Modelling of Water Use Decisions in a Large, Spacially Explicit, Coupled Simulation System

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KEYWORDS

Agent based modelling, simulation system, environmental management, decision support system, decision models, climate change, water use, innovation diffusion

ABSTRACT

This chapter presents the purpose, the basic concepts, the implementation, and a scenario run of the agent-based part of a large Decision Support System for the water resources management of the Upper Danube basin, Western Europe. 16 process models from 11 disciplines from the natural and the social sciences are integrated in the system. They use common spatial and temporal concepts to communicate with each other at run time. A variety of agents based on large scale empirical evidence serves to model the drinking water use of households. An example scenario run under global warming conditions shows the interplay between modelled water supply companies, households, climate, and groundwater resources.

INTRODUCTION: A COMPREHENSIVE MODEL OF SOCIAL AND NATURAL ASPECTS OF A RIVER BASIN: THE DANUBIA SYSTEM

One of the problems of environmental decision making is the lack of a sound, coherent, and dynamic representation of social and environmental processes and the integrated projection of possible developments into the future. It is widely accepted that computer based Decision Support Systems (DSS) can provide a useful basis to advance environmental decision making. However, such a DSS does heavily rely on a valid “core engine” which integrates the implementations of domain relevant processes from the different fields and disciplines and their interactions. The GLOWA-Danube project, sponsored by the German Ministry of Education and Research since the year 2000, aims at providing such an integrated, spatially explicit DSS to enhance water related decision making in the Upper Danube river basin under conditions of global environmental change (Mauser & the GLOWA-DANUBE project group, 2000; 2002; Ernst, 2002).

The river basin considered here has an extension of approx. 75.000 km^2 ranging from the Alps to the Bavarian lower plains and includes parts of southern Germany, Austria, and Switzerland. About 10 million people are living there, and the basin includes high mountains, agricultural regions as well as big cities such as Munich.

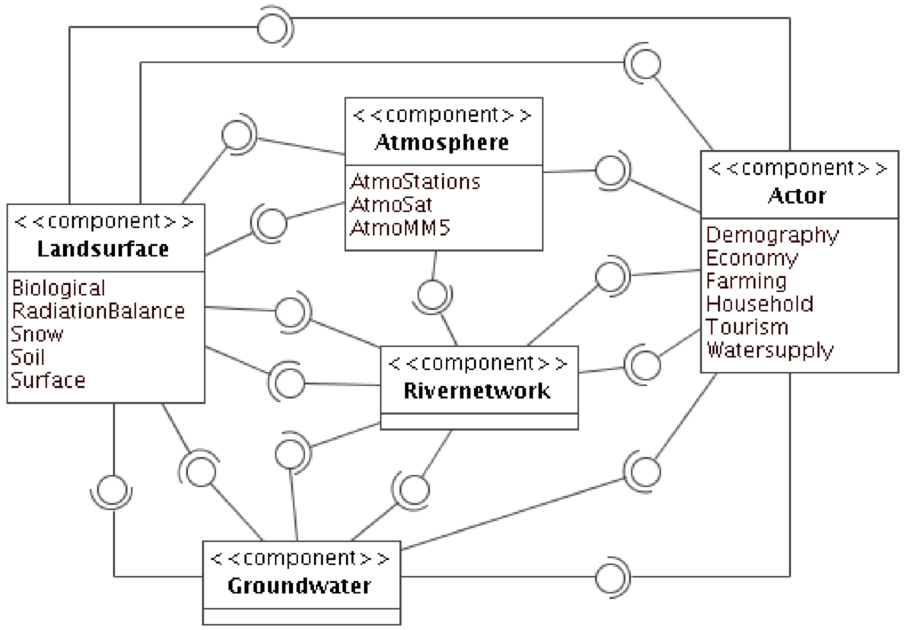


Fig. 1: The five DANUBIA components as a UML diagram. The components Landsurface, Atmosphere, and Actors each encompass multiple models which are coupled among each other analogously to DANUBIA main components.

