component has a concise demand of data (import) and a clear capability to provide information (export) for other components, i.e. it implements one interface (which is used by another model component) and uses another (which is implemented by the other model component) to communicate data and parameters for coupled modelling (Figure 6, compare Table 2).

Fig. 6: UML-based implementation of interfaces between DANUBIA model components (example showing the interfaces between the model components *Atmosphere* and *Landsurface*)

### 2.1.2. A web-based distributed system

A 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 (furtherly called objects) to run in a network on different computers at different locations (namely the places with the most expertise). 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 computer capacity. The standardized communication infrastructure, which is needed for the distribution of the objects in the network, has been implemented in order to integrate the different model elements of various groups, which were developed in different places and with different programming languages. Hence all project partners can maintain their model or various derivatives of their component locally, but contribute at the same time to the global model. Communication between the model components is realized by making use of Remote Model Invocation techniques (RMI) (Pitt et al. 2001). A central database stores all data relevant to more than one component, thus avoiding redundancies and inconsistencies, e.g. the simultaneous use of two different digital elevation models. Data relevant to one component only is kept locally with the component, avoiding unnecessary network traffic (Figure 7):

Fig. 7: The Communication of disciplinary models and execution of local computations by the application of web-based techniques and services over the **www** (using the Remote Method Invocation RMI). Solid lines indicate the model connections, dotted lines show the connections to the local and central database.

Each discipline contributes its part of the complex model compound as an object. In this respect, an object is an encapsulated unit, which pervades a distinct function in the Decision-Support-System and carries out the data exchange and the model synchronization through defined interfaces. Hereby, the object can be implemented in any desired language and can easily be replaced by any improved process description upon availability. This selected concept of a network-based, distributed model composition for integrative modelling is new. Along with the expansion of network technology and the internet, this concept will prevail and provide the basis for interdisciplinary work in the future. In this sense, the project delivers basic research in the development of interdisciplinary integration techniques. The realisation

of the above described concepts is exemplarily demonstrated for the *Landsurface-object* in Chapter 3.

## 2.2 The Modelling Concept

Beyond the use of industry standards, the following characteristics and concepts make certain that the set-up of DANUBIA is feasible: As shown schematically in Figure 8, DANUBIA is *raster based* at its core. This approach simplifies the interdisciplinary description of the interactions between the considered processes, by providing a uniform representation of model space to allow for spatially distributed, raster based model interfaces between core processes of interacting natural and social sciences (such as fertilization - plant growth – evapotranspiration – runoff production – water quality or, snowfall – tourism – water demand) .

Fig. 8: Schematic raster based modelling in DANUBIA using the “proxel”-concept.

DANUBIA uses the *concept of “proxels (process pixels)”*. Proxels are the basic objects 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 has different dimensions depending on the viewing scale, connects to its environment (other proxels) through fluxes. Encapsulation allows for an unambiguous management of involved processes, enables the management of the necessary parameters within an object and carries out data exchange with other objects via defined and standardized interfaces. For further development and improvement, all characteristics of a proxel can be handed down to the later versions of the programs, i.e. are available for reuse, scaling, and refinement. Socio-economic processes (migration, behaviour, market situation, perception, etc.) are also described on the basis of proxels. In DANUBIA, a proxel-area of 1 km<sub>l</sub> 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. While on-going detail studies on land surface processes in selected characteristic sub-catchment areas (~1000 km<sub>l</sub>) of the Upper Danube are performed on assumingly homogeneous micro-scale proxel areas of 1/10 ha to 1 ha, spatial units of 1km<sub>l</sub> comprise considerable heterogeneity of surface characteristics and hence require sub-scale parameterizations, for which the concept of “*Geo-complexes*” has been developed. Its objective is to provide hydrologically equivalent process descriptions across scales (microscale to 1-km<sub>l</sub> proxel) while reducing spatial heterogeneity to its substantial hydrologic information. Each proxel is described as a composition of diverse homogeneous units of vegetation, soil and topography, for which all fluxes can be individually determined. Once the areal fraction of each unit within a proxel is known, these fluxes are aggregated accordingly. Remote sensing plays a major role in dealing with the scale issue of process descriptions in the range of scales addressed by the DANUBIA system. It serves as a supplier of data and parameters for all project partners and is itself a matter of research in terms of a multiscale improvement of existing parameter retrieval algorithms and a run-time assimilation of highly resolved spatial information in the model.

## 2.3. The DANUBIA system architecture

Since the various data have to be available in different time steps, the mutual synchronization of the objects is a central task. This can be prepared with UML and independent of the discipline. These methodological approaches are breaking new ground. The possibility to reuse the developed code (through adaption in object-oriented programming or by wrapping existing models), the easy serviceability of the standardized interfaces and the inherent explicit documentation through the use of the Meta-Modelling Language in this approach, creates new integrative structures between the participating scientists. Figure 9 schematically outlines the system architecture in the case of two co-operating models A and B. For each single model the network communication is hidden by a corresponding wrapper which simulates each remote interface by a corresponding proxy that resides on the client side. The bold dashed lines indicate network borders of local systems. The essential task of the developer of an individual simulation model is the implementation



of the methods `compute()` (called by the time controller, which triggers the execution sequence of model components) and `init()` which is called by the model manager when a simulation is started. During initialization the model accesses the central DABUBIA database for retrieving site descriptions which must be consistent for all participating models. These already implemented methods will be further elaborated to allow semi-automatic generations of Web applications.

Fig. 9: System architecture with time controller and network wrappers

The core groups started with a first implementation of its functionality and continue by gradual improvements of the methods. Building upon this, validation, refinement, and application of the created objects and interfaces will follow with a wide selection of Global Change tasks and scenarios in the Upper Danube catchment. Subsequently to this initial methodological phase, regional stakeholders and interest groups will be included in the validation and improvement as well as in the development and handling of scenarios, in order to assure the relevance and applicability of DANUBIA.

