MODELLING GROUNDWATER FLOW AND NITROGEN TRANSPORT IN THE UPPER DANUBE CATCHMENT (GAUGE PASSAU) WITH REGARD TO GLOBAL CHANGE AND THE DEVELOPMENT OF SUSTAINABLE WATER MANAGEMENT SCENARIOS AND STRATEGIES

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Abstract. The German Federal Government finances the interdisciplinary research project GLOWA-Danube. It investigates the long-term changes in the water cycle inside the Upper Danube basin (77.000 km^2 up to gauge Passau). Its concrete aim is to build a complex numerical tool that combines the competence of eleven different institutes in domains covering the whole water cycle from the formation of clouds to the behaviour of the water consumer. The present article focuses on the work of the hydrogeology group, that is on the construction of a very coarse finite-difference groundwater model, capable of reproducing the complicated pattern of the groundwater flow and nitrogen transport. Geostatistical methods are used to create a hydrogeological model starting from a huge amount of information that is heretically distributed across the catchment area. Procedures aimed to improve and correct the results of the groundwater model on the coarse grid are under development. Additionally, a short review of the Water Resources Management component, its goal and concepts, is given.

Keywords: Danube, groundwater modelling, hydrogeology, geostatistics, upscaling, hydraulic conductivity, water resources management

MODELLIERUNG DER GRUNDWASSERSTRÖMUNG UND DES STICKSTOFFTRANSPORTES IM EINZUGSGEBIET DER OBEREN DONAU (BIS PEGEL PASSAU) UNTER BERÜCKSICHTIGUNG DES GLOBALEN WANDELS UND DER ENTWICKLUNG VON NACHHALTIGEN STRATEGIEN UND SZENARIEN ZUR BEWIRTSCHAFTUNG DES WASSERKREISLAUFS

Zusammenfassung. Das interdisziplinäre Forschungsvorhaben GLOWA-Danube, finanziert vom BMBF, untersucht die Veränderungen des Wasserkreislaufes innerhalb des Einzugsgebietes der Oberen Donau (77.000 km^2 bis Pegel Passau). Ziel ist es, ein komplexes Modell zu erstellen, in das die Erkenntnisse von elf beteiligten Forschungsinstituten einfliessen können. Diese Forschungseinrichtungen decken alle Komponenten des Wasserkreislaufs ab; sowohl naturwissenschaftlich-technische, als auch sozioökonomischen Fragestellunge. Schwerpunkt des vorliegenden Berichtes liegt auf der hydrogeologischen Gruppe, deren Ziel es ist, die Grundwasserströmung und den Stickstofftransport auf einem sehr groben Finite-Differenzen-Raster abzubilden. Die sehr heterogene Datenlage erfordert den Einsatz von geostatistischen Methoden bei der Erstellung des hydrogeologischen Konzeptmodells und der Zuweisung von hydrogeologischen Parametern. Das für eine Grundwassermodellierung sehr grobe Raster erschwert die Bestimmung geeigneter Parameter zusätzlich, so dass Upscaling-Methoden eingesetzt werden, um das Ergebnis der Modellierung zu verbessern. Abschließend wird in diesem Bericht ein Überblick über die Komponente von GLOWA-Danube gegeben, die sich mit Bewirtschaftungsstrategien und der Verteilung der Ressource Wasser auseinandersetzt.

Schlüsselwörter: Donau, Grundwassermodellierung, Hydrogeologie, Geostatistik, Skalierung, hydraulische Durchlässigkeit, Wasserwirtschaft

1. Introduction

The investigation and prediction of long-term water cycles regarding sustainable water use in large catchment areas such as the Upper Danube basin (77.000 km^2 at gauge

Passau, see Figure 1) require an interdisciplinary approach. While physical processes control the natural water cycle, water demand and quality are widely determined by human behaviour. GLOWA-Danube therefore aims at the development of an integrated, network-based decision support system "DANUBIA", comprised of several independent models describing different physical and socio-economic aspects of the water cycle. Currently eleven different research institutes at ten different universities in the German Federal States of Bavaria and Baden-Wuerttemberg as well as in Austria participate in this BMBF-funded project (BMBF: Bundesministerium für Bildung und Forschung, German Federal Ministry for Education and Research). The research group "Groundwater and Water Resources Management" at the Institute of Hydraulic Engineering (IWS) of the Universität Stuttgart contributes the groundwater flow and nitrogen transport model as well as an agent based water supply model. The groundwater flow and transport model that is currently being built will be upon completion with respect to area the largest multi-purpose numerical groundwater model ever built in Germany. The construction of a conceptual hydrogeological model for such an enormous area is a task requiring not only the gathering of a huge amount of field data, but also advanced data managing and evaluation tools. Additionally, geostatistical methods capable of considering the different degree of confidence of the values as well as the existence of discontinuities such as hydrogeological faults are utilised.