The DANUBIA system acts as the DSS's core engine and integrates 16 fully coupled process models from 11 scientific disciplines ranging from hydrology to environmental psychology and from meteorology to tourism research (for a description of DANUBIA from a computer science perspective, see Barth, Hennicker, Kraus & Ludwig, 2004). The system structure follows the structure of the domain: There are five components (Landsurface, Atmosphere, Groundwater, Rivernetwork, and Actor) as represented in fig. 1. Each component encompasses up to six models. For example the actor component, which gathers process models from the social sciences, comprises implementations of the Household, Demography, Economy, WaterSupply, and Tourism models. The components and their models are interconnected via a simulation framework which assures the communication linkage through interfaces, the setup and monitoring of simulation runs, the logging of model states, etc. Agent based modelling plays a central role in the actor component.

In the following, the Household model will serve as an example to describe agent based and spatially explicit modelling relating to domestic water use and water related satisfaction in the DANUBIA system. First, the empirical characteristics of domestic drinking water use will be sketched, followed by the description of a shallow model implementing the empirically observed relationships. Then, a more advanced, deep, decision making agent model will be presented together with its validation and a scenario run and its results. Finally, conclusions will be drawn and an outlook on the further research steps in the GLOWA-Danube project will be given.

CHARACTERISTICS OF DOMESTIC DRINKING WATER USE

The empirical data fed into building the shallow Household model encompass survey studies with up to now more than 1.400 subjects concerning habits of drinking water use as well as a large amount of spatially explicit statistical data about drinking water demand and other population characteristics. Further evidence, e.g. about technical features of water saving technologies, were extracted from the literature. As a first step, the data were used to configure 25 household types, differing in household size and income in a 5 x 5 matrix.

Some empirical characteristics of domestic drinking water use are: (1) Water use is to some extent dependent on the household income. Wealthier households have a tendency toward a higher per capita water demand, probably also due to a larger number of water using appliances, i.e. former investments. (2) However, drinking water seems to be price elastic only to a small extent. (3) The larger the household, the smaller the per capita water demand. Our data show e.g. savings through the more efficient use of dishwashers, resulting in relatively less dish washing by hand. (4) There are clear seasonal dynamics, resulting in a higher water demand in summer due to more showering and garden watering. (5) There has been a steady decline in household water use since the 1970s because of technological innovations (use of more water saving washing machines, toilets, and dish washers). (6) The larger the agglomeration where the household is located, the higher its per capita water demand. This might be due to a relative difference in household structure (i.e. the age of its members) and subsequently to a different lifestyle.

In a second step we empirically investigated the water use behaviour of sociological lifestyles, using the ten Sinus-Milieus® (provided by Sinus Sociovision) and the corresponding spatially explicit data of Microm® (Micromarketing Systeme und Consult GmbH). The Sinus-Milieus® are not only commonly used in commercial market research, but also in environmental research (e.g. Kleinhückelkotten 2005).

RECONSTRUCTING DECISIONS: A DEEP MODEL OF DECISION PROCESSES OF WATER RELATED BEHAVIOUR

The spatial representation in DANUBIA is realised using a 1x1 km unit, a “proxel” (for “process pixel”). This unit constitutes a compromise between the different disciplines participating in building the Decision Support System with regard to the scale and the shape of spatial representation. While some disciplines have difficulties in downscaling their results to the 1x1 km unit, others have to upscale, and yet others (the behavioural sciences) have to translate from and to data that are usually oriented towards administrative boundaries.

From more than 75.000 proxels representing the size of the Danube river basin, 9115 are inhabited. All of the model computations and all of the data exchange between models relate to specific proxels (ref. Kneer, Ernst, Eisentraut, Nethe & Mauser, 2003). The Household model receives input data from the Demography, Economy, WaterSupply, and Meteorology models during run time. Its output is mainly connected to the WaterSupply (water demand) and the Rivernetwork component (waste water), and to the user interface when providing data that are not used as inputs to further model computations but are presented to the end user (like household satisfaction).

In order to allow for the implementation of more complex decision processes within the agents of the actors component in DANUBIA, a generic framework for all actor models has been conceptualised, designed, and implemented. The most important elements of the so-called “DeepActor” framework are depicted by the UML diagram in fig. 2. Specific sensors relating to proxel information, to other actors, and also to simulated legal constraints, lay the ground for the decision algorithms to be defined by the specific actor model reifying the abstract base classes as provided by the framework. Decisions are made about the choice and instantiation of plans, themselves being chains of more specific actions.