### 3. The *Landsurface-object*

The development of the DANUBIA system requires the supply of functional objects to generate and then validate the coupling and interacting of system components. Due to the commonality in objects of interest, the project partners “Hydrology/Remote Sensing”, “Plant Ecology” and “Glaciology” have in close cooperation combined their existing expertise in an integrated description of interdependent fluxes of energy, water and matter at the land surface (Fig. 10).

Fig. 10: The modelled land surface processes in DANUBIA

These processes are directly coupled and their interactions are examined within the framework of a complex system, namely the *Landsurface-object*. The purpose of this object is to prevent multiple calculations of the same processes in the simulations, establishing an orchestrated framework which appears as a single encapsulated component to interface with the adjacent objects *Atmosphere*, *Rivernetwork*, *Groundwater* and *Actors* (Figure 11). A common analysis of algorithms indicated, that separate building blocks of the available models could be used, but would be implemented with newly restructured interactions. The DANUBIA synchronisation scheme requires an orientation to typical process sequences and related feedbacks in nature, such that each process component is individually computed at the specific locations in the distributed model. Therefore, traditional simulation sequences are rearranged in the *Landsurface-object*, which now comprises the components “RadiationBalance”, “Snow”, “Surface”, “Biological” and “Soil” (Fig. 7), each represented by process-based sub-models.

Fig. 11: Conception of the *Landsurface-object* in DANUBIA

In order to maintain individual responsibilities and avoid inconsistencies, the interdependent processes communicate directly within the *Landsurface-object* and via the WWW.

The new components are designed according to leading competence: The research group *Hydrology / Remote Sensing* is in charge of the development of the components “RadiationBalance”, “Surface” (assisted by *Glaciology*) and “Soil”; “Biological” is under construction by *Plant Ecology* and “Snow” is implemented by *Glaciology*. The object-oriented structure of the *Landsurface-object* allows for parallel evaluations with those components not immediately required at particular locations (such as “Biological” and “Snow”) and, thereby, reduces unnecessary inertness in the network-distributed system. For the implementation of algorithms in newly generated Java source code, a variety of already existing models, such as routines describing the radiation balance of surfaces, the soil water movement and runoff production have been re-written and implemented in DANUBIA-compatible Java code and are currently refined in the process. The division of competence is summarised in Table 1:

Table 1: Assignment of competence to the “Landsurface”-components

The spatial concept of DANUBIA regulates the spatial management of proxels by means of so-called proxel tables, which enable an exchange of spatial parameters in terms of Data Tables. Each proxel is identically equipped with a set of common parameters to define its location in space, its adjacencies as well as some parameters invariable during run-time, such as topography, landuse etc. which are accessible via a central DANUBIA database, from which all further calculations can unambiguously proceed. The computation of the single terms (Table 1) demands a concise internal definition of model sequence. While the *Landsurface-object* initializes with an hourly timestep at the DANUBIA TimeController (developed by the project group *Computer Science*) for communication with its environment, the internal process chain has to be finer resolved to assure short-term response of data and parameters. Therefore, all components of the *Landsurface-object* are processed within the model timestep and hence fed back to external data input with a maximum delay of one (model-) hour (Fig. 12).

Fig. 12: Sequence of distributed calculations of the *Landsurface-object* within the DANUBIA model time-frame

The Unified Modeling Language UML has been excessively utilised to define the interfaces between the components of the *Landsurface-object* and to organize the exchange of data and parameters with the neighbouring objects *Atmosphere*, *RiverNetwork*, *Groundwater* and *Actors* via the *LandsurfaceController-object*. Table 2 summarizes the parameters, which are exchanged between the *Landsurface-object* and its neighbours via the mutually concerted interfaces.

Table 2. Summary of data and parameter import and export of the *Landsurface-object*

In addition to an explicit structure, UML provides the opportunity to generate Java-source code from its class diagrams. This function has been used to build the basic code framework of the *Landsurface-object*, which has been filled with functional content based on already existing, well tested model components taken from PROMET (Mauser and Schädlich 1998, Strasser and Mauser 2001) and PROMET-V (Schneider and Mauser 2000), PROXEL<sub>NEE</sub> (Reichstein 2001), BIOME<sub>BGC</sub> (Thornton 1998) and PEV-SD (Escher-Vetter 2000).

#### 4. Status of implementation of DANUBIA (version 0.9)

All sub-components of the *Landsurface-object* have been fully transferred into a DANUBIA-compatible structure and extended to executable DANUBIA components. The embedding in an outer wrapper as well as the connection to the DANUBIA TimeController is completed (see Fig. 9), so that a preliminary runtime-version of the *Landsurface-object* in the DANUBIA (version 0.9) is now available. After 15 project months, this prototype combines preliminary versions of the following expert model objects for execution in a web-based modelling environment:

<i>Atmosphere</i> object:	to spatially and temporally interpolate measured meteorological parameters
<i>Landsurface</i> object:	to model water and energy fluxes at the land surface (comprising the five different model components <i>RadiationBalance</i> , <i>Snow</i> , <i>Surface</i> , <i>Biological</i> and <i>Soil</i> )
<i>River Network</i> object:	to model water fluxes in surface waters
<i>Skrytý text</i>	
<i>Groundwater</i> object:	to model water fluxes in the saturated zone
<i>Skrytý text</i>	
<i>Actors</i> object:	to model water fluxes in households

First applications of the DANUBIA prototype have been performed on a LINUX cluster, using nine nodes to run the available model components. Analyses showed, that the system itself is running, the interfaces and the data exchange between the components are performing correctly and the resulting spatial and temporal patterns of the different parameters are consistent. The framework design allows fast and simple changes to e.g. a sub-catchment, another period or another spatial resolution, provided that the data are available and algorithms are suitable for another spatial scale.

Efforts are now under way to quickly implement the respective model components of the participating social science disciplines, which include a variety of actor models, such as farmer, tourist, water supplier and economist.

