GLOWA-DANUBE: INTEGRATED MODELLING OF LAND SURFACE PROCESSES IN MESOSCALE CATCHMENTS USING DANUBIA

Anja Colgan[1], Roswitha Stolz[1], Rolf Hennicker[2], Andreas Kraus[2], Mathias Ludwig[2], Michael Barth[2], Stefan Niemeyer[1], Ralf Ludwig[1], Wolfram Mauser[1]

[1)] Department of Earth and Environmental Sciences,
Chair of Geographical Remote Sensing, University of Munich,
D-80333 München, Germany, tel: +49-89-2180-6671, fax: +49-89-2180-6675
email: anja.colgan@iggf.geo.uni-muenchen.de, w.mauser@iggf.geo.uni-muenchen.de

[2)] Institute of Computer Science, University of Munich,
Oettingenstrasse 67, D-80538 Munich, Germany

Abstract: The objective of GLOWA-Danube is to develop and to validate integration techniques, integrated models, and integrated monitoring procedures to simulate physical and social fluxes in mesoscale catchments. Basic milestones in the development of the integrated decision support system DANUBIA are presented. DANUBIA is designed as an internet-based platform, integrating the distributed simulation models of the participating disciplines, such that transdisciplinary effects of mutually dependent processes can be analysed and evaluated. The development of DANUBIA is based on object-oriented software engineering and web engineering methods, specific data management strategies, an adjusted time management for model synchronisation and the Unified Modelling Language UML. The organisation of space and time in DANUBIA is illustrated in detail. The integrative nature of GLOWA-Danube is exemplarily outlined by the "*Landsurface-object*", which merges the specific expertise of the project partners "Hydrology / Remote Sensing", "Plant Ecology" and "Glaciology" in order to integratively describe the physical and biological characteristics of land surface processes. In order to avoid redundance and thus ambiguous results, the participating sub-models were partially decomposed and restructured to allow for concise and efficient process representation.
Keywords: GLOWA-Danube, Integration, DANUBIA, Decision Support, UML

GLOWA-DANUBE: INTEGRIERTE MODELLIERUNG VON LANDOBERFLÄCHEN-PROZESSEN IN MESOSKALIGEN EINZUGSGEBIETEN MIT DANUBIA

Zusammenfassung: Das Forschungsziel von GLOWA-Danube ist die Entwicklung und Validierung von integrativen Techniken, Modellen und Monitoring-Verfahren zur Modellierung von physikalischen und sozialen Prozessen in mesoskaligen Einzugsgebieten. Wesentliche Schritte bei der Entwicklung des Entscheidungsunterstützungssystems DANUBIA werden aufgezeigt. DANUBIA ist als internet-basierte Plattform konzipiert, auf der die netzwerkverteilten Modelle der beteiligten Disziplinen integriert werden. Ziel ist es, damit die fachübergreifenden Auswirkungen wechselwirkender Prozesse untersuchen und bewerten zu können. Die Entwicklung von DANUBIA basiert auf objektorientierter Software-Entwicklung und Methoden des Web-Engineerings, spezifischen Datenverwaltungsstrategien, einem angepassten Zeitmanagement zur Modellsynchronisierung und auf der Unified Modelling Language UML. Die zentralen Aspekte des Raum- und Zeitmanagements in DANUBIA werden ausführlich dargestellt. Der integrative Ansatz in GLOWA-Danube wird am Beispiel des "Landsurface-Objects" skizziert. Dieses Objekt verbindet die Expertenmodelle aus den Forschungsgruppen "Hydrologie/Fernerkundung", "Pflanzenökologie" und "Glaziologie" zu einer objektorientierten DANUBIA-Modellkomponente, welche die physikalischen und biologischen Prozesse an der Landoberfläche integrativ beschreibt. Diese Umstrukturierung gewährleistet, dass jeder Prozess im Modellverbund nur an der Stelle der größten Fachkompetenz beschrieben wird und somit Redundanzen und konsequent mehrdeutige Ergebnisse vermieden werden.
Schlüsselworte: GLOWA-Danube, Integration, DANUBIA, Entscheidungsunterstützung, UML

1. Introduction

1.1. The GLOWA-programme

In 1999, the German Federal Ministry of Education and Research (Bundesministerium fuer Bildung und Forschung, BMBF) started a programme on the Research of Global Change of the Water Cycle (Globaler Wandel des Wasserkreislaufs, GLOWA). The overall objective of the programme is to investigate the effects of global change on regional water resources and to develop strategies for a sustainable management of water within a catchment area. Central to this objective is the integration of all water-related disciplines in order to find integrated solutions to water resource competition and water use conflicts, in contrast to the disciplinary approaches of the past. To achieve this ambitious objective, atmospheric processes, ecosystem functions and their natural variability as well as the strong influence of human activities have to be accounted for in a scientifically based way. Currently, the GLOWA programme supports five projects in Europe, Africa and the Middle East. One of these projects, GLOWA-Danube, is presented here.