The *DeepHousehold* model, as one of the implementations of a specific actor model, reconstructs domestic, water related decisions. Domestic water use has strong habitual components (much of the day to day water use of people is not or no more triggered by conscious decision making), while there also are important conscious, deliberate decisions, e.g. when adopting water saving technological innovations or changing one’s habits. The *DeepHousehold* model thus provides representations for both processes: a bounded rationality based deliberate decision making mechanism together with an integrated habit component.

Relevant decision parameters include the behaviour of other actors in the agent's network, the water price, weather conditions, environmental consequences of the behaviour, habits, and the individual history of the agent.

DeepActor models can be particularly useful if a realistic typology can be implemented that leads to a large variety of different behaviours. For example, households can be classified according to size, income, age range or lifestyles. Within the deep actor model concept, the actor type determines a set of core attributes, preferences, possible plans comprising different actions to respond to changing conditions, to enable highly differentiated agent behaviour. All *DeepHousehold* agent types have different core attributes, but share the same set of plans. Our typology introduces the household's attitude towards progress and modernization as an additional important dimension. The *DeepHousehold* agents are clustered in Sinus-Milieus®. The distribution of the ten milieus of the *DeepHousehold* agents is represented for each inhabited proxel.

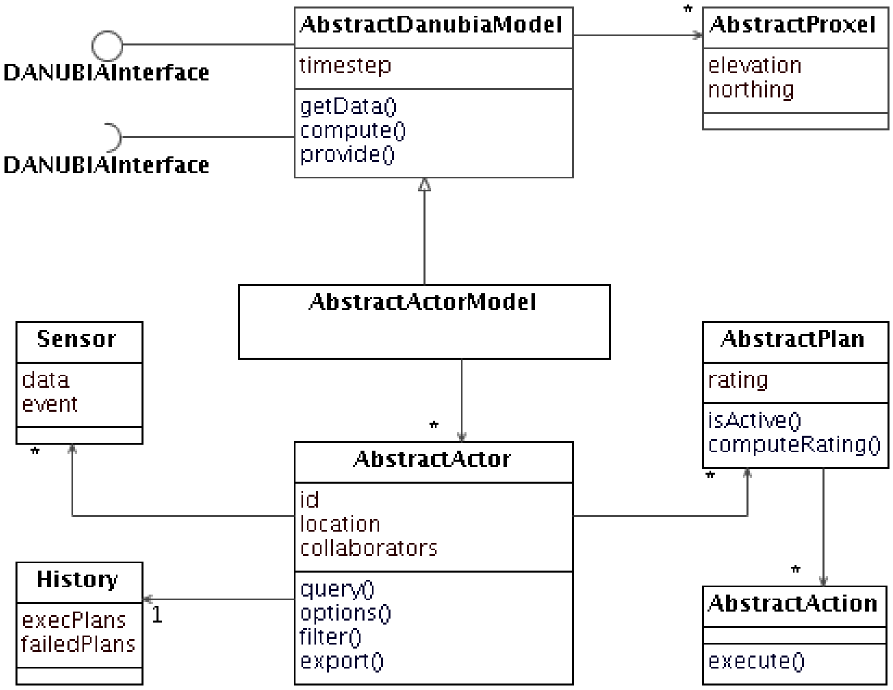


Fig. 2: A UML structure diagram showing the object classes in the DeepActor framework of DANUBIA. The DeepActor framework is an extension of the DANUBIA developer framework. The framework refines and adds (abstract) base classes aimed to provide a common conceptual and architectural basis for the development of agent-based social simulation models in GLOWA-Danube. Actual agent-based models are derived from this framework.

As shown above, actors decide based on their inner state and the state of their environment, determined by physical parameters and by conditions resulting from decisions of other actors. Communication both between actors within an actor model and between actors of different models is essential for relaying information concerning the social and physical environment. Within the deep actor models, this communication is achieved by means of data transmitted via sensors. In the current *DeepHousehold* model, the communication between different *DeepHousehold* agents triggers the diffusion of water-related technologies: Actors base their decision regarding these technologies upon their respective utility. The behaviour of peers within the social network of an actor is part of the underlying utility function: The more peers within the network currently have installed some technology A, the higher the utility for that technology A is. The relative weight of the behaviour of peers in the utility function depends on the agent type, with modern and educated agents paying less attention to the behaviour of their peers than actors with more traditional values.

In the *DeepHousehold* model, (conscious) decision making is implemented by calculating the subjective expected utility (SEU) of all the alternatives, which are plans in the set of known plans. In the case of habitual behaviour without any occurrence of special events (see below), no SEU calculation needs to be done and the basic habit plan is chosen. In the following paragraphs, the process of decision making in the *DeepHousehold* model is described.

