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Large-scale water resources management within the framework of GLOWA-Danube—The water supply model

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Abstract

The research project GLOWA-Danube, financed by the German Federal Government, investigates long-term changes in the water cycle of the upper Danube river basin in light of global climatic change. Its aim is to build a fully integrated decision support tool "DANUBIA" that combines the competence of eleven institutes in domains covering all major aspects governing the water cycle. The research group "Groundwater and Water Supply" at the Institute of Hydraulic Engineering (IWS), Universitaet Stuttgart, contributes a three-dimensional groundwater flow model and a large-scale water supply model which simulate both water availability and quality and water supply and the related costs for global change scenarios. This article addresses the task of creating an agent-based model of the water supply sector.

The water supply model links the various physical models determining water quality and availability on the one hand and the so-called "Actor" models calculating water demand on the other by determining the actual water supply and the costs related, which underlie both technical and physical constraints (e.g., existing infrastructure and its capacity, water availability and quality, geology, elevation, etc.). In reality, water supply within the study is organised through a three-tiered structure: long-distance, regional, and a multitude of community-based suppliers. In order to model this system in which each supply company defines its own optimum, an agent-based modelling approach (implemented using JAVA) was chosen. This approach is novel to modelling water supply in that not only water supply infrastructure but more importantly the decision makers (communities, water supply companies) are represented as generalised objects, capable of performing actions following rules that are determined by the class they belong to.

Keywords: Decision support system; Sustainable water supply; Water supply model; Agent-based modelling; Stakeholder involvement

1. Background

The GLOWA-Danube project, which began in 2001, aims to detect regional effects of Global Climate Change coupled with human activities (water and land use) on the water cycle in the upper Danube catchment using an integrative modelling approach. The chosen study area offers an extremely good data basis for all disciplines and is therefore particularly suitable for the development of the decision support system. It is, however, the explicit aim that the general approach and structure of the DSS be transferable for adaptation and use in other river basins with different natural and societal characteristics, also those which have not been as exhaustively studied as the Danube basin.

By nature a water-rich environment, the upper Danube basin today displays signs of strain from these pressures, which could lead to serious water shortages or quality problems and thus to water conflicts in the future: accelerated glacial melt in the Alps, accumulation of pollutants and nutrients in surface and groundwater resources, and changing local weather and rainfall patterns which could lead to periodic flooding or drought and to changing conditions

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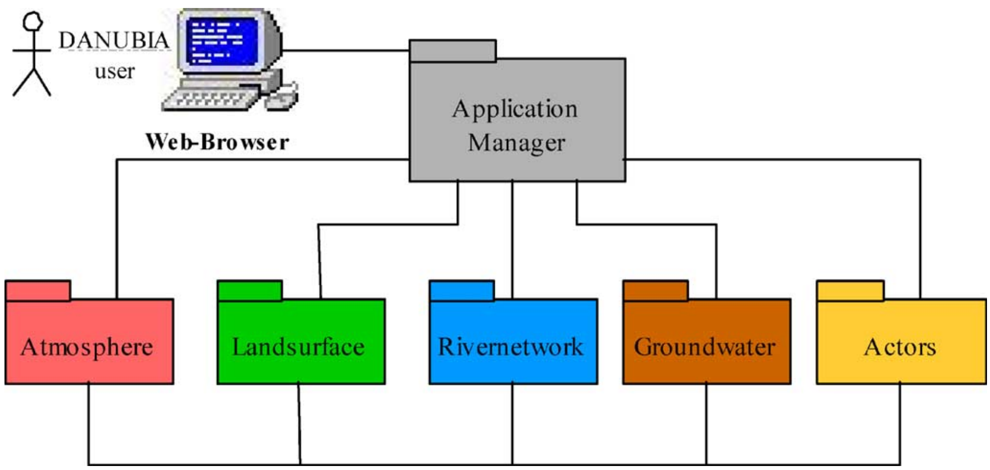

Fig. 1. Schematic representation of the web-based decision support system DANUBIA.

for agriculture. An interdisciplinary approach is required to meet the central GLOWA-Danube aim. Several independent physical models are being developed in the fields of meteorology, hydrology, plant ecology and more. In turn, however, water demand and quality are widely determined by human behaviour. So-called "Actors" models for the most part agent-based models cover the disciplines of economy, agricultural economy, tourism, environmental psychology, computer science, and, not least of all, water supply. The water supply model *WaterSupply* assumes thereby the central mediation role between the groups by administering the available resources to the various users and their needs. The development and integration of the models from the relevant disciplines in a web-based Global Change decision support system DANUBIA constituted the main challenge of the first project phase of GLOWA-Danube (2001–2003) (Mauser and Stolz, 2002). Fig. 1 displays a schematic view of DANUBIA.