1.2 GLOWA-Danube

The GLOWA-Danube project was chosen to investigate and to explore new integrative techniques and methods, leading to a decision support system for water resource management in the Upper Danube catchment area. The project partners of GLOWA-Danube form a broad scientific basis. 13 different partners from natural as well as socio-economic sciences from Germany and Austria are currently involved in the project.

Co-ordination:	Dept. for Earth and Environmental Sciences, University of Munich
Hydrology / Remote Sensing	Dept. for Earth and Environmental Sciences, University of Munich
Meteorology:	Institute for Meteorology, University of Munich Institute for Meteorology, University of Mainz
Groundwater:	Institute of Hydraulic Engineering-IWSUniversity of Stuttgart
Surface Water:	Institute for Water Research and Geoinformatics IAWG, Munich
Plant Ecology:	Institute for Plant Ecology, University of Bayreuth
Glaciology:	Institute for Meteorology and Geophysics, University of Innsbruck
Precipitation (RS):	Institute for Geography, University of Marburg
Environmental Psychology:	Institute for Psychology, University of Freiburg
Environmental Economy:	Ifo-Institute Munich
Agricultural Economy:	Institute of Farm EconomicsUniversity of Hohenheim
Tourism Research:	Institute for Geography, University of Regensburg
Computer Sciences:	Institute for Computer Sciences, University of Munich
Human Capacity Building:	WAREM, University of Stuttgart

In the first project phase, research is focussed on the development of a prototype of a web-based Global Change Decision Support System called DANUBIA. This tool for integrative environmental monitoring is based on existing data of the study region and on existing disciplinary models for the description of the various water-related processes. The DANUBIA system will be able to produce scenarios of the consequences of future global change and to give support to decision makers by clarifying the impacts of different potential water resource management strategies. With the help of such a system, it will be possible to develop and to analyse scenarios from natural and social science perspectives.

1.3 The study area

The Upper Danube catchment under investigation is defined by the discharge gauge Achleiten near Passau. It covers Southern Germany, the West of Austria, the valley of the River Inn in Switzerland and small parts of the Czech Republic and Italy, comprising about 77,000 km² and 8.2 million inhabitants. The catchment area is characterised by strong gradients in relief, physiogeography and meteorology. Whilst in the southern parts it is a true Alpine catchment, the central region consists of flat to undulating mountain foreland terrain. The northern boundaries are characterised by typical low mountain ranges. The land cover and land use is at present mostly determined by human impact. The water resource management in the Upper Danube is complex and characterised 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 "tributary", contributes up to 52% of the average discharge of 1420 m³/s to the discharge measured at gauge Achleiten downstream of Passau.

Due to the strong gradients in almost all natural and socio-economic factors the chosen study region is highly sensitive to the consequences of future global climate changes. Already existing water use conflicts between agriculture, industry, tourism and a changing population structure may increase severely in the future.

2. The Decision Support System DANUBIA

The major objective of GLOWA-Danube is to develop and to 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 modelling 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 (Mauser and Ludwig 2002).

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. Finally, DANUBIA will be made available to all parties concerned with water resource 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 (Mauser and Ludwig 2002).

2.1 System Architecture of DANUBIA

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 new methodologies in computer sciences during the last years. These form the basis of a DANUBIA system architecture, which is described in the following:

<u>Interfacing DANUBIA model components</u>

A formal language is used, which enables the involved disciplines to jointly model complex processes and interactions in an integrated system. This meta-modelling language describes the abstract modelling essence in a way that is independent of the respective discipline. In software engineering, the Unified Modelling Language (UML) has established itself as a quasi standard for large projects with heterogeneous partners (Booch et al. 1999; Hennicker and Koch, 2001). In the GLOWA-Danube project, UML was used for the design of the model framework of the DANUBIA system (Niemeyer et al. 2002). 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. Each single model plays two roles, acting as a supplier and also as a user of information. After careful (partner-wise) analysis of requested and supplied information a set of interfaces between GLOWA-Danube models were generated and graphically documented with the UML. The DANUBIA system is composed of five model components (*Atmosphere*, *Landsurface*, *Rivernetwork*, *Groundwater* and *Actors*), which group logically related models together (*Fig. 1*).