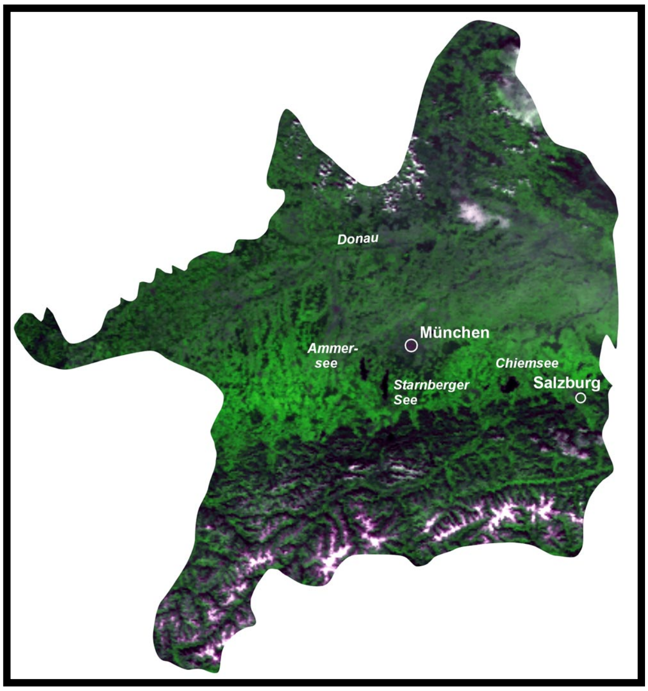

Figure 1. Satelite image of the Upper Danube water catchment modelled on the GLOWA-Danube project

The direct coupling of different models with each other requires the use of a unique grid on the base of which the data exchange can take place. After analysing the significant scales of each physical process that was modelled and the available computer power a uniform rectangular 1km*1km grid was chosen. From the point of view of a groundwater model this is a very coarse grid, potentially resulting in serious problems that have to be addressed for the results to keep their physical meaning. As shown in Rojanschi (2001) the difficulties when modelling groundwater flow on coarse grids relate mainly to the upscaling of layer parameters, such as hydraulic conductivity, and to the upscaling of point and linear boundary conditions such as wells and rivers. An extended literature review lead to the conclusion that despite a large amount of research concentrated to the subject, no standard upscaling methods exist that can be directly applied in the context of the GLOWA-Danube project. The main difficulty is the implementation of hydrogeological units, whose width is equal or smaller than the grid size. This is the case for the narrow alluvial aquifers that conduct the water accumulated from rain fallen in the Alps to the Danube. These aquifers have an average width in the order of hundreds of meters and their direction is mostly diagonal to the grid. After comparing existing methods it was decided to use for the upscaling of the hydraulic conductivity field a combination of general and block neighbourhood laplacian methods (Wen and Gomez-Hernandez, 1996) and for its implementation the results of White and Horne (1987) and Whu et. al. (2002).

Regarding the implementation of wells in the model, problems result not only from the fact that many wells can be located within one cell for which a single piezometric head value is being computed, but mainly from the difference between the effective radius of each well and the implicit radius of the "finite-difference well". It is intended to apply for this problem the analytical approach pioneered by Prickett (1967) and confirmed by Learner (1988).

Another sensitive problem is related to the implementation of surface water bodies in the coarse grid groundwater model. Rojanschi (2001) showed that the errors occur mainly due to the shifting of the location of the rivers to the centre of the cells (a block-centred finite-difference approach is being used). The possibility of developing a more theoretically based method than simple inverse modelling (calibration) is being evaluated.

While, despite its new challenges, the numerical modelling of groundwater flow and transport is clearly defined by physical laws, the situation is different for the Water Supply model, which represents the connection between the water resources (groundwater and surface water) and the water consumer. In an agent-based approach the possibilities to optimise the distribution of water and, especially, to automatically transmit the stresses (e.g. overexploitation, insufficient water quality) from one end to the other of the above mentioned connection are being tested.

2. The GLOWA-Danube project

GLOWA-Danube was started in 2001. The members of GLOWA-Danube cover the disciplines meteorology, hydrology, remote sensing, groundwater and hydrogeology, water resources management, glaciology, economy, agricultural economy, tourism, environmental psychology, plant ecology and computer science. GLOWA-Danube aims to develop integrative techniques, scenarios and strategies to cope with regional effects of Global Change on the water cycle in the Upper Danube catchment with respect to human activities (water and land use), climate change, vulnerability of mountain environments, water use conflicts, water management technologies and transboundary water management. The heterogeneity of the mountain-catchment requires an explicit representation of all water-related processes within GLOWA-Danube. As main integrative challenge of the first project phase GLOWA-Danube develops and applies the web-based Global Change decision support system (GCDSS) DANUBIA (Mauser & Stolz, 2002) (see Figure 2). DANUBIA will, in a consistent and transferable manner, combine the expertise of all disciplines involved. DANUBIA in its final state will be used to monitor, analyse and model the impacts of Global Change on nature and society by combining a multitude of environmental, social and economic aspects formulated by the water related stakeholders. In the second phase of the project it will be used to improve scientific knowledge by formulating and testing complex scenarios of future development and in measuring the degree of sustainability of different scenarios. DANUBIA will thereby enable to identify most appropriate alternatives in watershed management.

