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Using the Multiactor-Approach in GLOWA-Danube to Simulate Decisions for the Water Supply Sector Under Conditions of Global Climate Change

**Roland Barthel · Stephan Janisch · Darla Nickel ·
Aleksandar Trifkovic · Thomas Hörhan**

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Abstract GLOWA-Danube (www.glowa-danube.de) is an interdisciplinary project that aims to develop integrated strategies and tools for water and land use management in the upper Danube catchment (Germany, Austria ~77,000 km^2). The project is one of five within the GLOWA research program (www.glowa.org) dealing with Global Change effects on the water cycle in six meso-scale catchments (up to 100,000 km^2) in Central Europe, West Africa and the Middle East. In the GLOWA-Danube project, 16 natural science and socio-economic simulation models are integrated in the coupled simulation system DANUBIA. This article describes the underlying concept and implementation of *WaterSupply*, a multiactor-based model of the water supply sector with a focus on water resource utilization and distribution of individual water supply companies. Within DANUBIA, *WaterSupply* represents the link between water supply and demand, where the former is simulated by a groundwater and a surface water model and the latter by water consumption models of four different sectors (domestic, industrial, agricultural and tourism). *WaterSupply* interprets the quantitative state of water resources for defined spatial and temporal

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R. Barthel (✉) · A. Trifkovic
Institute of Hydraulic Engineering, Universität Stuttgart, Stuttgart, Germany
e-mail: roland.barthel@iws.uni-stuttgart.de

S. Janisch
Institute of Computer Science—Programming and Software Engineering,
Ludwig-Maximilians Universität Munich, Munich, Germany
e-mail: janisch@pst.ifi.lmu.de

D. Nickel
Ecologic—Institute for International und European Environmental Policy,
Berlin, Germany
e-mail: darla.nickel@ecologic.eu

T. Hörhan
Federal Ministry of Agriculture, Forestry, Environment and Water Management,
Division VII/1, National Water Management, Vienna, Austria

units according to sustainability requirements and assesses the state of resources in relation to present water supply schemes and the dynamics of user demand. *WaterSupply* then seeks both to optimize the resource use of supply companies and to identify critical regions for which further adaptation of the water supply scheme will become necessary under changing climatic conditions. In this article, a brief description of the GLOWA-Danube project and the integrated simulation system DANUBIA is followed by a short presentation of the DEEPACTOR framework, which provides a common conceptual and technical basis for the socio-economic simulation models of GLOWA-Danube. The main body of the article is devoted to the concept, the implementation and simulation results of *WaterSupply*. Results from different scenario calculations demonstrate the capabilities and the potential fields of application of the model.

Keywords Multi-actor approach • *WaterSupply* model • Global change • DANUBIA • Danube • Integrated water resources management

1 Introduction

1.1 Background and Context of the Presented Model

The emphasis of this article is on the conception, implementation and testing of the ‘*WaterSupply*’[1] model, which was developed to identify critical regions for the water supply sector resulting from changing demands and states of resources under conditions of Global Change. The *WaterSupply* model is embedded with 15 other natural science and socio-economic models in the coupled simulation system ‘DANUBIA’. DANUBIA was implemented within the GLOWA-Danube project, which focused on the water cycle of the upper Danube catchment in Germany (www.glowa-danube.de; Ludwig et al. 2003).

The project background and modeling framework of GLOWA-Danube and the central idea of the GLOWA initiative are essential for understanding the concept and scope of the *WaterSupply* model and are therefore described in Sections 1.2 and 1.3. In Section 1.4 we briefly discuss and compare approaches presented by other authors for addressing the issues at hand. Section 2 introduces the ‘DEEPACTOR’ approach to simulating human response to Global Change. This is the theoretical basis of *WaterSupply*. The *WaterSupply* model itself is then illustrated in detail in Section 3. Section 4 presents results of *WaterSupply* in the upper Danube catchment using a choice of different climate scenario simulations in combination with different socio-economic mega-trends. In Section 5, model validation options and the requirements for transferring the model to other catchments are discussed.