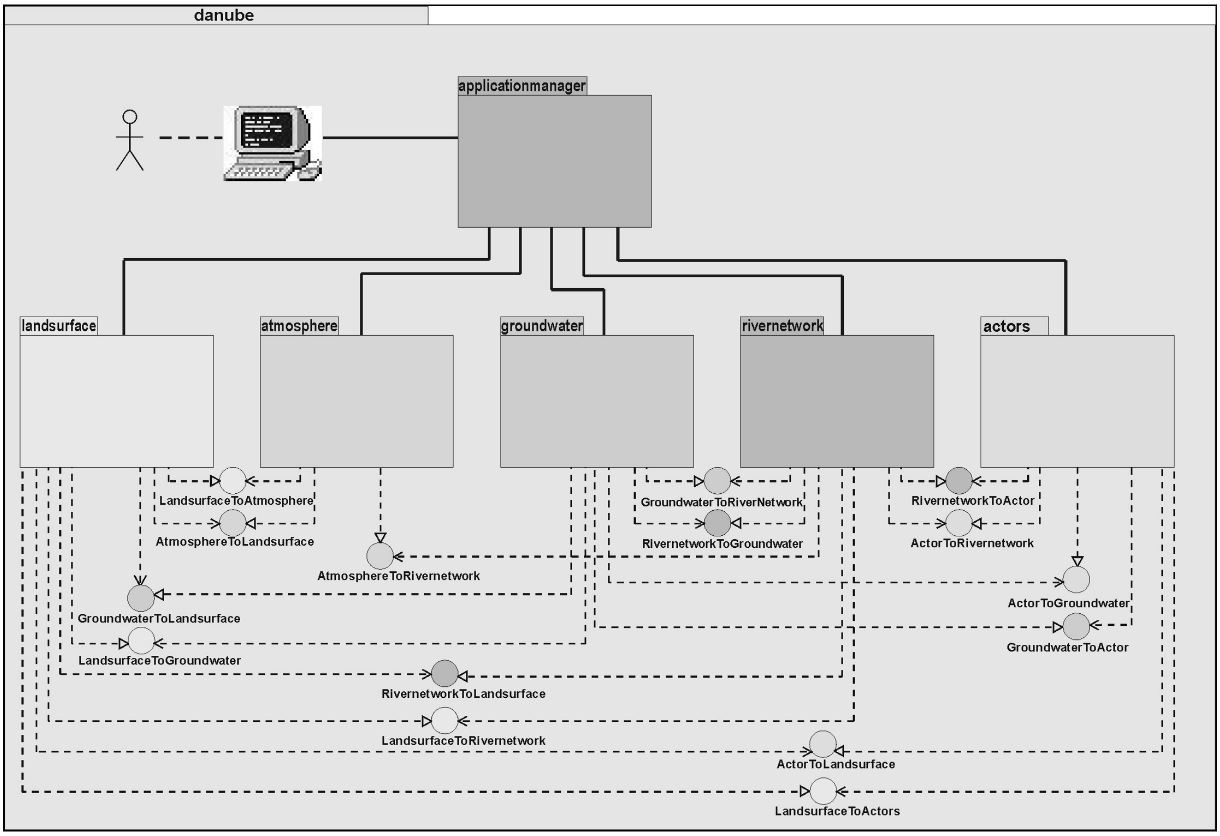


Figure 1. A simplified UML class diagramme of the DANUBIA system

Each component is equipped with a controller handling the exchange of information with other components. *Figure 2* shows a sketched form of an interface diagramme between the components *Landsurface* and *Atmosphere*, which exchange information through the interfaces *LandsurfaceToAtmosphere* and *AtmosphereToLandsurface*. The circles in *Figure 2* represent the interfaces between individual model components, through 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) to other components, i.e. it implements one interface (which is used by another model component) and uses another (which is implemented by the client model) to communicate data and parameters for coupled modelling.