DECISION MAKING

The different *DeepHousehold* agents possess individual profiles, which they obtain during the *initialising* step (step 1). In the *DeepHousehold* model, the rational choice approach is refined by a situated component in every decision. In the *sensor query* step (step 2), an agent perceives its physical, social, and legal environment, which allows it to adapt to the current situation. In *options* (step 3), an agent selects the plan set which can be relied on during the decision process. The subjective expected utilities are calculated in a *filter* step (step 4), before the actions associated with the chosen plans are executed and the new values are *exported* (step 5). Each step will now be explained in more detail.

Step 1 (*initialising*): Decisions depend on the preferences in an agent's profile. There are different profiles for each of the implemented milieus, which are initialised at the very beginning of the model run. Every actor is assigned an ID, a location and a set of collaborators (i.e. the agents in an agent's network). There is also information on the agent's age, its income and the number of persons in the household (since agents in the model represent households).

The milieus differ with respect to the perceived importance of the environment, of prices and of the behaviour or opinion of peers or significant others in the acquaintance or family networks. These values are inherited from the milieus and represent the individual components of the rational-choice decisions.

Step 2 (*sensor query*): For the situated component of the decision, an import of data of the current environmental state is necessary, which is realised through the sensors (see fig. 2). The sensors also signal the occurrence of special events which may trigger further, more in-depth calculations. The agent processes data about air temperature, population, water price, and drinking water flags produced by the WaterSupply model (see section 6). Events triggering a thorough decision making process are e.g. a high air temperature or a drinking water quantity flag being calculated and set by the water supply model. A quantity flag can have four levels, where level 1 means "no shortage", level 2 means "news in print media or radio about a water shortage", level 3 means "specific appeals from a community official to save water" and level 4 "manifest water scarcity and supply by tank vehicles". For the rational-choice calculations, the temperature, drinking water quantity flag value etc. have to be transformed into index values between 0 and 1. For the quantity flag, the index calculation takes not only into account the current level of the flag but the also the duration of it having been shown on a specific proxel. A level 1 flag is transformed in an index of 0.0 while a level 4 flag is the upper range of "no water" and therefore 1.0. Since people do not pay to much attention to a single newspaper article the index value for the first occurrence of flag 2 starts with 0.10 and increases with the second occurrence to 0.12 and 0.15. Announcements from town officials like a major or through loudspeakers from cars driving through the streets, are taken more seriously and therefore the index value starts with 0.3 and increases over the time to 0.4 and 0.5.

Step 3 (*options*): Depending on the events that occurred, the set of active plans is generated as a subset of the plans known to the agent. Every plan defines an option concerning one kind of water use and its quantity or intensity. For example, the water use „shower“ is calculated through the multiplication of the shower length, the shower frequency and the shower flow of the household’s shower head. In the current implementation, the shower length is set to 6 minutes as a mean that has been suggested by our empirical data.

In the following, we give some examples for the selection of active plans:

The plan “shower frequency” becomes the goal of a thorough decision process if the water price is raised by 5% or more, if there is a drinking water quantity flag, or if the average daily temperature raises above 10°C.

Shower heads are appliances which, from time to time, have to be replaced by newer, most probably more efficient ones, so 1% of the agents decide every month about the acquisition of a new shower head.

Conscious decisions about the frequency of taking baths occur if the water price is raised, a drinking water quantity flag appears or the temperature is very low (i.e. people like to take baths when its cold outside).

Step 4 (*filter*): Every agent calculates its decision under consideration of its individual preferences, the situational circumstances and the plan alternatives. For example, the shower frequency plan group consists of five plans (to shower twice a day, once a day, every second day, once a week, and to shower not at all). These sub-plans differ in the values of their attributes entering the calculation. These attributes are the costs of executing the plan, its impact on the environment and the fit of this plan to the milieu the agent belongs to.

These attribute values are multiplied with a corresponding factor, which is the sum of the individual preference (e.g. the importance of the environment) and the situational circumstances (e.g. the numerical index of the drinking water quantity flag event).