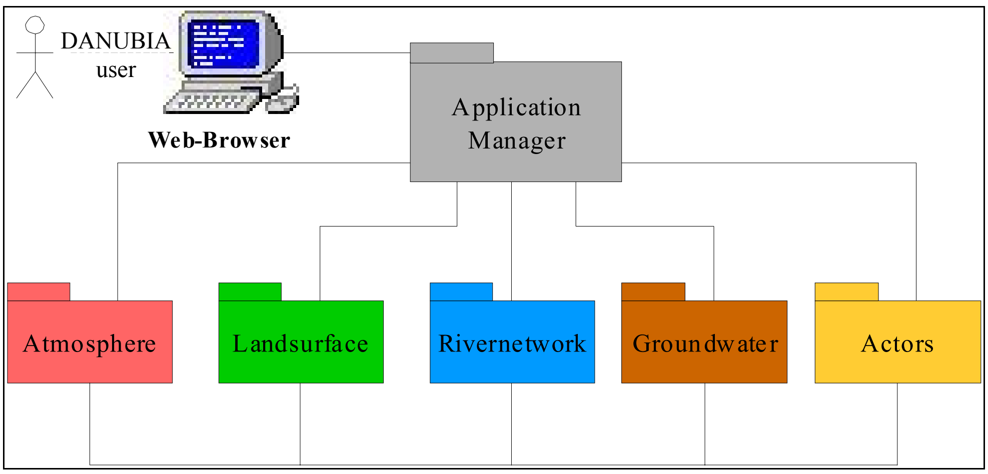

Figure 2. Schematic representation of the web-based decision support system DANUBIA

3. Development of the decision support system DANUBIA

The main characteristic of DANUBIA is its strictly modular concept. As of April 2002, nine different model components run parallel on different computers connected via a local network (first successful public presentation of the DANUBIA prototype took place at the GLOWA status conference in May 2002, Mauser and Stolz, 2002). At the end of the first project phase, all 15 models will be implemented and the local network will be fully replaced by an internet connection.

To develop the DANUBIA prototype the following steps were taken (Mauser & Stolz, 2002):

- Inventory of available disciplinary modelling approaches and definition of common model architecture and interfaces between disciplines. The area of competence of each of the 15 models had to be clearly defined such that no redundant "intersection" occur in the numerical computation of the physical processes: No physical variable is computed by more than one model. Despite the apparent simplicity of this statement one has to remember that it is common for models treating different parts of the water system to overlap: e.g. when modelling saturated groundwater flow it is common to use simplified estimates of groundwater recharge and evapotranspiration rates although these processes occur in the unsaturated zone. This overlapping is done on the expense of accurate description of the physical and chemical processes. This inherent problem of disciplinary models is solved by the integrated approach of DANUBIA. Each model computes only those processes that belong to its core of competence and the input and output data is clearly defined by the interfaces that connect the models (see Figure 3).

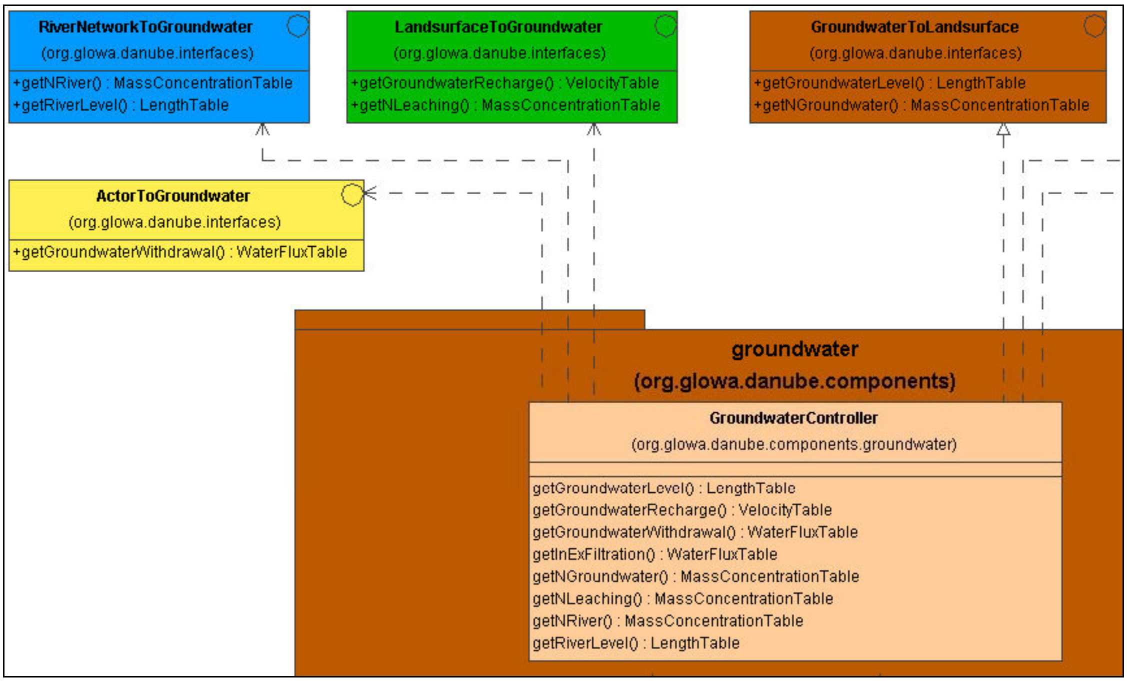

Figure 3. Cut out of the DANUBIA network structure. The UML graphical conventions were used.