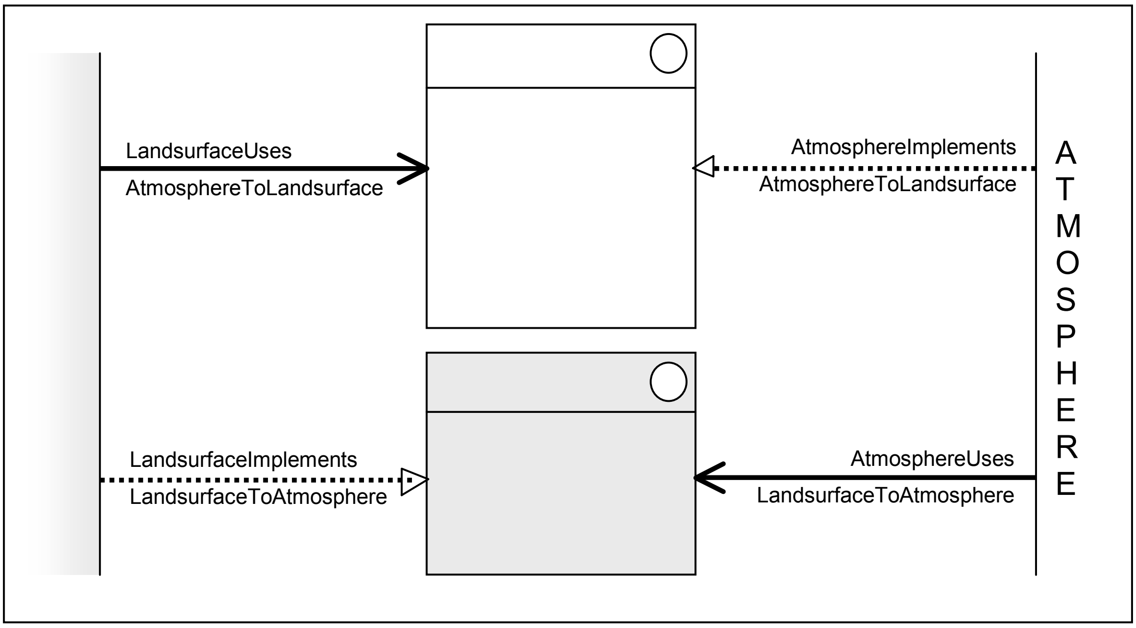


Figure 2. UML-based implementation of interfaces between DANUBIA model components (example showing the interfaces between the model components Atmosphere and Landsurface)

Model synchronisation

Any model simulates water-related processes over a specific period of time (days, months or years). For integrative simulations a global time control is necessary which coordinates the single models to work properly together. A time controller concept, which constitutes the heart of the DANUBIA system, was developed and implemented by the computer science group of GLOWA-Danube. The fundamental task of the time controller is to administrate the overall time period for which an integrated simulation should run and to control the order in which the single models are repeatedly stimulated to perform their next computation step. In particular, the time controller solves the following major issues:

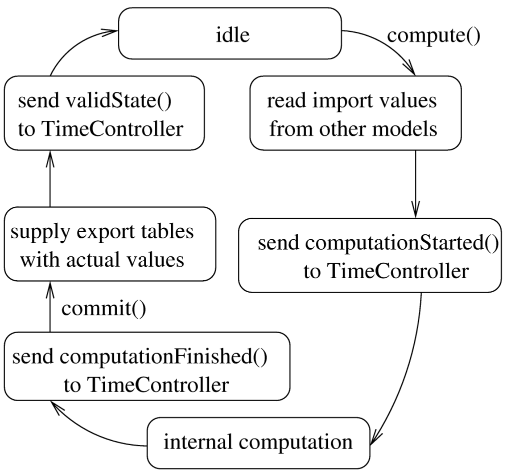


Figure 3. State model for distributed simulations

a) Each simulation model has an individual time step (model time) for which computations are periodically executed (ranging from minutes, like in meteorology, to months, like in social sciences).

b) Values that are accessed through interfaces must be in a consistent state and must be valid with respect to the global simulation time.

For a precise analysis of the coordination of distributed models the state model in *Figure 3*, which shows the general scheme of state transitions performed by each of the GLOWA-Danube components, was developed

The signal compute() is sent from the time controller to the model in order to initiate the next computation step. To ensure consistency of values, each model component supplies its results (as export tables) only when all other models have finished importing data from the previous time step. This condition is controlled by the time controller which explicitly sends a commit() signal if a model is allowed to transfer new values to its export table.

The mutual synchronisation of the objects can be prepared with UML independent of the discipline. The possibility to reuse the developed code (through adaptation in object-oriented programming or by wrapping existing models), the easy serviceability of the standardised 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 4* 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 initialisation the model accesses the central DANUBIA database for retrieving site descriptions, which must be consistent for all participating models (see chapter 3).