For the direct coupling of these independent models with each other for the purpose of parameter exchange, a uniform rectangular 1 km × 1 km grid was chosen for all models. Spatial, raster-based modelling is not common in socio-economic sciences. The compulsory 1km grid therefore imposes great difficulties on the Actors models, and in particular on *WaterSupply*. These difficulties will receive more attention further on in this article.

2. Motivation and aim of the water supply model

The specific aim of *WaterSupply* is the creation of a model which is not only able to simulate the present day system of water extraction, treatment and distribution, but also its development and change with time. A number of factors can trigger change in a water supply system in the form of modernisation or decay, expansion, centralisation or decentralisation. Some of these factors are of a natural source. For example, climate and changes in weather patterns can increase or diminish local water supplies and/or the quality of the water. Yet most changes are brought about by decisions made by relevant actors in the field of water management or their behaviour. Systems of water rights, and other political instruments governing the distribution and quality of water resources, place direct demands on the state of water supply systems and determine trends such as centralisation/decentralisation and liberalisation. Competing uses of water resources such as navigation, fisheries, or tourism, have a long-term effect upon water quality, as do the behavioural norms of certain productive branches of the economy: for example, the use of fertilizers and pesticides in agriculture. Water demand changes as a population increases or decreases, as new industrial parks are built, as the technical feasibility and acceptance for the practice of water reuse (e.g., waste water reuse for irrigation, commercial and private gray water recycling, etc.) advances or as consumers make increasing use of water-efficient technologies. All of these factors in turn require decisions to be made on the part of the water supply administration. Is it necessary to tap on to new resources, are new methods of water treatment required, does the water pricing systems cover all costs, does scarce water need to be allocated, and, if yes, how should the needs of different users be weighted?

A brief look at the situation of water supply in the model area clearly illustrates this dependency on human decisions. In the model area alone over 1000 local and a handful of long-distance companies supply the approx. Ten million inhabitants and industry with drinking water, mostly from groundwater. This represents, in comparison to other European regions, a highly atypical and decentralised structure, which can be italicised by a simple ratio: the number of companies supplying 1 million consumers for various European countries (Table 1).

Table 1
Number of water supply companies for various European countries (BMBF, 2000)

	Total number of supply companies	Number of supply companies per 1 million consumers
Federal Republic of Germany	*6959*	*88.2*
The Netherlands	22	4.4
England/Wales	29	0.7
France	5	0.13

This finely structured system in the model area is, for the most part, a result of the high degree of autonomy of the municipalities (communities), which are traditionally responsible for water supply. Whereas today, the great majority of the water supply companies are still owned and run by the municipalities, recent trends show that formal privatisation (a company receives a private legal form of organisation but is still owned by the municipality) and material privatisation (a company is actually sold to a private third party) are becoming increasingly common (UBA, 2001).

A further significant characteristic of water supply in the model area is its focus on ''supply-side'' management. Over the past century, the water supply system has continually expanded to meet the demands of the user. As long as demand was on the rise, this system was ideal for all parties involved (customers, engineers, utilities, etc.) (Tillman et al., 1999). Today, however, demand stagnates due to a higher degree of environmental awareness, and, more importantly, from more efficient technologies. Therefore, the local water supply systems are often over-dimensioned and inefficient.