1.2 The GLOWA-Danube Project and Danubia

Worldwide, both administrative authorities and the research community are voicing an increasing interest in integrated approaches for describing, modeling, and forecasting physical, social, economic, and political processes related to the hydrological

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[1] Model names, model parameters and model related terms are printed in *Italics*.

cycle, in particular with regard to Global Change. The Glowa-initiative (Global Change of the Water Cycle) was established in response to this growing interest. Six meso-scale river basins (up to 100,000 km^2) were selected in Central Europe, Africa and the Middle East to investigate the effects of Global Change on the physical and socio-economic domains of the water cycle and to develop integrated tools for water and land use management on a regional scale (www.glowa.org; BMBF 2008). The upper Danube watershed (up to Passau) was selected as a representative catchment in the temperate mid-latitudes, covering an area of approx. 77,000 km^2 and encompassing much of southern Germany and north-western Austria (Switzerland, Italy and the Czech Republic together cover only 3% of the area; see Fig. 1).

The upper Danube is a catchment with a water surplus. Hence the relevance for Global Change Research in this area is characterized less by water shortage than by a lack of substantiated definitions of the various existing conflicts and possible future functions in a regional management of the water resources. The natural environment in the upper Danube is very sensitive to climate change. It is to be expected that climate change will lead to strong water and land use changes. However, these changes are also affected by other factors that are not related to climate change. Among these are the creation of cultivated plants with a higher resistance to cold, precipitation, and parasites and their changed yield structures, changes in the vegetation growth and the water use efficiency due to increased CO$_2$ concentrations, especially at higher altitudes.

At the core of the Glowa-Danube project, which began in 2001, is the development of the coupled simulation system Danubia. Danubia is a system that

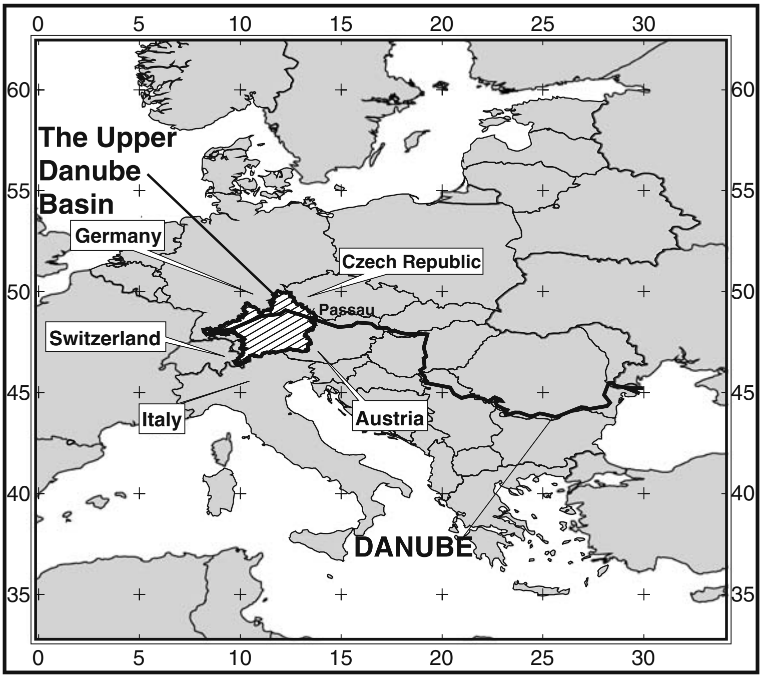


Fig. 1 Location of the upper Danube catchment, the investigation area of Glowa-Danube

can be used identifying and quantifying regional effects of Global Environmental Change coupled with human activities on the water cycle and for investigating the sustainability of future water resource management alternatives (Mauser and Strasser 2005; Ludwig et al. 2003; Barthel et al. 2008b).