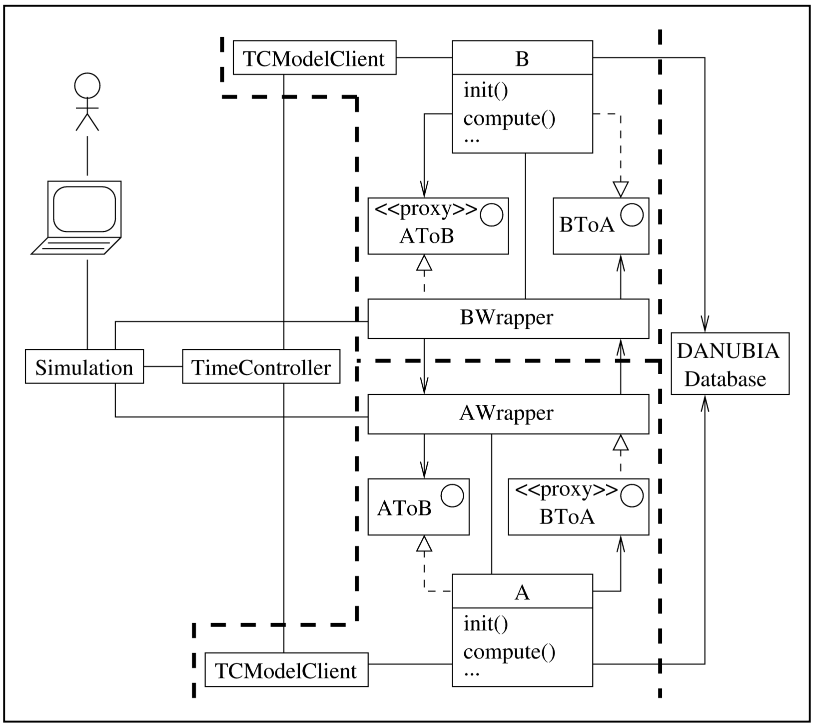


Figure 4. DANUBIA system architecture with time controller and network wrappers

3. Data management

An important requirement during integration of the models in the DANUBIA system is that consistency of data on which simulations are based is ensured. From the modelling point of view data consistency in terms of space, time and content are most important. Additionally data consistency within a storage medium (e.g. a database) is of concern.

To achieve these requirements data management and spatial concept are at a central place in the DANUBIA architecture (see above). The development of a common concept of modelling space included that all project groups adapted to the proxel concept (Niemeyer et al. 2002), the definition of simulation areas as two-dimensional net of proxels and the definition of a common projection.

The data management concept implements the common definition of space by transforming all data to this particular spatial reference. Furthermore, any data that are shared between two or more models must be identical in content, so that no parameter can be described differently by different groups. Since the models run on a distributed system it is necessary to hold and maintain all shared data (e.g. DEM, land use, administrative boundaries) at a central location. For this project a central database offers the best data management implementation.

3.1. Data provision

DANUBIA-simulations for the Upper Danube catchment are based on a 1km x 1km raster. This creates dissimilar problems of scale for the different disciplines; the socio-economic disciplines are required to downscale their models from district boundaries to the 1km raster, whereas the natural science disciplines have to up-scale their models from homogenous microscale (10 – 100m raster) to the mesoscale. The latter are developing methods to use subscale information while modelling at the mesoscale. At three test sites with areas between 100 and 900 km² processes will be modelled at the microscale (30 – 100m). It was therefore essential to obtain data at different scales. The study area spans over 5 countries (section 1.3.). Data on these regions had to be obtained from several national or regional authorities. On one hand this results in a greater effort and expense in locating and purchasing data for the entire catchment. On the other hand, problems arise from the differences in data accuracy and scale. Standard GIS methods were used to resample data (Richards, 1993) from different sources to a common scale, to mosaic the data into single data-layers and to transform the data to the common projection. The data that were purchased include the Digital Elevation Models, the community and district boundaries, data from the German Hydrological Atlas (BMU 2000) and the CORINE land use classification (Bossard et al. 2000). Further, more detailed data on land use and leaf area index (LAI) were obtained through digital analysis of remote sensing data.

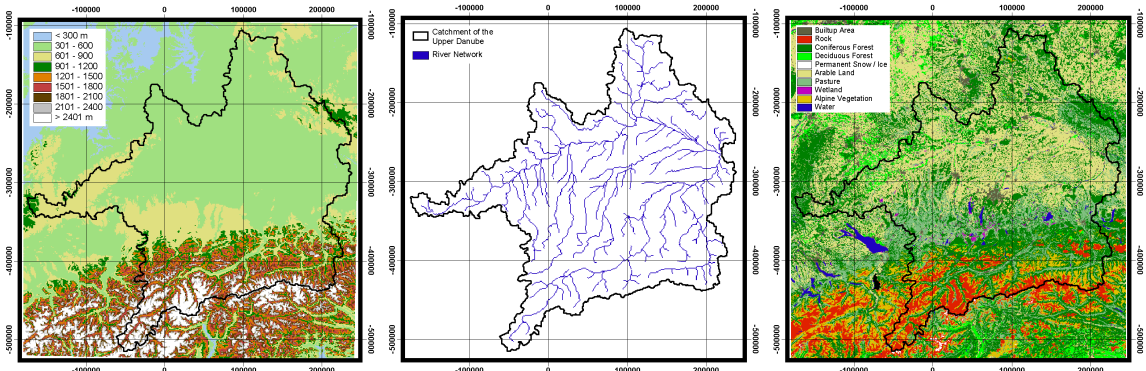
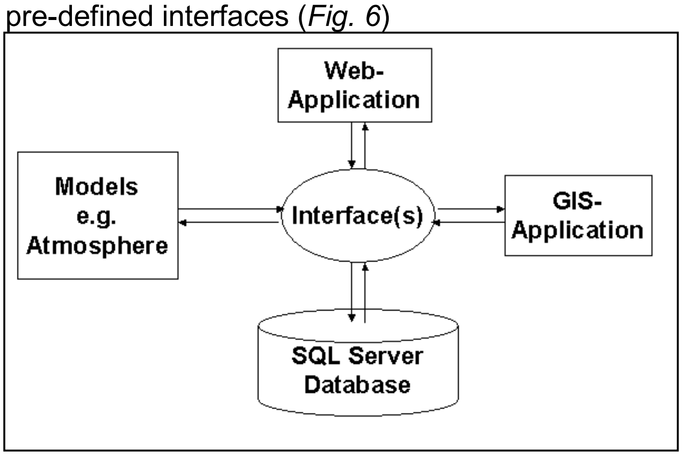