- The raster-based object-oriented "proxel" (PROcess-piXEL) concept was invented to allow common spatially explicit modelling in each disciplinary field (see Figure 4).
- Definition of a common description of space and time on the basis of a 1-km^2 raster.
- Utilisation of a common description language to describe the architecture of DANUBIA and the interfaces between the disciplines. The Unified Modelling Language (UML; Booch et al., 1999) was used for this purpose.
- Selection of a suitable common programming language to implement the disciplinary model and interfaces on the web in accordance with the formalised UML-description. Java is used for this purpose because of its cross platform capabilities, that is for its

independence of the operating system that runs on different computers. Java "wrappers" are being developed to integrate models that are written in different programming languages into the DANUBIA system (e.g. the groundwater flow model MODFLOW is written in Fortran).

- Careful analysis of timing and development of execution sequences for the different models by means of a simulation manager and of a time controller that were created by the computer science group. The managing of 15 different models running in parallel on 15 different computers and being coupled (one model needs as input the output of another model) was not an easy task. A particular challenge was the harmonising of the time factor, as the time steps used by the different models during their parallel runs vary between several minutes (for the meteorological models) to several months (for the socio-economic models).

4. Model components developed at the IWS (Universität Stuttgart)

The first task of the research group "Groundwater and Water Resources Management" within the framework of GLOWA-Danube is to develop a model of the three-dimensional groundwater flow for the upper Danube catchment area. According to the size of the model area and the Proxel concept, a finite difference model approach (MODFLOW; McDonald & Harbaugh, 1988) was chosen. The choice of MODFLOW was justified by the robustness of the model, proven in many years. It is world-wide one of the most used models, and its modular aspect makes the modification of its code a relatively easy task. At a later stage, a transport model to simulate the transport of nitrogen based on MT3D (Chunmiao & Hathaway, 1990) will be added.

The second task is to develop a model for the simulation of water supply to the domestic as well as to the agricultural and the industrial sector. The model consists of an information system that includes drinking and industrial water withdrawals, quality and costs. Due to the possible opening of the market in the water sector, access to information on these topics is limited. Therefore, the database is still under development. Based on this information, a model will be created that can respond to changing consumption, cost and quality requirements as well as to varying physical input parameters such as decreasing extraction rates due to decreasing regional groundwater levels.

The groundwater and the water resources model will be linked with each other as well as to the models of the other participating institutes. The groundwater model (named also "Groundwater" object as a part of the DANUBIA system) interacts with a surface water model ("Rivernetwork" object) that computes the routing of the water along the basin river network and with the "Landsurface" model that models the physical and chemical processes occurring at the ground-surface and in the first two meters of soil. The connection between "Groundwater" and "Rivernetwork" is defined by means of an in-, ex-filtration rate 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, of the piezometric head in the uppermost layer in the groundwater model and of a parameter signifying the hydraulic conductivity of the aquitard separating the two water bodies. The connection between "Groundwater" and "Landsurface" is defined by the computation of recharge rates into the saturated groundwater and of evapotranspiration rates occurring though capillary rise from the saturated groundwater. The water supply model ("WaterSupplyActor" object) interacts with "Groundwater" and "Rivernetwork" on the supply side and with the other actor groups ("HouseholdActor", "FarmingActor", "Economy", "TouristActor") on the demand side.

4.1. The groundwater component

The main focus of research in the first stage of the project was on the development of the three-dimensional hydrogeological model. The gathering and processing of data for a drainage area of this magnitude (covering approximately 77.000 km is a rather challenging and tedious task. Geostatistical methods are utilised and will be enhanced if necessary to describe the subsurface in areas that are poorly investigated.

The particular challenge lies in the modelling of groundwater flow and substance transport for a large grid fixed to 1000*1000 m and in the constant exchange of in- 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 the heterogeneity of geologic structures and of the geohydraulic boundary conditions in order to simulate groundwater flow and substance transport without an adaptation of the grid.

Parallel to the development of the flow and transport model its integration in the structure of DANUBIA is pursued. Hence, all models and underlying databases must be designed to enable the control of input and output data, spatial correlation and timing through central controllers.

4.1.1. <u>Modelling groundwater flow with MODFLOW - hydrogeological model</u>

The finite difference model MODFLOW was chosen due to reasons already mentioned, but also because its cell-based approach matches the proxel concept of DANUBIA in a nearly ideal way (see Figure 4). Data exchange with other models is directly possible without the necessity of 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 especially with regard to the implementation of boundary conditions, such as rivers or drains (see section 3.1.2).