## 5. Summary and Perspectives

GLOWA-Danube is breaking new ground in many areas. The integration of expert knowledge of various disciplines plays the key role for the success of the project. The following aspects are of central importance:

- the agreement to a common raster-oriented model structure between all involved project partners,
- a common meta-modelling language, which is independent of disciplines,
- the clear identification of common interfaces for information exchange between sub-models within the DANUBIA DSS,
- a common documentation accompanying the technical and scientific advances
- the establishment of a multi-level communication structure between the project groups consisting of bilateral cooperation, working groups, workshops, and colloquia.

Two essential methods proved to be very valuable for the development of integration methods for the modelling of the water flow in the test area: The application of the meta-language UML for the formalization and structuring of the interdependence of sub-models, and the technical coupling of these sub-models over the internet by Java-based RMI technology.

Thus, the project is to be conceived as a distributed expert network and developed on the basis of re-useable, refineable, and documented sub-models. The applied industry standards are open, exactly designed and coded, excellently documented and expandable. Extensive experience about their applications in industry is available (Jones, C. 1996). The beginning of the network development has taken place in the areas of *Hydrology*, *Plant Ecology*, *Glaciology*, *River Network*, *Groundwater* and *Psychology*. The network modelling prototype created during the first year period now serves as the fundamental platform to which additional sub-models can be coupled and from which further developments can descend.

In order to develop mesoscale models and yet to interpret the results at the microscale, transition in the process description from microscale to mesoscale and vice versa becomes necessary. This is a common cross-cutting theme to almost all projects partners which have a high degree of experience in this field of research. Models dealing with sub-scale processes have already been developed in different groups, and developed upscaling techniques from microscales to mesoscale have already been proven to be very successful in different disciplines. In this respect, remote sensing is used as a fundamental tool for integrative multiscale monitoring and for regionalization purposes. Additionally, the already mentioned commonly agreed upon raster-based model structure makes the transfer of scaling-techniques relatively easy. Data from diverse sources, like in-situ measurements and especially remote sensing, will be assimilated in the development and validation process of DANUBIA to promote these efforts.

A large step towards a common description of the processes in the natural and social sciences has been taken in the first year of the project (2001). The current achievements are now expanded and refined to create a concise and applicable system, which will serve the decision making process in a wide range of water related issues.

Within the first working period it has been shown that a web-based model integrating natural as well as socio-economic sciences can be performed using an object-oriented approach.

The next steps during the first research phase are focusing on:

- the implementation of additional models: a farming actor, a tourism actor, drinking water supply and an economy actor
- the direct coupling of the MM5 mesoscale meteorological model instead of the current atmosphere model that depends on data from meteorological stations, in order to be able to model the future
- improving the current simplified model-prototype
- validating the model results
- testing to what extent the current process description are suitable for other spatial scales
- running first scenarios

One of the major topics in the next research phase will be testing the possibilities of transferring DANUBIA to other regions, especially moving downstream the Danube catchment.

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### **5. Literature**

- Booch, G., Rumbaugh, J, Jacobson, I.: The Unified Modelling Language User Guide. Addison-Wesley, Reading, 1999
- Engelen G. (ed.): 'MODULUS: A Spatial Modelling Tool for Integrated Environmental Decision-Making', Final Report, Contract ENV4-CT97-0685, Directorate General XII, Environment IV Framework, Brussels, Belgium, 2000
- Escher-Vetter, H. : Modelling meltwater production with a distributed energy balance method and runoff using a linear reservoir approach – Results from Vernagtferner, Oetztal Alps, for the ablation seasons 1992 to 1995. In: Zeitschrift f. Gletscherkunde. u. Glazialgeol., Nr. 36, pp.119-150, 2000
- Hennicker, R., Koch, N.: Systematic Design of Web Applications with UML. In: K. Siau, T. Halpin (Eds.): Unified Modeling Language: Systems Analysis, Design and Development Issues, Hershey, PA (USA), London (UK): Idea Group Publishing, 2001.
- Jones, C: Patterns of Software System Failures and Success, Int. Thomson Computer Press, 1996
- Mauser, W. and Ludwig, R.: GLOWA-Danube – A research concept to develop integrative techniques, scenarios and strategies regarding global changes of the water cycle. In: Beniston, M. (Ed.): Climatic Change: Implications for the hydrological cycle and for water management. Advances in Global Change Research, Vol. 10. Kluwer Academic Publishers, p. 171-188, 2002
- Mauser, W. and Schädlich, S.: Modeling the Spatial Distribution of Evapotranspiration on Different Scale using Remote Sensing Data, J. Hydrol. (Special BAHC Issue), Vol. 212, p. 237-250, 1998
- Mauser, W., J.D. Tenhunen, K. Schneider, R. Ludwig, T. Stolz, R. Geyer, and E. Falge: Assessing Spatially Distributed Water, Carbon, and Nutrient Balances at Different Scales in Southern Bavaria; in: Tenhunen, J.D. et al. (eds.) Ecosystem Approaches to Landscape Management in Central Europe. Ecological Studies, Vol. 147. Springer Verlag. Berlin, 2000
- Pitt, E., McNiff, K. and McNiff, K.: Java.rmi: The Remote Method Invocation Guide. Addison Wesley Professional. Reading, 320 p., 2001.

Reichstein, M.: Drought effects on ecosystem gas exchange in three Mediterranean Ecosystems – A combined top-down and bottom-up analysis of eddy covariance and sap-flow data. PhD thesis Univ. Bayreuth, pp. 150, 2001

Schneider, K. and Mauser, W.: Using Remote Sensing Data to Model Water, Carbon and Nitrogen Fluxes with PROMET-V. In: Remote Sensing for Agriculture, Ecosystems and Hydrology, SPIE Vol. 4171, p. 12-23, 2000

Strasser, U. and Mauser, W.: Modelling the Spatial and Temporal Variations of the Water Balance for the Weser Catchment 1965-1994; J. Hydrol., Vol.. 254, p. 199-214, 2001

Suleiman, R., K.G. Troitzsch, N. Gilbert (Ed.): Tools and Techniques for Social Science Simulation, Physica Verlag, Heidelberg, 2000