Figure 5. Three examples of data layers purchased and adapted in a GIS to a common projection and resolution

3.2. Central Database

In DANUBIA the database acts as a source of all shared data during model initialisation and as a recipient of selected output data during the model run. The database may also be accessed from the web-user-interface. Access to the database is only possible through pre-defined interfaces (*Fig. 6*)



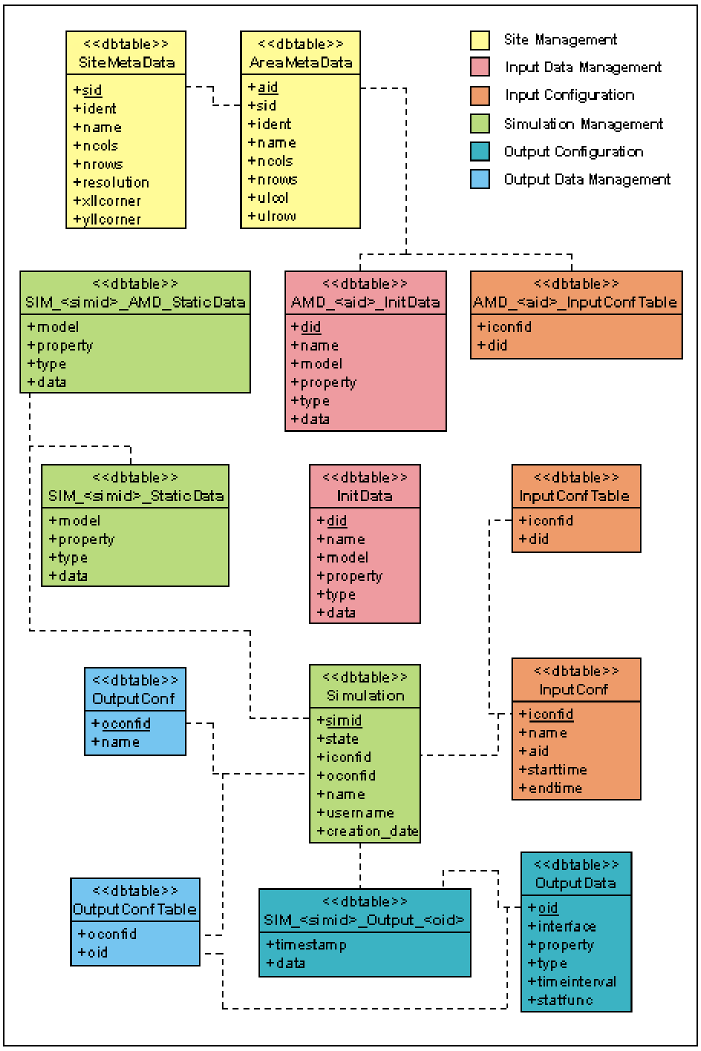
As relational database management system (DBMS), which offers many advantages due to its robustness and simplicity (Barthelme 2000) the SQL Server 2000 was chosen. The spatial data are stored as *binary large objects* (BLOBs). However, data are exchanged between the database and DANUBIA components in the form of objects of a predefined DANUBIA datatype.

Figure 6. Access of various applications to the database server

The structure of the database was designed in order to satisfy all current and future aspects of DANUBIA. It presently features the storage of input and output data and their corresponding simulation area reference, as well as the storage of simulation configuration meta-data. As the requirements of DANUBIA change, the structure of the database may be amended.

Key features of the database:

- Flexible structure to allow for future alterations
- Storage of all shared initialisation data to ensure data consistency
- Storage of user-selected simulation output data in order to answer scientific questions and scenarios
- Storage and management of spatial and non-spatial data in one database



The tables SiteMetaData and AreaMetaData contain information on the study sites for which simulations may be run.

Once the web-GUI (graphical user interface) will be available the user of DANUBIA will able to chose from the list of simulation areas, to view the available input data for that area and to chose a dataset if different datasets are available for one parameter and to select a number of output parameters and their temporal aggregation from a pre-defined list. Spatial input data are related to a specific simulation area (extent, resolution). The input configuration (selected data for initialisation) and output configuration (selected result datasets) for each simulation are stored for future reference (simulation meta-data).

User access to the DANUBIA system and the database via the web-GUI will also be managed through the DBMS.

Figure 7. The database structure

The database component, which was also implemented in Java, provides a mechanism of storage and access to spatial data which is crucial to the DANUBIA system. Each raster layer is stored as a DataTable object (a predefined data type of DANUBIA), which itself is packed into a serialised binary large object (BLOB) and stored in the database. The main advantage is that any type of object (e.g. java.lang.String) may be packed into a BLOB and therefore spatial and non-spatial data can be managed in the same manner. Furthermore any object of a pre-defined DANUBIA datatype can be read directly from the database during initialisation and also can be written into the database during simulation.