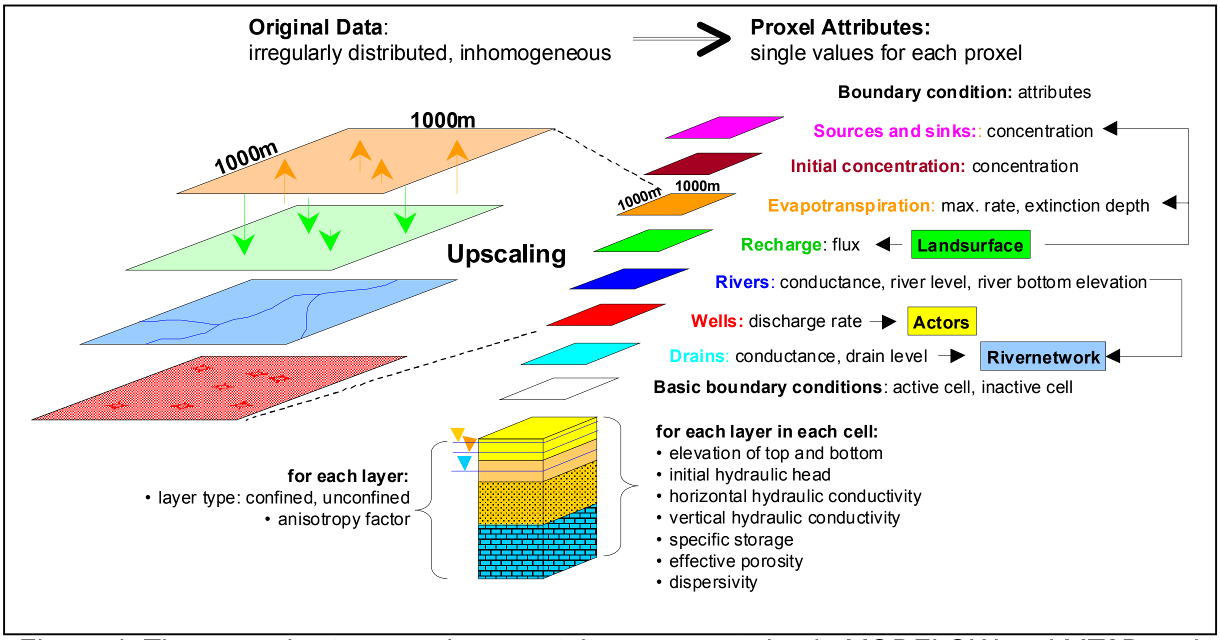

Figure 4. The groundwater proxel concept, its representation in MODFLOW and MT3D and its interaction with other DANUBIA objects

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. The conceptual model consists of four layers, comprising the strata “Malm Karst”, “upper Tertiary Molasse” (Neogene), “lower Tertiary Molasse” (Paleogene) and “Quaternary” (see Figure 5). The units “upper” and “lower” Molasse are for the most part synthetically defined and only oriented on the lithostratigraphic units where this is stringently required by the geological situation. The upper Tertiary unit is an approximately 50 m thick layer, within which the important local structures can be modelled independent of the properties of the subjacent Molasse. The Quaternary layer is for the most part defined by local water permeable structures (valley aquifers, alluvial gravel plains). The hydro-stratigraphical units subjacent to the Malm will not be considered explicitly, as here the groundwater exchanges rates are negligible for GLOWA. Therefore the base of the carstic "Jura" aquifer constitutes the model basis.

In the Palaeozoic Basement in Northeast Bavaria, local hydraulically disconnected 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 which allows 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. The alpine region covers approximately 30% of the catchment area and contributes more than 50% of the total precipitation. Their outstanding role in the water cycle of the region is therefore evident. However, 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. In addition to that, karstification that plays an important role in certain parts of the Northern Alps adds to the difficulties in modelling this area.

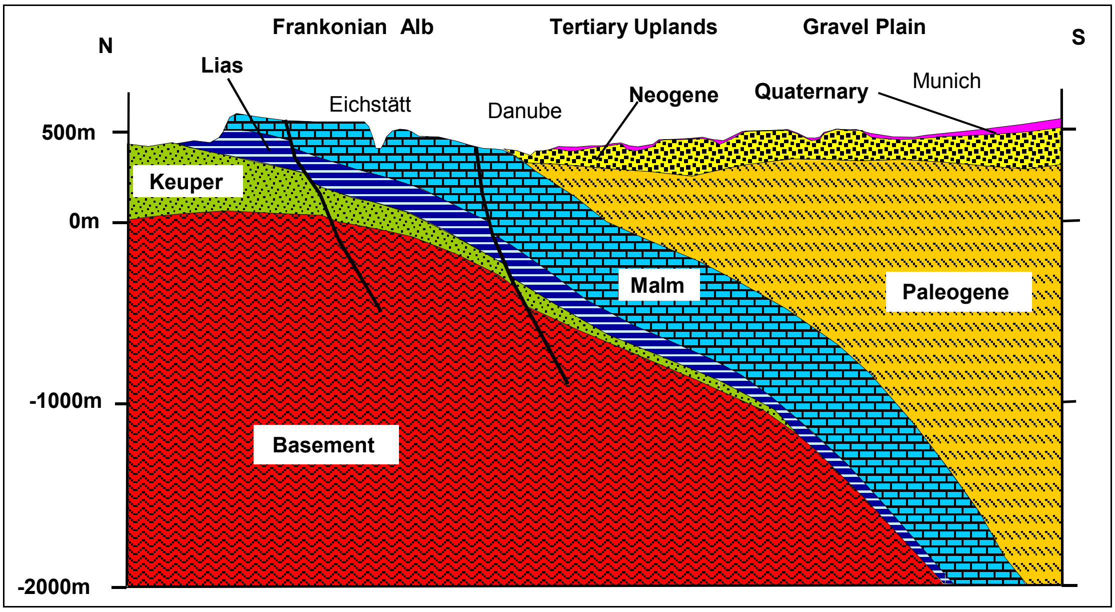

Figure 5. Cross-section through the conceptual hydrogeological model GLOWA-Danube. The Alps region was not included due to the very complex 3D structure difficult to summarize in a 2D scheme

Parallel to the conception of the hydrogeological model, interviews have been carried out with all the important institutions of the Federal States Bavaria and Baden-Württemberg concerning the availability of data and the possibility for gaining access to this data for use in the GLOWA project. While the state departments are very interested in the GLOWA project and willing to share their data, it has become apparent that the data situation is highly variable. This has proven to be especially true for the spatial density of available hydrogeological data. Therefore, interpolation techniques are currently utilised for areas with little or no data. Especially non-deterministic methods, which are based on a statistical analysis of the spatial structure of the investigated parameter, are very practical for estimating unknown parameter values. To increase the number of sample values for parameters that are difficult to measure, cokriging will be applied in order to correlate hydraulic head measurements and hydraulic conductivity.