Step 5 (*export*): The actions of the chosen plans are executed and the consequential state changes are exported to the proxel. The execution of multiple plans within one decision step is possible. Their aggregated individual consumption decisions define the dynamically changing water demand on the proxel level and as such the micro-foundation of the macro-phenomenon to be modelled. The total water demand for one proxel is computed as the result of the individual water demands of each of the lifestyle type agents multiplied by the number of agents of each type per proxel. After step 5, a new cycle can start with a sensor query.

Besides the drinking water demand (and subsequently the waste water quantity produced by the households), the model currently derives the domestic water related satisfaction from the drinking water allocated for household use in relation to its water demand. It is calculated as 1 minus the quantity flag index as described above.

VALIDATION OF THE MODEL

For the validation of the model, a threefold approach was chosen, relating (1) to the comparison of the model’s performance to the overall water consumption, (2) to the consumption of the specific water use types, and (3) to seasonal changes in temperature, respectively.

First, the modelled drinking water demand was compared to the statistical water demand. A snapshot of the resulting modelled drinking water demand in one month for all agents can be seen in fig. 3. The area with the highest water consumption per km^2 is the Munich region, located in the middle of the basin. In sum, the model produces with 17.4 m^3/s a slight water demand overestimation of approx. 1% compared to the detailed reference statistic of the year 2001, including all inhabited proxels.

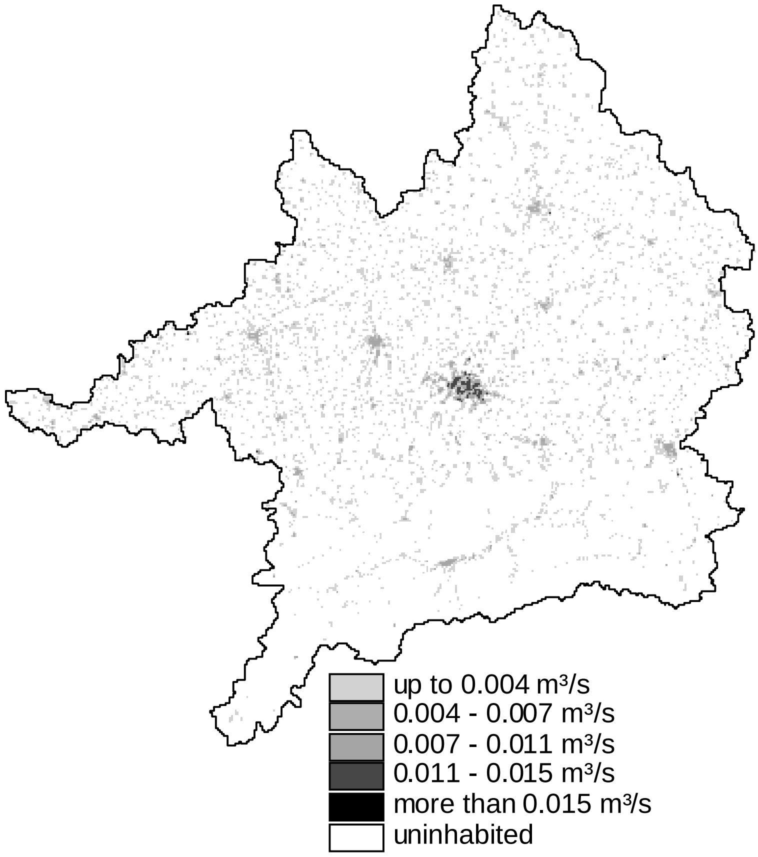


Fig. 3: A map of the drinking water demand in the Upper Danube river basin of one month as modelled by the *DeepHousehold* model in DANUBIA. The spatial resolution of the model is 1 km^2. One can distinguish the only sparsely populated region of the Alps with the Inn river valley in the South of the basin, and the larger cities further North, e.g. Munich in the middle.

Second, the modelled fractions of the different types of water uses were compared to statistical data. The results indicate that the model on the one hand overestimates the water demand for personal hygiene: our household actors consume about 65 litres per person and day for showering, bathing, teeth brushing, and hand washing, while statistical data (Abke, 2001) indicate a water demand of around 46 litres. On the other hand, the water demand for dish washing (model: 6, statistical data: 8 litres) and cleaning (model: 1, statistical data: 8 litres) is underestimated. Modelled water demands for washing machine, toilet use, and food preparation closely match statistical data.

Finally, due to a lack of monthly disaggregated statistical data for water consumption in Germany, the evaluation of seasonal changes in the water demand on a monthly basis is made on the grounds of a graphical analysis. The *DeepHousehold* model shows reasonable reactions to the modelled air temperature.