4. The Landsurface-object – an example for integrated modelling using DANUBIA

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 research groups “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. 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, establishing an orchestrated framework which appears as a single encapsulated component to interface with the adjacent objects *Atmosphere*, *Rivernetwork*, *Groundwater* and *Actors*. A common analysis of algorithms indicated, that separate building blocks of the available models can be maintained, but need to 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 location in the distributed model. Therefore, traditional simulation sequences are rearranged in the *Landsurface-object*, which comprises the components “RadiationBalance”, “Snow”, “Surface”, “Biological” and “Soil” (Fig. 8), each represented by process-based sub-models. 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 GLOWA-Danube research group “Hydrology / Remote Sensing” is in charge of the development of the components “RadiationBalance”, “Surface” (assisted by “Glaciology”) and “Soil”; “Biological” is constructed by the research group “Plant Ecology” and “Snow” is implemented by the research group “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 (see Niemeyer et al. 2002).

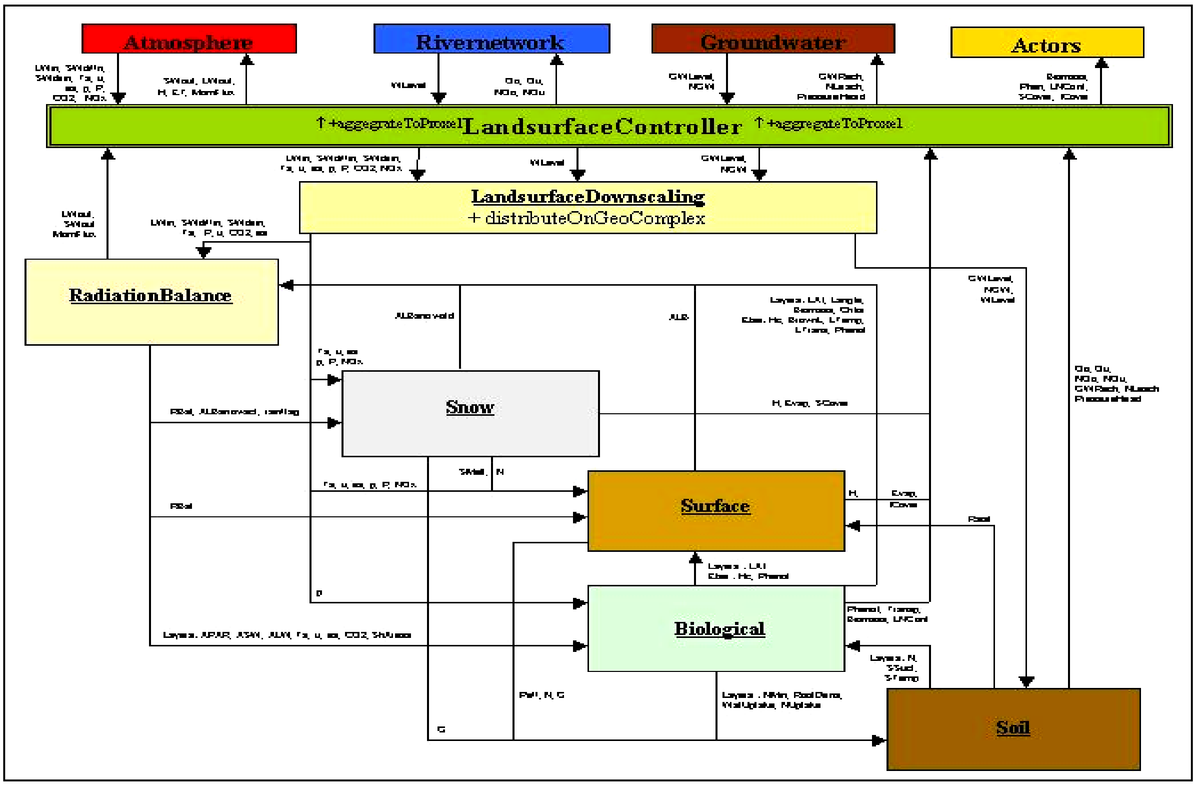


Figure 8. Conception of the Landsurface-object in DANUBIA

For the implementation of algorithms in newly generated Java source code, a variety of already existing models were reused and refined in the process. The division of competence is summarised in Table 1:

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 melt water 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 CO2 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**

The computation of the single terms (Table 1) demands a concise internal definition of model sequence. While the Landsurface-object initialises with an hourly time step at the DANUBIA time controller for communication with its environment, the internal process chain has to be finer resolved to assure the short-term response of data and parameters. Therefore, all components of the *Landsurface-object* perform their computations within one external model time step and results are fed back to external components with a maximum delay of one model time step.