Even when data is available, it is often in a form that demands high efforts for digitalisation, georeferencing and interpretation. During the remainder of the first project phase, the data acquisition will be continued with a special emphasis on the improvement of existing geostatistical methods.

4.1.2. <u>Upscaling of small but important hydrogeological features</u>

While building the groundwater model, a second challenge must be addressed, namely the upscaling of local, heterogeneous structures to fit the square kilometre 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 (see Figure 6). While these alluvial river valleys have small cross sections, they are at the same time significant aquifers due to their deposit's coarse grain size and the valley's steep gradients. Particularly when such structures run diagonally to the grid, their discretisation presents a great challenge.

The upscaling of the hydraulic conductivity field to the scale of the model grid has been recognised for many years (e.g. Desbarats, 1987) to be one of essential problems regarding the accuracy of the results of a groundwater model. The validity of the fundamental equation in saturated groundwater flow, the Darcy equation, is theoretically conditioned by the existence of a representative element of volume (REV) (Freeze and Cherry, 1979). That implies that the Darcy equation should be applied only at scales at which the porous media can be assumed to be a continuous one. This is only true at scales that are much larger than the micro-scale of the fundamental heterogeneity characterising the soil, but much smaller than the meso-scale marking the transition between several hydrogeological units. This condition is seldom met when modelling, as the grid size is normally chosen to comply with the project objective and with the available computer power. Another important aspect is the difference between the scale of measurement of the hydrogeological parameters and the modelling scale, which is often at least one order of magnitude larger. Therefore when modelling groundwater flow, an almost obligatory step is the construction of the grid-size hydraulic conductivity field based on information from a finer scale. The main aim of this step (upscaling) is to minimise the errors resulting from modelling on a coarse scale as compared to a theoretically correct but not-usable very fine grid model.

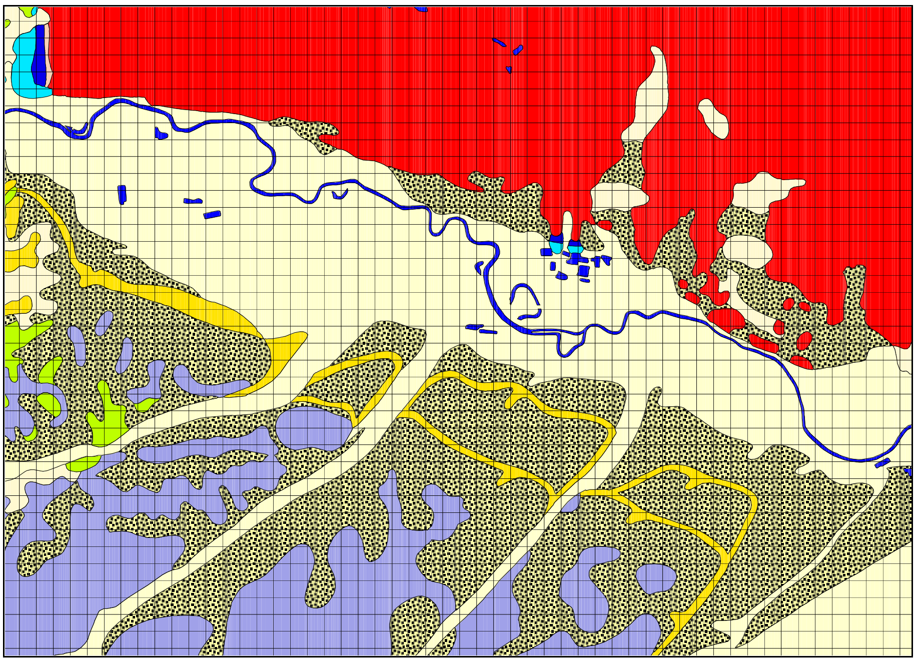

Figure 6. Cut out of the hydrogeological map of the Upper Danube catchment. The map was simplified by joining hydrostratigraphical units with similar features. The yellow zones indicate the high permeability alluvial aquifers. The underlying GLOWA-Danube grid is also shown.

Because of the importance of upscaling (Rojanschi, 2001) an impressive amount of work was dedicated all around the world to the attempt to solve this problem. Renard and de Marsily (1997) counted more than 200 articles dedicated exclusively to this topic. Renard and de Marsily (1997) and Wen and Gomez-Hernandez (1996) published extended reviews of the existing methods, analysing their implicit and explicit assumptions and stating their limitations.