DANUBIA comprises a total of 16 disciplinary models. Models from the fields of meteorology, hydrology, remote sensing, groundwater and hydrogeology, plant ecology, and glaciology address the physical processes which control to a great extent the natural water cycle and water availability. So-called '*Actor*' models cover the socio-economic aspects of the water cycle: the industrial sector (*Economy* model), the agricultural sector (*Farming* model), the tourism sector (*Tourism* model, Sax et al. 2007), the domestic sector (*Household* model, Ernst et al. 2005, 2008; Schwarz and Ernst 2009), the water supply sector (*WaterSupply* model—this article; Barthel et al. 2005) and demographic development (*Demography* model). Their joint responsibility is the calculation of the water demand, water extraction and water prices. Going beyond this, *Farming* simulates activities of farmers which result in land use changes (Apfelbeck et al. 2007) and *Economy* predicts household income and industrial development (Zimmer 2008).

As a common notation for the specification of system structure and data exchange, the Unified Modeling Language UML (Rumbaugh et al. 2005) was used by all project partners in GLOWA-Danube. The UML component diagram in Fig. 2 shows the five main components of DANUBIA, each of them comprising multiple simulation models which were developed by the different project partners. Interfaces specify the methods used for data exchange between coupled simulation models. For each model there is an interface specifying its required import data (sockets in Fig. 2) and an export interface, specifying the data which is provided (balls in Fig. 2). Figure 3 shows the interfaces that specify the exchange parameters of *WaterSupply* with other models within and outside the *Actor* component. The interfaces are used to ensure consistent interconnections for the data exchange during coupled simulation runs. Typically simulations are executed as a distributed system where the single simulation models are located on different computers, and therefore executed in parallel to each other.

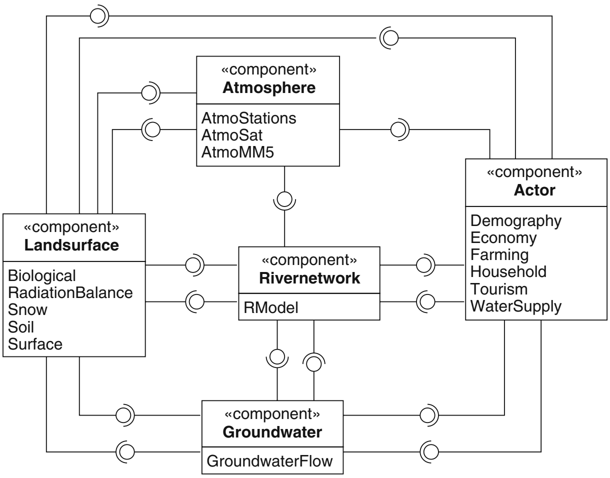


Fig. 2 The five main components of the coupled simulation system DANUBIA

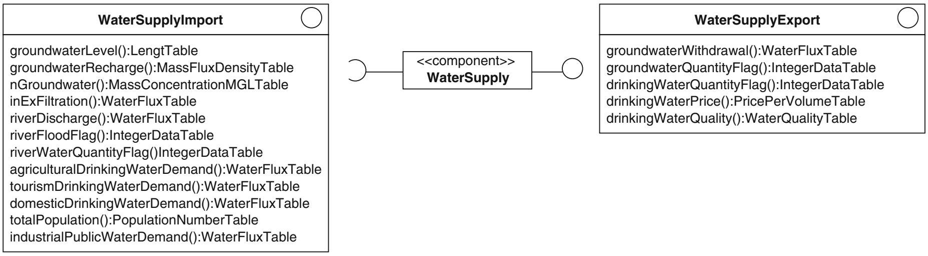


Fig. 3 Interfaces of *WaterSupply* specifying exchange parameters with other simulation models