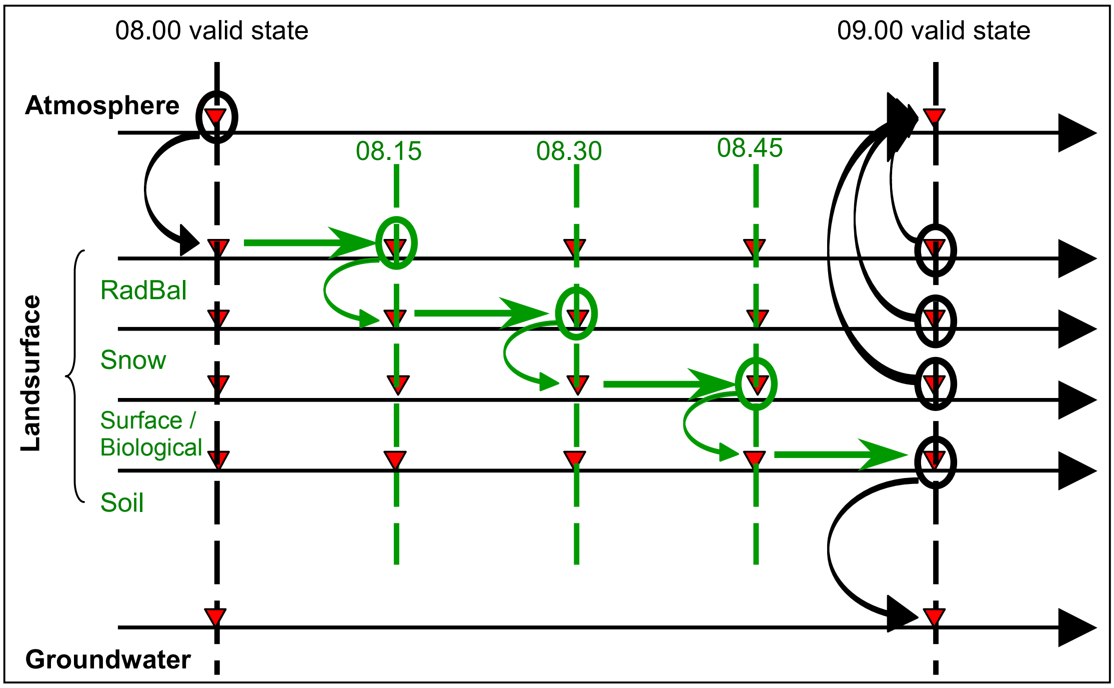


Figure 9. Sequence of distributed calculations of the Landsurface-object within the DANUBIA model time-frame

UML was extensively utilised to define the internal interfaces of the "Landsurface" components and to organise the exchange of data and parameters with the neighbouring objects Atmosphere, RiverNetwork, Groundwater and Actors via the LandsurfaceController-object.

The basic code framework of the Landsurface-object was filled with functional content based on already existing, well tested model components taken from PROMET-V (Schneider and Mauser 2000), $\text{PROXEL}_{\text{NEE}}$ (Reichstein 2001), $\text{BIOME}_{\text{BGC}}$ (Thornton 1998) and PEV-SD (Escher-Vetter 2000). All sub-components of the Landsurface-object were fully transferred into a DANUBIA-compatible structure and were extended to executable DANUBIA components. The embedding in an outer wrapper as well as the connection to the DANUBIA Time-Controller was successfully completed (Fig. 9), so that a preliminary version of the Landsurface-object in the DANUBIA (version 0.9) framework is now available.

4. Perspectives

The core groups of GLOWA-Danube have completed a first implementation of DANUBIA. The executable DANUBIA prototype serves as a proof-of-concept, from which further developments can now descend. The next steps during the first research phase of GLOWA-Danube is to implement additional models to finalise the scheme of a highly integrative approach. 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, the applicability and the regional transferability of DANUBIA.

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6. References

Barthelme, N. : Geoinformatik: Modelle, Strukturen, Funktionen. Springer, Berlin, 2000

Booch, G., Rumbaugh, J, Jacobson, I.: The Unified Modelling Language User Guide. Addison-Wesley, Reading, 1999

Bossard, M., Feranec, J., Otahel, J.: CORINE land cover technical guide – Addendum 2000. Technical report No 40, European Commission, European Environment Agency, Copenhagen, 2000

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Hydrologischer Atlas von Deutschland. Berlin, 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.

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

Niemeyer, S., Mauser, W., Ludwig, R. and Stolz, R.: GLOWA-Danube: Integrative Techniques, Scenarios and Strategies regarding the Global Change of the Water Cycle. In: Proceedings of the 21st Conference of Danube Countries, Bucarest, Romania, 2002.

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

Richards, J. A. (1993): Remote sensing digital image analysis: an introduction, Springer, Berlin

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

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