3. The conceptual water supply model

If the model was meant to simulate the present day water supply, it would suffice to model the technical system alone. However, if the model should enable response, growth and change with time, it is necessary to address the decisions listed above and many more made by the relevant actors and the impulses which lead to certain decisions. To meet this goal, the use of agent-based modelling was chosen. An agent can be defined as a computer system (in our case representing a person or group of people) which is situated in, and perceives, its environment; has defined objectives; and is able to carry out flexible, autonomous action to meet these objectives (Jennings et al., 1998). Whereas agent-based modelling has received much attention over the passed decades, the use of this type of modelling for water supply systems is something very new. In recent years, valuable research has been carried out at the ETH Zuerich with the purpose of revealing the dynamics of behaviour and decision-making of actors in water supply systems and the resulting effects upon design and development of such systems. The ultimate goal was, with the help of an agent-based model, to identify means of increasing the adaptability of these systems to changing conditions (Tillman, 2001). The research was carried out at the utility level. Working on a river basin scale, the water supply model of GLOWA-Danube will, naturally, use a coarser approach.

The following steps are planned for the development and implementation of the GLOWA-Danube agent-based model (Fig. 2):

The development of a conceptual water supply model entails defining the boundaries and area of expertise of the model, as well as the parameters to be exchanged

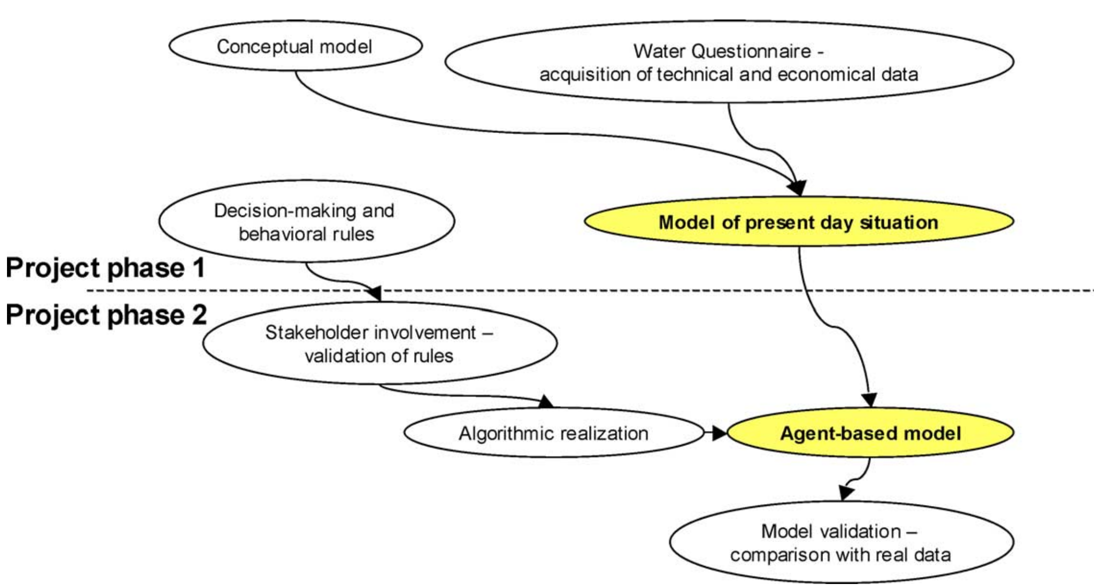

Fig. 2. Development of *WaterSupply*.