Tenhunen, J.D., P. Kabat (Ed.): Integrating Hydrology, Ecosystem Dynamics, and Biogeochemistry in Complex Landscapes, John Wiley & Sons, Chichester, 1999

Thornton, P.: Biome-BGC: Description of a numerical simulation model for predicting the dynamics of energy, water, carbon and nitrogen in a terrestrial ecosystem. PhD thesis Univ. of Montana, USA, 1998

## Figures

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Fig. 8: Schematic raster based modelling in DANUBIA using the “proxel”-concept

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## Tables

- Table 1: Assignment of competence to the “Landsurface”-components  
Table 2. Summary of data and parameter import and export of the *Landsurface-object* in DANUBIA

Fig. 1: Issues of an integrated Global Change Research in alpine watersheds

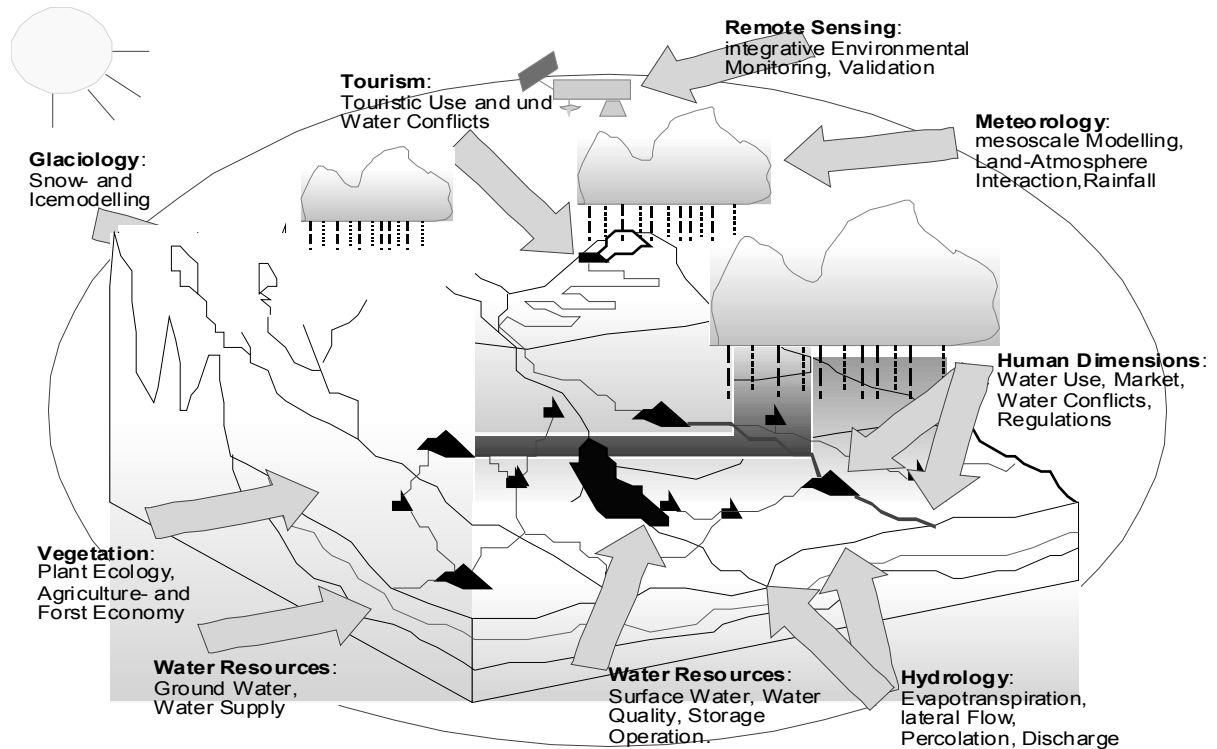


Fig.2: Landuse (derived from CORINE) and topography of the Upper Danube catchment (1 km spatial resolution)