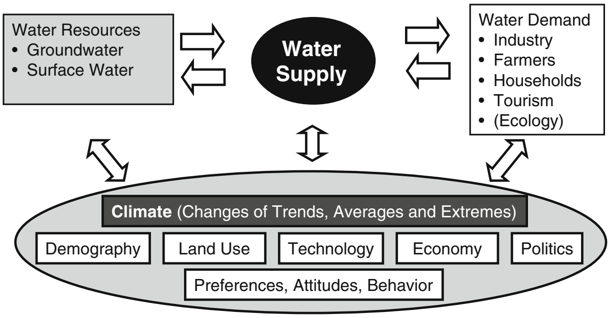
Beyond a common notation for an integrated specification, Danubia provides a Java developer framework for the implementation of simulation models and a runtime environment which coordinates models according to their local, model-specific time step (Barth et al. 2004; Hennicker and Ludwig 2005, 2006). The DeepActor framework, an extension of the developer framework of Danubia, provides a common conceptual and technical basis for the realization of socio-economic simulation models in Glowa-Danube. Its main features are briefly summarized in Section 2. A more detailed account, in particular the integration of the above mentioned socio-economic simulation models within Danubia, is provided in Barthel et al. (2008a).

The primary application of Danubia is for the evaluation of consequences of Global Change Scenarios on the water cycle in the upper Danube catchment. Global Change is here understood as a combination of climatic, demographic, political and technological change, including behavioral and attitude changes of water users and consumers. Scenarios, defined for the period 2011–2060 are based on the global Climate Change scenarios presented by the IPCC (Bates et al. 2008; Solomon et al. 2007) in combination with socio-economic mega-trends (societal trends or scenarios). The development of climate scenarios is described in more detail in Section 4.2.

1.3 Objectives and Role of the *WaterSupply* Model in Danubia

Simulating water supply systems requires the integration of natural and socio-economic processes, the consideration of multiple actors with different options and preferences, a regional scale focus, and distributed models which are spatially and temporarily explicit. Figure 4 shows the specific relation and interdependencies of

Fig. 4 Relations and dependencies of water supply under the influence of Global Change



the water supply system to Global Change. It is obvious that Global Change affects the conditions of both the supply and demand side as well as the water supply system itself (water supply companies, supply network etc.). These changes are not independent and therefore require that all three system elements be considered in an integrated way. In addition, any analysis regarding the future of the systems requires the definition of consistent scenarios including climatic and socio-economic change.

In Danubia, the *WaterSupply* model forms the link between various physical models determining water quality and availability and several socio-economic models determining water consumption and demand (Figs. 2 and 3) and in doing so evaluates the impacts of both climatic and social change. Having a central focus on public drinking water supply, its purpose is to simulate the supply of drinking water under changing boundary conditions, first and foremost changes in water demand or water availability and quality.

Availability and quality of water are modeled by the *Groundwater*, *Rivernetwork* and *Landsurface* components of Danubia (Fig. 2). The *Groundwater* model (Barthel et al. 2005, 2008b) is based on MODFLOW 2000 (Harbaugh et al. 2000) whereas *Rivernetwork* and *Landsurface* are based on DAFLOW (based on Jobson 1989) and PROMET (Mauser and Bach 2009, manuscript submitted) respectively. The demand side is represented in Danubia by the simulation models *Household* and *Demography*.

The *WaterSupply* model is used to locate critical regions which could experience water stress in the future and to evaluate the effects of different interventions to solve or to prevent such problems. *WaterSupply* does not model water supply companies on an individual technical level, i.e. the technical infrastructure (pipe diameter, size of storage tanks etc.) of each water supply company (*WSC*) is not considered. A *WSC* is defined by the relations of a supply company to other objects (*Sources*, *Consumers*, and other *WSC*). The physical representation of these relations is not explicitly considered. A main feature of *WaterSupply* is its capability to simulate different responses of *WSC* with respect to changing definitions of 'sustainability'. That means, as a part of the scenario definition (see Section 4.2), a user can specify whether a resource is used to its technical limit or if more value is given to sustainability, social and ecological criteria (see scenario definitions in Section 4.2). The concrete aims of *WaterSupply* are described in detail in Section 3.