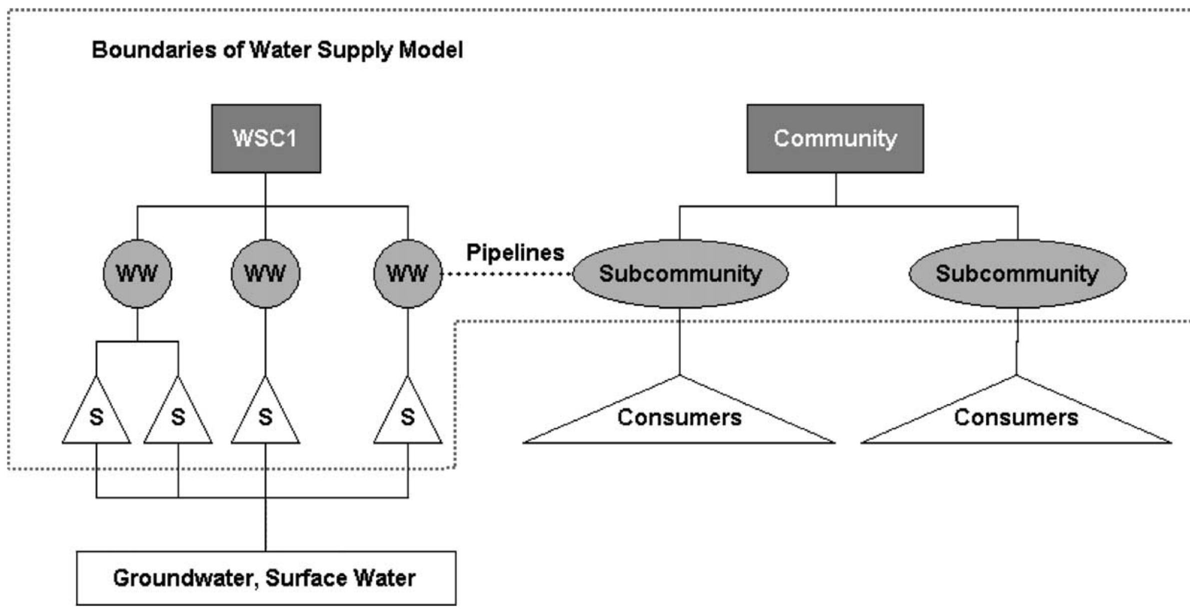

Fig. 3. The boundaries and the main objects of the water supply model.

between *WaterSupply* and other models. Second, the necessary model objects and agents must be chosen at a resolution appropriate to the size of the area to be modelled.

For example, *WaterSupply* receives the information "maximum groundwater withdrawal" from the groundwater model and cannot withdraw more than determined by this model. On the other side, *WaterSupply* receives the information "consumer demand" from the consumer groups and must decide if this demand can be met fully with the available infrastructure and water resources. *WaterSupply* further acquires new resources, provides for the operation, maintenance, modernisation and expansion of the infrastructure, regulates contracts between user groups (e.g., municipalities) and water supply companies, and last but not least generates the actual costs of water supply. With the latter, the economics group calculates the water price, which is passed on to the consumers and possibly has an effect upon their water consumption behaviour, which in turn may necessitate a response on behalf of *WaterSupply*. An appropriate response to such feedbacks requires an analysis over time to differentiate between long-term trends and short-term phenomena, and hence the storage and interpretation of model input and output over many model time-steps, as well as the definition of alternative responses for different trend patterns. Here, both the resolution of time (1 month time steps) and space (1 km) in DANUBIA present a handicap which will merit special attention. Many local or short-term phenomena, for example extremely high demand peaks or local water quality problems, which would necessitate a response, may go unrecognised in averaged input and output data exchanged between the models. One or more small-scale models with a finer spatial and temporal resolution will there be necessary for a comparative assessment of the implications of resolution upon the model results.

The main components of *WaterSupply* are represented by the following objects in the model: water supply companies (WSC), water works (WW), sources (S) (springs, wells, etc.), resources, pipelines, access points, communities, sub-communities. Each of these objects has a defined set of characteristics and/or functions and stands in a particular hierarchical relationship to the other objects as shown in Fig. 3. Only a small number of the objects will later show the necessary qualities to be considered *agents*, namely the water supply companies and the communities. These will communicate with consumer agents of other GLOWA-Danube models, as is also depicted in Fig. 3. A brief description of Fig. 3 follows, to give the reader a first impression of the conceptual model.

The right-hand side of Fig. 3 displays the hierarchy community sub-community and consumers. The community represents the real-world municipality, which carries the legal responsibility for water supply. The community can either own a public water supply company, part of a company which is jointly run with neighbouring communities, sign a contract for water supply with a long-distance water supply company, or do any combination of the above in order to comply with its legal responsibilities. A variable number of sub-communities are assigned to each community, whereby each sub-community receives drinking water by definition from a different water supply company. The sub-communities are characterised by a population, a set of consumers and a specified (geographical) point of delivery for drinking water.