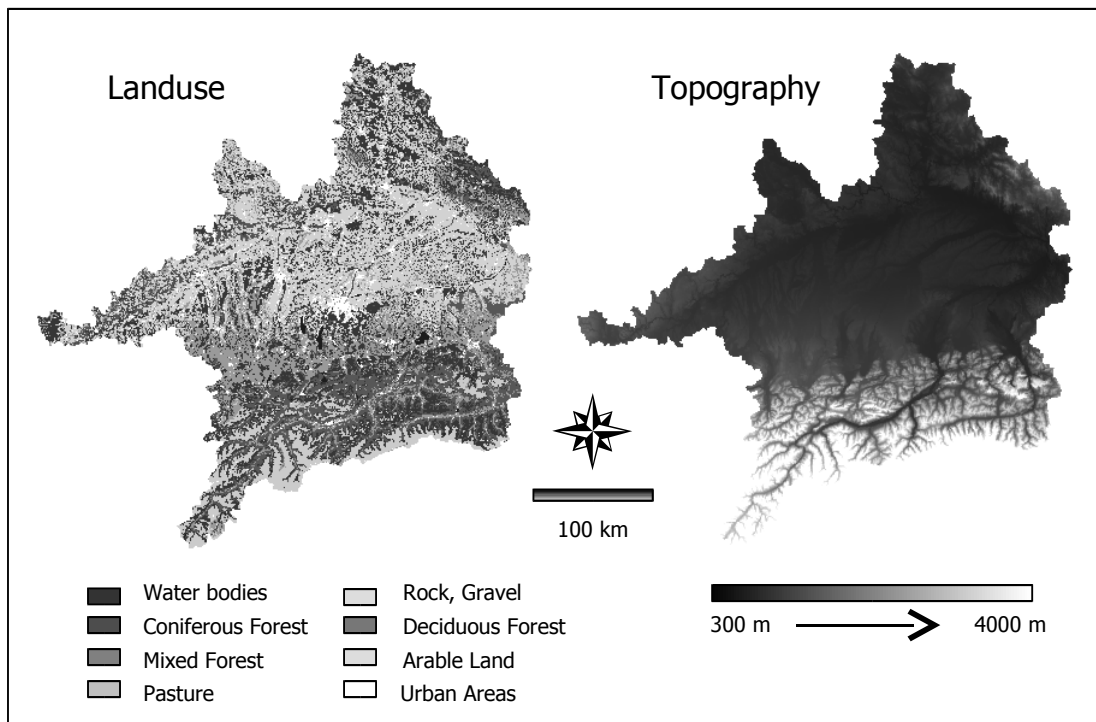




Fig. 3: Scenario generation and decision making in DANUBIA

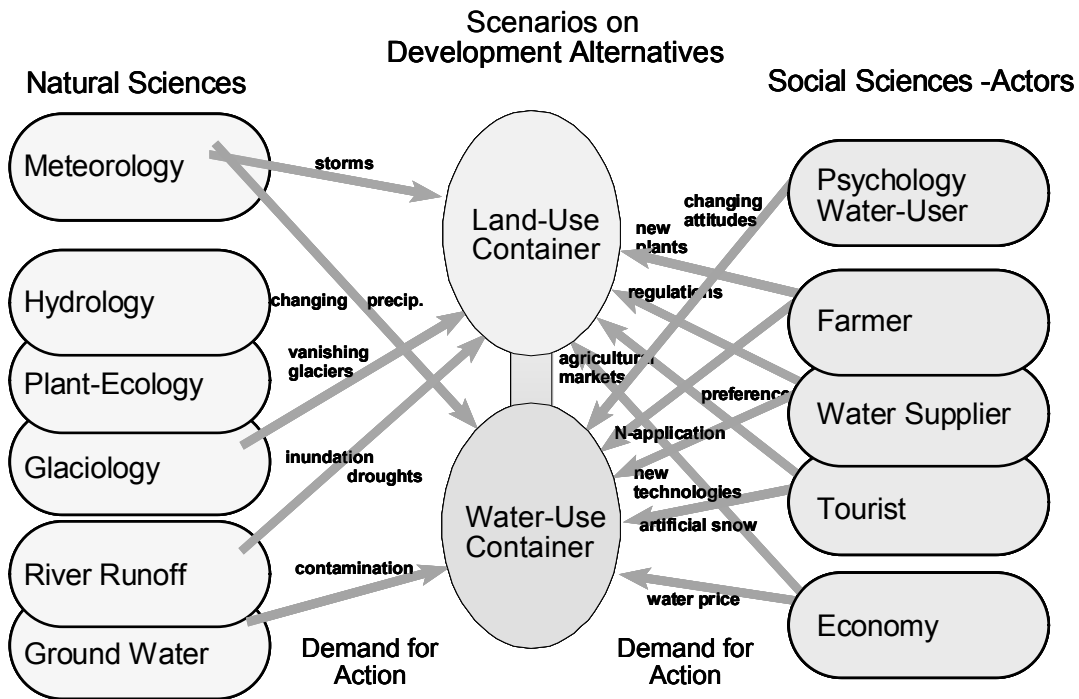


Fig. 4: Interfacing models using UML

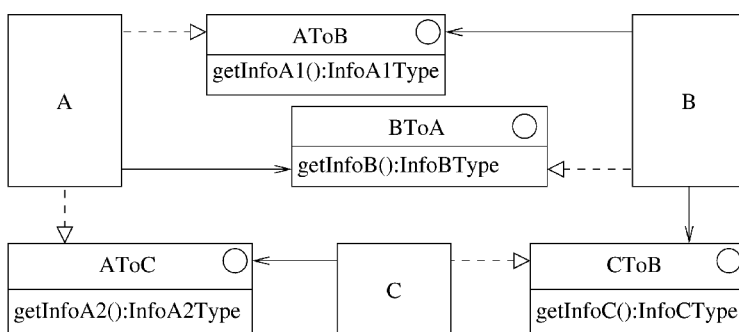


Fig. 5: A simplified UML class diagram of the DANUBIA system

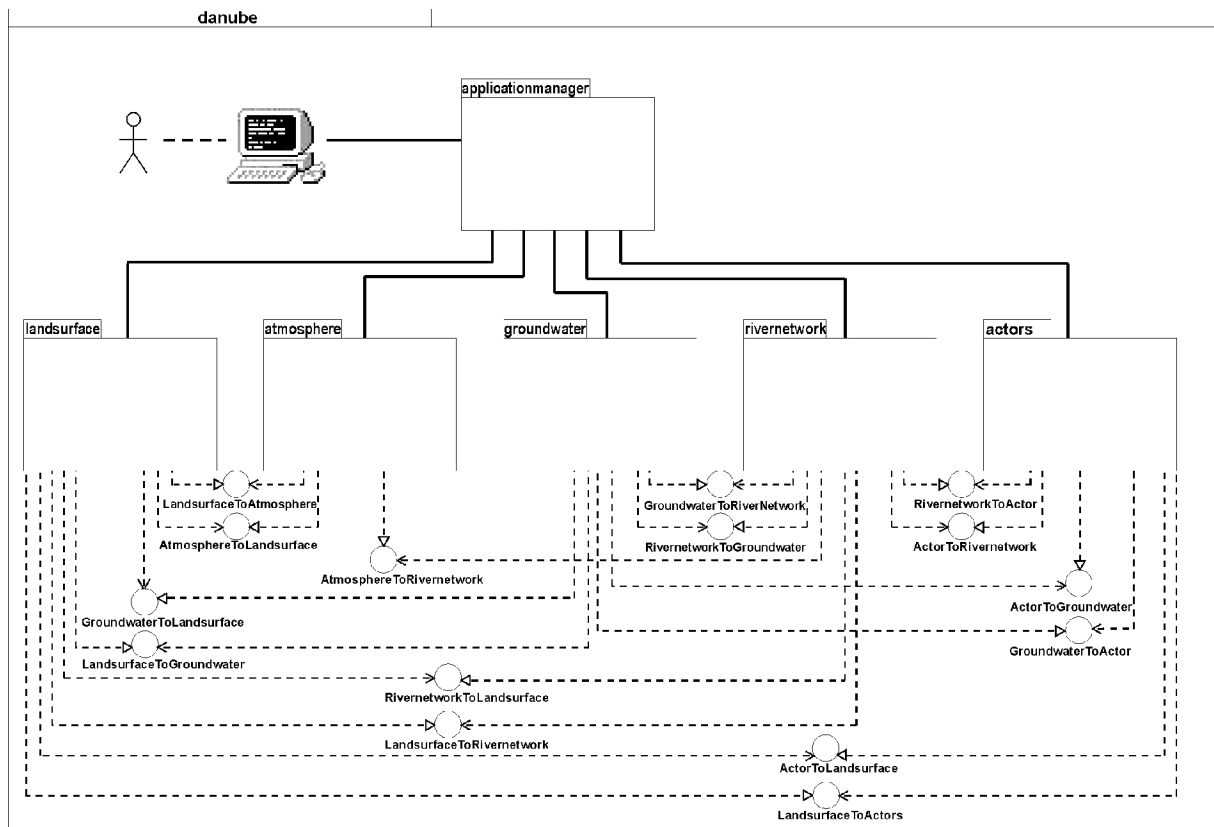