All the methods have the same fundamental approach. They start from a fine-grid hydraulic conductivity field and compute a coarse field at the modelling scale (see Figure 7). The criteria used for the optimisation are the correct reproduction of the global response and local response, respectively (Indelman and Dagan, 1993). The global response requires that the flow field on the coarse grid is the same as the one computed on the fine grid. The local response requires the same restriction for the piezometric head field. The first criteria is said to be a necessary one, the second a sufficient one. Thus the minimum and the maximum limits in the performance of any upscaling method are defined.

Renard and de Marsily (1996) classified the existing methods into three main categories: heuristic, deterministic and stochastic. The heuristic methods are the simplest ones, proposing rules for the calculation of plausible values of the upscaled (or block) conductivity. They are based on the observation demonstrated by many authors (e.g. Matheron, 1967) that the equivalent hydraulic conductivity of a block must be greater that the harmonic average and smaller than the arithmetic average of the all the fine grid values belonging to this block. Methods such as the power average method (Journel, 1986) calculate averages over the fine grid cell values, which are then weighted by calibration parameters. The main advantage of these methods is their speed and their simplicity. Their drawback is that they do not consider explicitly the fine-grid structures forming the hydraulic-conductivity field, and also that they require an excessive amount of effort to be located into the calibration phase.

The second category is that of the deterministic methods. They assume the perfect knowledge of the geological conceptual model (and thus of the hydraulic conductivity field) and try to compute the block-constant hydraulic conductivity tensor by analytical or numerical methods. The analytical methods are normally limited by restricting assumptions, valid only for special cases (e.g. high permeable porous media penetrated by less or not permeable lenses). An exception is the renormalization method (King, 1989) which uses a successive grouping approach to move from the fine to the coarse grid field. The numerical methods (also called Laplacian methods - Wen and Gomez-Hernandez, 1996) tackle the problem by solving the groundwater model on the fine grid either for the whole area to be modelled (global approach - White and Horne, 1987) or only on an area around each block (block approach - Wu et. al., 2002). The global approaches have the big disadvantage that they require the solution of the system on the fine-grid, avoiding this computation being one of the reasons one performs the upscaling procedure. The block approaches require the solving of a large number of small models, where the proper definition of boundary conditions for every block model is problematic. For both approaches one can say that although they consume a huge amount of CPU time one needs to apply them only one time to get a coarse grid hydraulic conductivity field.

Finally the stochastic methods assume that the geological model is not perfectly known and the explicit knowledge of the hydrogeological structures is replaced with the estimation of statistical parameters such as geometric average or variance. Their applicability is restricted by assumptions such as the fitting of the values to a log-normal distribution curve, which are not fulfilled in the general case studied here.

In the context of GLOWA-Danube the focus is on the correct modelling of highly permeable alluvial aquifers, whose width is in many places much smaller than 1000 m and which are generally diagonal to the grid. After analysing the existing methods it seems that the most appropriate one would be a block approach Laplacian methods with a full tensorial coarse scale conductivity field. This requires the extension of the MODFLOW model to make the implementation of non-diagonal cross-values for the hydraulic conductivity possible.

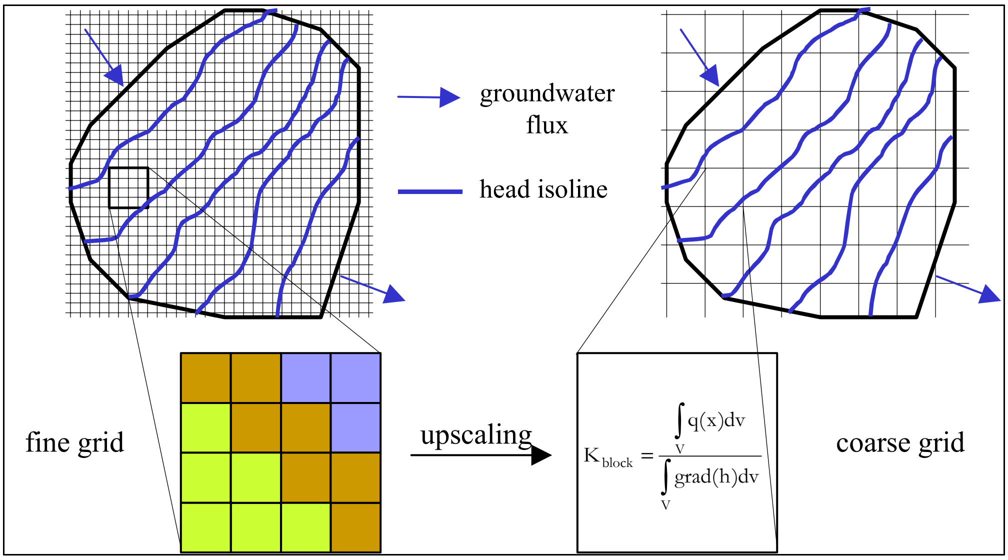

Figure 7. Conceptual representation of the upscaling of the hydraulic conductivity field from the fine to the coarse grid. The equation for the block conductivity K_{block} is taken from Renard and de Marsily (1997), q is the Darcy flux (m/s), h the piezometric head (m). The equation is written on only one direction, in reality K_{block} is a tensor.