Starting from the bottom of the left-hand hierarchy in Fig. 3, the sources are characterised by a position, source type (spring, well, surface water), depth, age, maximum licensed withdrawal rate, water quality, withdrawal costs and an assignment to a specific water works. Each water work, again characterised by age, capacity, treatment steps, treatment costs, quality of drinking water supplied and assignment to a specific water supply company, can additionally tally the amount of water supplied by the various sources of the water work, the maximal amount which can be withdrawn from these sources, and the total costs for withdrawal. A water supply company maintains one or more water works and holds contracts with one or a number of communities. In communication with the community and the consumers (demand) and drawing upon the characteristics of the water works, it compares different options for meeting the demands and makes decisions regarding modernisation and expansion, the selling of excess drinking water to neighbouring communities, the need to tap on to new resources, etc., following its own set of goals, one main goal being, of course, economical efficiency.

4. Data basis

Sufficient data on water supply to create and validate a model for such a large area is not available from the authorities, common interest organisations or in the public statistics. Whereas these include area-wide data concerning both water withdrawal and water rights for each extraction site as well as water extraction, quality, treatment, and distribution on a community basis, detailed information concerning costs of water supply, water treatment and water imports and exports across political and company boundaries are not available. In order to gain access to more specific information regarding individual water supply companies, the Water Supply group has carried out a wide-spread questionnaire addressed to all water supply companies in the GLOWA-Danube model area well over 1000 in total in Bavaria, Baden-Wuerttemberg, Austria and Switzerland. The questionnaire contains questions pertaining to the two distinct fields "economics and pricing" and "technical aspects", and aims at gathering information regarding the present day situation of the water supply system, the developments over the past 10 years, as well as developments planned for the immediate future. As the questionnaire is time-consuming for the water supply companies and touches some sensitive issues, it is being carried out with the support of state authorities, which should secure the success of the endeavour.

A catalogue of rules for decision-making is currently being compiled from the results of a widespread questionnaire which was addressed to all water supply companies within the model area. The aim of the questionnaire was to collect comprehensive data on technical equipment and quality standards, on past and present developments such as technical expansion or changes in the company structures, and on the distribution of competencies influencing decision-making processes in the area of water supply. This data, together with information available from databases provided by various governmental agencies and information to be won through active stakeholder involvement in the project in the future, will serve as the basis for simulating the present day water supply system as well as possible future developments in this sector which result from decisions made by the relevant system actors.

5. Model implementation and validation

At the current stage, the rules are fairly simple: the infrastructure components of water supply companies are unchangeable, and no optimisation of actions occurs. The model algorithms are now input–output relations, but more realistic decision algorithms will be achieved in future by the stepwise introduction of the various constraints and criteria often economical—that are basis for decision-making in the real world.

Parallel to the activities described above, the conceptual model is presently being implemented using Java. Whereas in the first prototype of DANUBIA, "Danubia 0.9", simply the input- and output ports for data exchange between the water supply model and other models exist, a model of the present day supply system will be fully integrated in DANUBIA by the end of 2003 with the information and data gained through the questionnaire.

Given the size of the system being modelled and the situation regarding data availability on the basis of water supply companies, it will not be possible to validate *WaterSupply* for the entire upper Danube Basin. The plausibility of the model results can be analysed by comparing these to aggregated data gained from community or district statistics on water extraction, treatment, import and export, pricing and consumption. However, a validation of individual parts of the model will be carried out with the help of small-scale models described above, for which a comprehensive data basis exists.

6. Outlook

Towards the end of the first project phase, the focus will shift towards the active integration of the stakeholders from the field of water resources management. In preparation, a catalogue of decision-making rules will be prepared as a basis for discussion. During the second project phase, these rules will be debated with the relevant stakeholders and adapted where necessary. Based on these rules, algorithms for decision-making will be developed and integrated in the water supply model to create an agent-based model, with agents able to respond to their environment, communicate with one anther and behave in a goal-oriented manner to bring about change in the water supply system in response to changing conditions with regard to the climate, water quality, political and social boundary conditions, and changing demand. The second project phase will furthermore be dedicated to the refinement of the various GLOWA-Danube models and to the formulation, testing and comparison of complex scenarios of future development with the aim of identifying sustainable forms of water management and consumer behaviour. The definition of scenarios will be carried out in joint effort with the stakeholders involved.

Ultimately, DANUBIA will be able to serve as a tool for monitoring, analysing, and modelling the impacts of Global Change on nature and society in the Upper Danube basin for various future scenarios, taking into account a multitude of environmental, social, and economic aspects formulated by the water-related stakeholders.

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