Fig. 6: UML-based implementation of interfaces between DANUBIA model components

(example showing the interfaces between the model components *Atmosphere* and *Landsurface*)

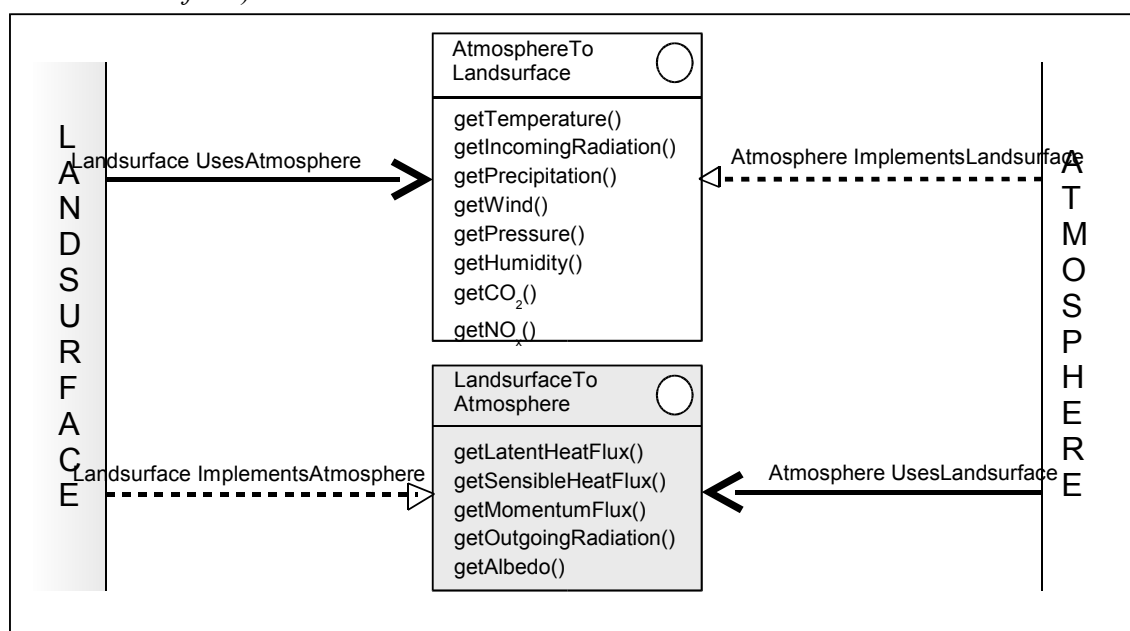


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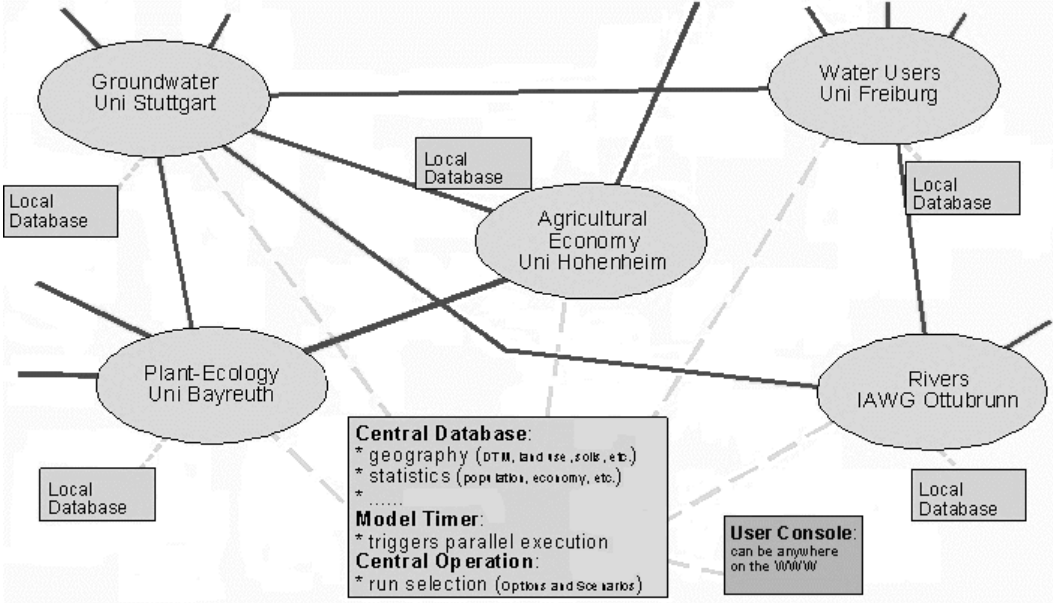