4.1.3. Upscaling of point (wells) and linear (rivers, drainage) boundary conditions

Another aspect of a groundwater flow model that is sensitive to coarse scale modelling is the implementation of wells and linear third-order boundary conditions such as rivers or drainage. The reason for their sensitivity to upscaling is the fact that their action on the aquifer is concentrated on an area much smaller than that of the cell in our case. This has as a result that, when the respective feature, e.g. a river, does not "fit the grid", it is shifted to the cell-centre and "spread" by averaging it over a whole cell. A well might have an real radius of 20 cm and a radius of influence of a few hundred meters, but on a 1000 m*1000 m grid these numbers cannot be implemented. What one can do is to try to examine the extent of the shifting and the spreading, evaluate its effects and correct them. For the case of wells tested methods exist that carry out this task. For the case of surface water bodies methods are still to be developed.

The relation between the real the modelled wells was studied by researchers since the beginning of numerical computations (Pritchett and Garg, 1980). The main idea is to establish a clear relationship between the implemented well and an analytical Theis well, that is, a well for which a clear analytical solution is available. Prickett (1967) proved that a finite-difference well is equivalent to an analytical Theis well with an effective radius of 0.208a, where a is the size of grid. Starting from this point, the solutions of the 0.208a Theis well and of the real well have to be compared and the differences between the solutions must be evaluated. An exhaustive summary of such a procedure is described in Lerner (1988), who also tests the method on a regional aquifer with the same grid size as in GLOWA-Danube and proves the validity of the theory.

The problem is more complex for the case of rivers and drainage. Because of the usually complicated geometry and because of the lack of data, the implementation of the surface water body to aquifer hydraulic connection is done with a simple Darcy approach with the hydraulic conductivity of the interface (the riverbed) being a calibration parameter. The water level in the river is averaged over the stretch contained in the cell. This procedure becomes increasingly difficult to use as the cell size increases. With the increase of the cell size, the number of different surface water bodies, the water level difference for the respective stretches and the complexity of their hydraulic connection with the aquifer also increase significantly (see Figure 8). Another problem comes from the way the digital elevation model, one of the backbones of any groundwater model, was built. The relationship between the local land, groundwater table and surface water elevations might be radically changed when averaging over a large cell area. To our knowledge no standard solution exists at this time. There is a need for a systematic approach when dealing with this topic to better understand the behaviour of the model and to increase the physical meaning of its parameters.

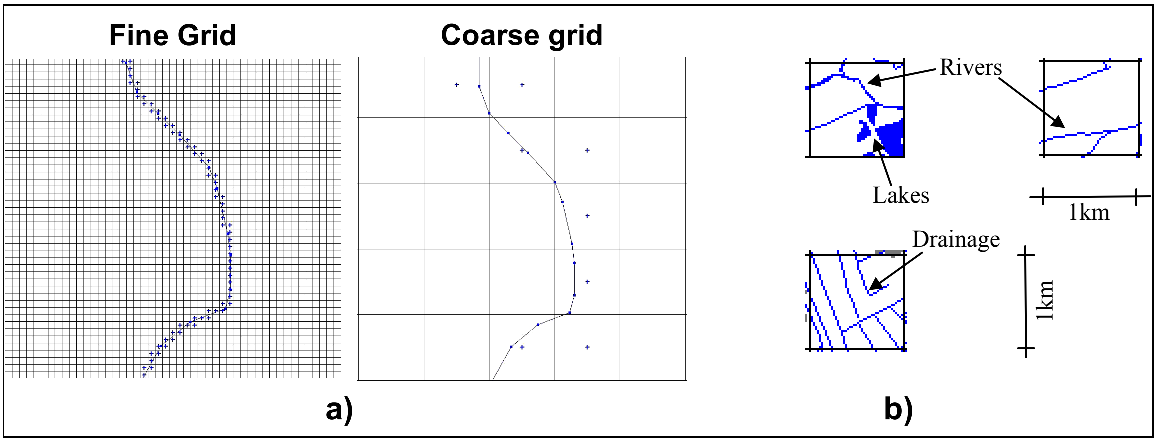

*Figure 8. a) Shifting of the river location at the implementation on a coarse grid (blue-marked cells = river cells); b) Cuts of the Upper Danube basin hydrographic network showing the difficulty of modelling at a 1km*1km scale: in one cell many complex features are present, but still they must be lumped to a unique parameter*

4.2. The water supplier component

The model "WaterSupplyActor" provides a link between the "Actors objects" (Models concerned with human impact on the water cycle) on 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 ("Household Actor", Economy, "Tourist Actor", and "Farming Actor"), develops a supply strategy, decides which water resources to use in order to meet the demands and informs the models "Groundwater" and "Rivernetwork" accordingly.

Data on the potential water resources (quantity and quality) for each proxel is obtained from the "Groundwater" and "Rivernetwork" models at each time step. This data is used as input for the model calculations performed in the model " WaterSupplyActor ". 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 by means of Java interfaces (drinking water, raw water for industry and agriculture). It compares this demand data with the potentially available water resources. Making use of a decision support system (DSS), a supply strategy is developed. If the supply meets the demand, a DSS determines the economically and ecologically best possible source of water (groundwater only, surface water only, import of water, or conjunctive use) and conveys the necessary extraction rates to the supply models. Should the supply side not be able to meet the demand (due to changing climatic conditions or changing water quality), the model uses priority rules. Based on economical, political (e.g. agriculture vs. domestic use) or ecological (e.g. wetlands/lakes) parameters, the DSS decides on a supply strategy such that the maximum benefit for a majority of users is guaranteed.

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