A SCENARIO RUN OF THE *DEEPHOUSEHOLD* MODEL

The following example and its first results draw upon two prototype deep actor models, WaterSupply and Household, which were implemented using of the DeepActor framework developed by the computer science group of GLOWA-Danube. These two models represent a crucial link between natural and social processes of water use via groundwater availability, groundwater extraction, distribution, and its use in the households.

Test simulations have been run and will be presented here for a 35 year (2000 – 2035), dry climate scenario[i]. Its aim is to test the functioning and the interplay of the two models on the basis of a powerful climatic driving force. The scenario contains rather extreme climatic conditions: Based on a trend of increasing temperature of 4°C per 100 years (which conforms to the IPCC A2 scenario), observed meteorological data from the eight driest years between 1970 and 2003 were taken to provide the weather conditions.

The central function of the WaterSupply model is to continuously compare developments on the demand side with the present state of supply infrastructure and of water resources in order to satisfy the consumers, while respecting the technical, economical and ecological constraints. To this end, the WaterSupply actor model comprises 1717 supply agents, which draw from over 8.000 sources. WaterSupply agents as well as sources are located on the proxels which represent their correct geographical location.

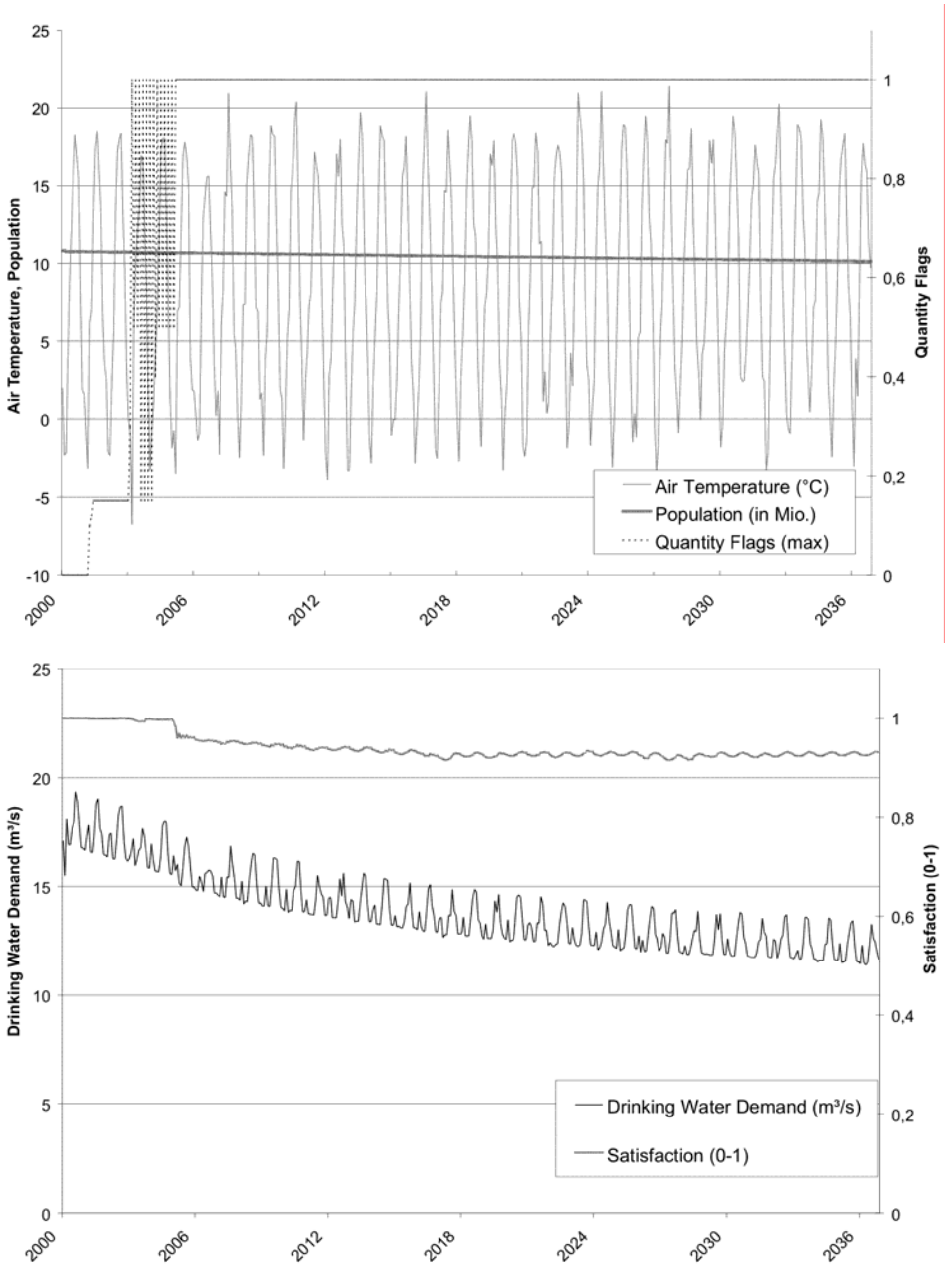
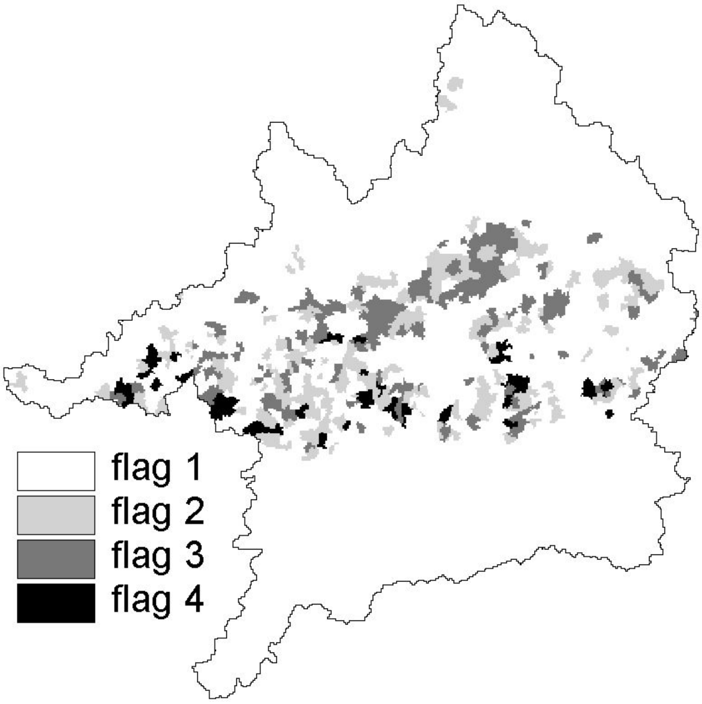