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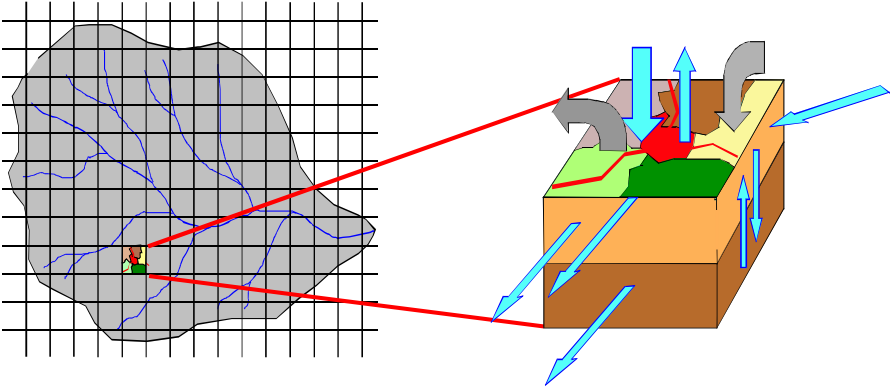


Fig. 9: System architecture with time controller and network wrappers

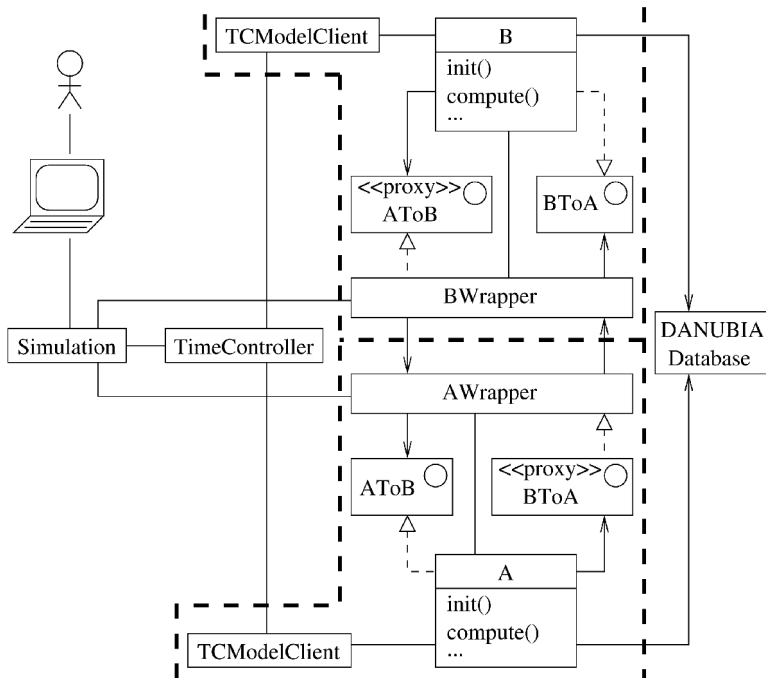


Fig. 10: The modelled landsurface processes in DANUBIA

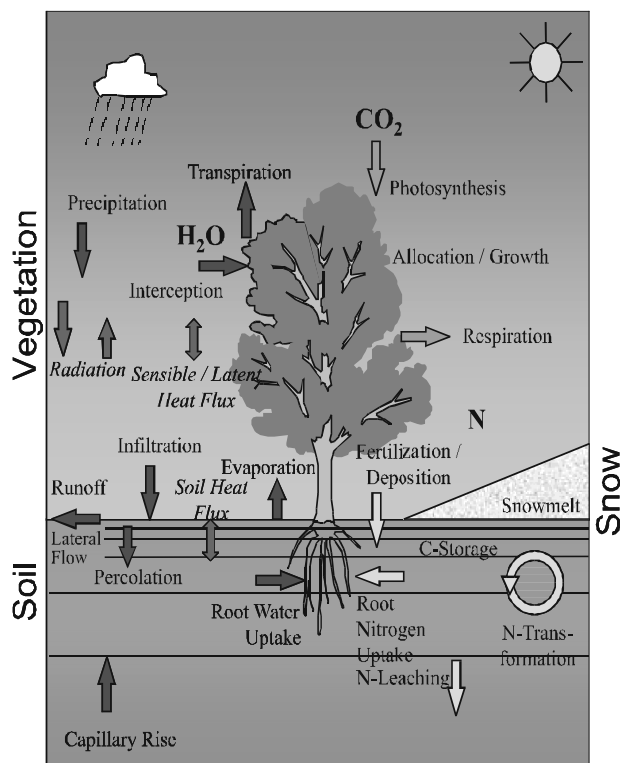


Fig. 11: Conception of the *Landsurface-object* in DANUBIA

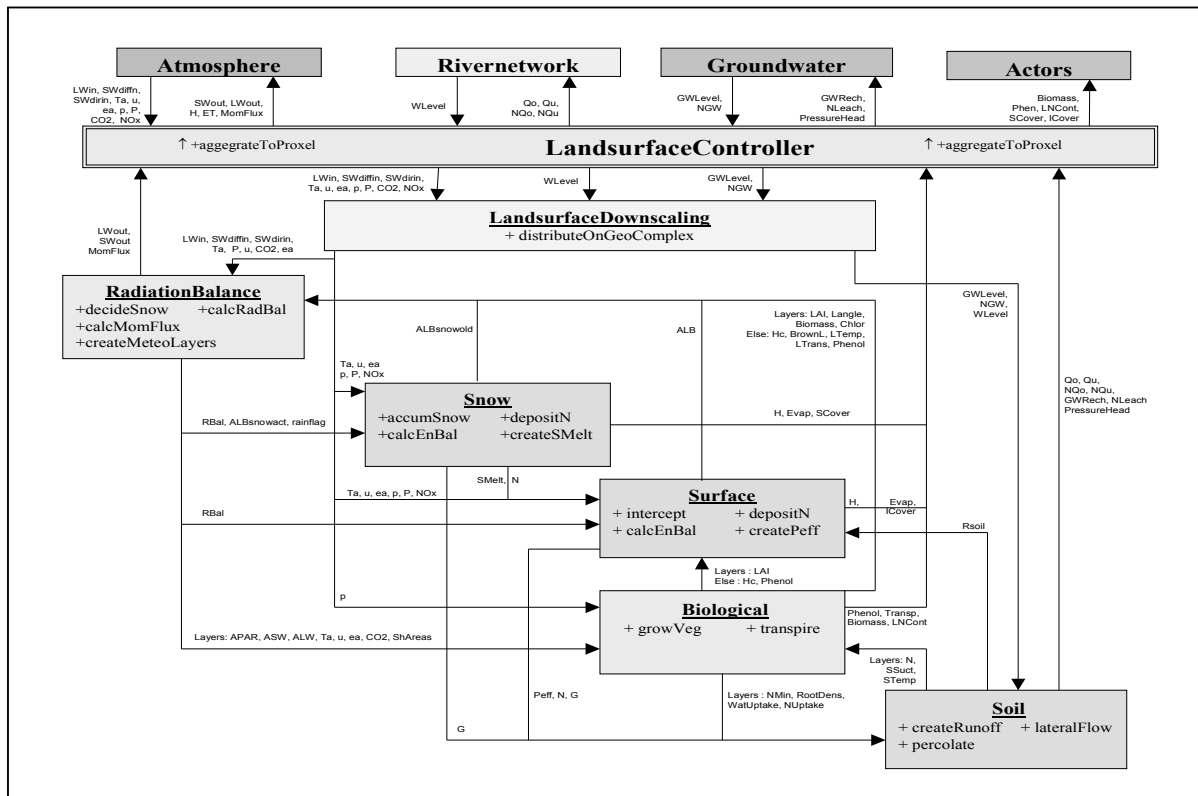


Fig. 12: Sequence of distributed calculations of the *Landsurface-object* within the DANUBIA model time-frame

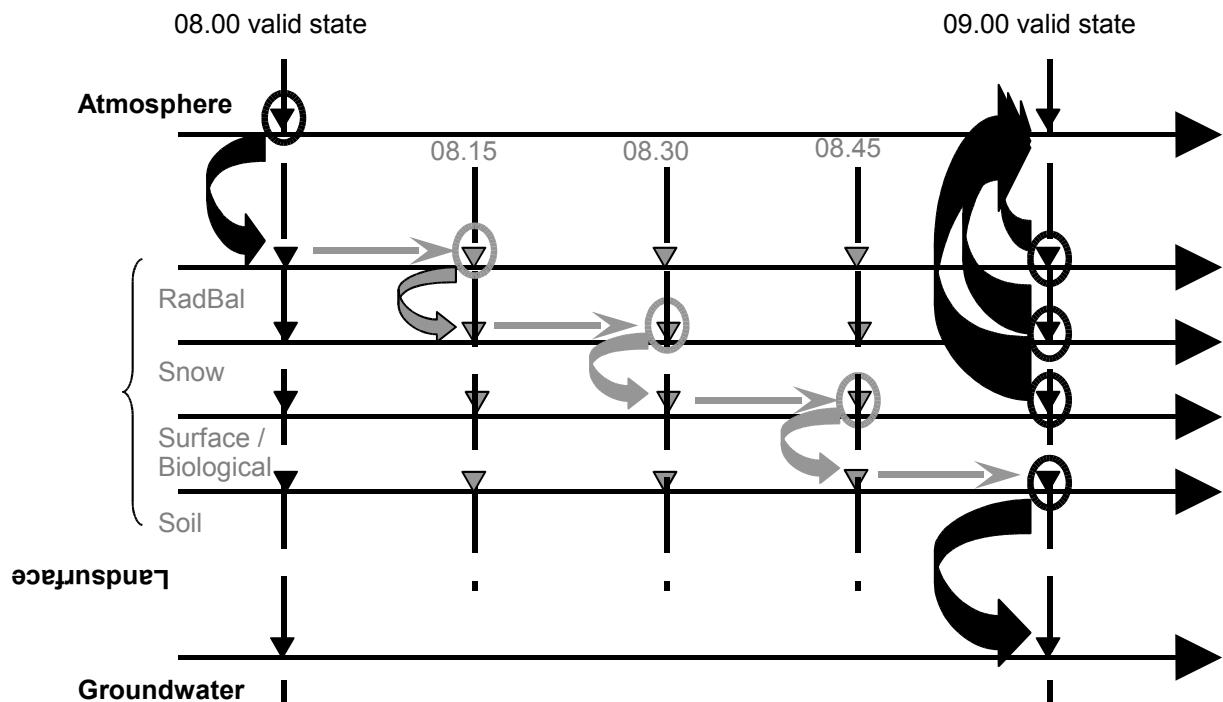


Table 1: Assignment of competence to the “Landsurface”-components

“Landsurface” component	performs the calculation of
RadiationBalance	radiation balance of all surfaces, phase of precipitation, momentum flux, stacked distribution of meteorological parameters in the canopy
Snow	accumulation and depletion of snowpack, energy balance of snowpack, nitrogen deposition in the snowpack, snow meltwater production
Surface	interception and evaporation, effective precipitation, energy balance of all snow-free surfaces, nitrogen deposition at the land surface
Biological	stomatal and canopy conductance, transpiration, photosynthesis and carbon gain, soil CO <sub>2</sub> efflux, N-uptake, N-cycling, ecosystem structural change, plant growth, harvest of usable products
Soil	stacked soil water fluxes (infiltration, exfiltration, groundwater recharge, capillary rise), soil temperature profile, soil nitrogen balance, runoff generation, lateral flow

Table 2. Summary of data and parameter import and export of the *Landsurface-object* in DANUBIA

Landsurface-object	Atmosphere	River Network	Groundwater	Actors
imports	air temperature air humidity precipitation wind CO <sub>2</sub> , NO <sub>x</sub> air pressure incoming radiation	river level	groundwater level nitrogen concentration in groundwater	landuse fertilizing
exports	evapotranspiration, sensible heat flux, momentum flux, outgoing radiation, albedo	surface runoff, subsurface runoff, nitrogen in runoff	groundwater recharge nitrogen leaching	snow cover phenology biomass leaf nitrogen content