Fig. 4: Driving forces (above) and modelled results (below) of the 35-year-scenario run on the aggregated level. When considering the three main driving forces air temperature, population and quantity flags, the quantity flags show a clear shift towards water scarcity in some regions, while the air temperature shows corresponding seasonal changes and the population

decreases to a small extend. The water demand also shows seasonal changes. The water-related satisfaction is correlated to the level and the duration of quantity flags and therefore decreases during the scenario run.

For the example scenario run presented here, only two contrasting milieus (post-materialists, traditionals) have been taken into account for the *DeepHousehold* model. The results of the run are depicted in fig. 4 and fig. 5.
A typical signal in the water supply – domestic water demand chain passed between the WaterSupply and the Household models are the so-called quantity flags, which are set by the suppliers and seen by the users. The flags inform about the quantitative and (in a later implementation version) qualitative state of water resources. The Household actors interpret these flags as if they were press reports or appeals to save water and react in accordance with them. The drinking water quantity flag levels used in the model are: (1) No problems reported, (2) multiple reports in the local newspaper about water supply problems, (3) a first public appeal to save water issued by the mayor, and (4) official restrictions for water use.



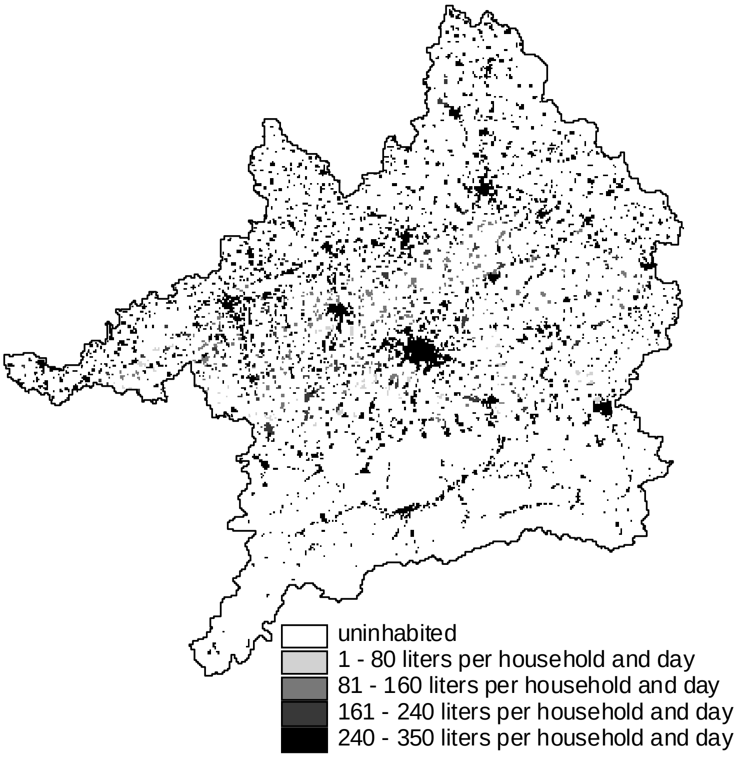


Fig. 5: Drinking water flags as produced by the deep WaterSupply actor model (above) and drinking water demand from the *DeepHousehold* model (below) toward the end of the 35 year hot and dry scenario run (shown here: June 2030). The domestic water consumers represented in the figure are those with post-materialist orientation. Areas of water shortage can be identified in the upper map (grey and black flags). They indicate the spatial extent and the growth over time of areas which will likely suffer water use conflicts in a dry Danube future, given a water supply infrastructure not radically different from today's. In these regions, domestic water consumption is reduced as a reaction to the shortages.

CONCLUSIONS AND OUTLOOK

Rising temperatures, reduced precipitation, shrinking groundwater aquifers: If this scenario is Danube's tomorrow, it is necessary to have more precise ideas about the interplay between natural and social factors in the water cycle. How will a changing hydrological regime and water demand changes reciprocally effect each other in both space and time? Can there be known more about the probabilities of conflicts and their possible locations and causes? Tackling such questions is made possible in GLOWA-Danube through the integration of the socio-economic components by means of deep actor models of domestic, industrial, agricultural and tourist water use and water supply. The scenario reported here is one step in this direction.

The model is able to reflect – beyond an estimation of future behaviour – phenomena such as agents' learning and changes in their habits, or deliberate decision making with regard to water shortage scenarios, the purchase of new appliances. Even the upcoming of new technologies could be integrated with some knowledge about their characteristics.

According to our empirical findings, the Household model is being extended using all Sinus-Milieus® and thus integrating all our empirical data for habits and plan evaluation. The aim is to reach a high degree of precision of backcasting while having a sufficient theoretical depth and explanatory power. Thus, several studies are either on the way or planned to empirically substantiate the model, covering the areas of habits, innovation diffusion, water-related risk perception and environmental attitudes.

The deep actor framework shown here gives the possibility to implement interaction between agents through networks. This in turn allows for a fine grained modelling e.g. of the adoption of innovative technologies. Those changes in the agents' behaviour might account for non-linear behaviour of the populations, a question that will be one leading the investigations to come.

Another research question will be the simulated effect of political interventions (by information, pricing, the influence of role models and the like). A large variance of scenarios is planned to be simulated using differing climates or socio-economic factors as driving forces. All simulations will take place with the coupled models within the DANUBIA system. The simulation results will be discussed with experts from the field and other stakeholders, in order to make adjustment and refinement to the modelled processes, e.g. flag calculation, plans and actions. Discussions could also be fruitful with respect to defining and testing rules of allocation in case of dramatic water shortages.

It will be important to know how such modelled interventions will interact with quantitative and qualitative demographic changes that are to be expected in the region, i.e. a slightly shrinking and clearly ageing population. The model will be used to tackle questions of social sustainability, embedded in the framework of sustainability of the water cycle under conditions of global climatic change.

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[i] The run has been realised with the special efforts of the GLOWA-Danube groups from the geography department at the Ludwigs-Maximilians-University, München (especially Wolfram Mauser) and from the University of Stuttgart (Roland Barthel and Darla Nickel).