1.4 Previous and Related Works

Predicting future water availability and water demand has always been one of the central questions in water resources management. Accordingly, a large number of approaches for simulating and predicting the state of resources and the evolution of demands exist (see e.g. Hajkowicz and Kerry 2007; Xu and Singh 1998; Alvisi et al. 2003; Ekinci and Konak 2009; Tillmann et al. 1999). The majority of these approaches either deals with demand or supply predictions on a sectoral basis, and are dedicated to the description of small-scale systems in a discrete[2] way, or are lumped regional

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[2] *Discrete* here means modelling systems on a technically or personally explicit level, i.e. real infrastructure, people or institutions.

models. Thus, the scope and field of application of such approaches do not match the DANUBIA *WaterSupply* approach. The following discussion is focused solely upon comparable integrated regional scale approaches.

There is a growing demand for integrated management and assessment of resources on a *regional scale* (UNESCO 1987; GPW 2000; Quinn et al. 2004; Bouwer 2002) which has accordingly generated a growing number of regional integrated research projects and approaches (e.g. Gaiser et al. 2003, 2007; Scoccimarro et al. 1999; Krysanova et al. 2007; Rodgers et al. 2007; van der Keur et al. 2008; Koch and Grünewald 2008; Volk et al. 2007; Maia and Silva 2009). Fully *integrated* simulation models that address both environmental impacts and socio-economic effects have been presented by Wu (1995), Kirshen et al. (1995), Watkins et al. (2004) and Yamout and El-Fadel (2005). However, these focus on smaller systems and the local scale. Athanasiadis et al. (2005) and López-Paredes et al. (2005) provide *regional and integrated* models for water management, including both water suppliers or municipalities and area residents. Moss et al. (2000) sketch a promising approach within the FIRMA project that explicitly includes policy makers and consumers. The negotiation process simulated in the approach of Thoyer et al. (2001) and the model of Espinasse and Franchesquin (2005) have a local, small-scale focus. Berger et al. (2007) and Feuillette et al. (2003) describe integrated approaches to model water management which are not applicable to central European water management, as in both cases the availability of water resources has a major influence on farming and therefore on the household income as well. Recently, there is an increasing number of studies dealing with the role of actors in the water supply sector and ways to analyze and subsequently model their behaviour (e.g. Timmermans 2009). However, these studies do not go as far as implementing large scale fully integrated models to simulate water management on a river basin scale.

In our opinion, a modeling framework that enables decision makers to assess the state of water resources against the backdrop of dynamically changing natural conditions and increasing sustainability requirements and that allows complex possibilities for water supply schemes development is yet to be developed.

2 Simulating Human Response

As mentioned in the previous section, *WaterSupply* is an *Actor* model. *Actor* models in DANUBIA are a group of models that simulate human response to Global Change in different sectors (Fig. 2). All *Actor* models, and in particular the *WaterSupply* model, are based on the common 'DEEPACTOR' approach (Barthel et al. 2008a).

Human response to Global Change—be it of climatic, technical or political origin—can in most cases be described as a reaction to changing conditions and is quite often based on a decision process. In contrast to physical processes, human response can usually not be modeled adequately by sets of globally applicable equations (Axtell 2000) To represent and simulate response, GLOWA-Danube follows a multiactor approach, which draws upon the concepts of agent-based simulation in social sciences (Gilbert and Troitzsch 2005; Davidsson 2002; Macy and Willer 2002), or more generally, upon the agent concepts of (distributed) artificial intelligence (Russell and Norvig 2003; Weiss 1999). Since we rely on concepts of agent-based modeling rather than on the technical implications of software-agents in general, we speak of 'actors' instead of 'agents' and of 'multiactor'- instead of 'multi-agent' modeling.

Our approach is implemented using the DeepActor framework, an object-oriented developer framework which is briefly described later in this work. The suffix 'deep' is used in Danubia to distinguish between socio-economic simulation models that rely on an equation-based modeling approach ('flat' models) and the DeepActor models that rely on the DeepActor framework. The DeepActor approach and framework are described in detail in Barthel et al. (2008a).

Both the Danubia developer framework and the DeepActor framework provide basic building blocks for model implementations in form of (abstract) base classes and predefined relationships among them. A concrete DeepActor model may implement different specializations by extending the respective base class. As shown in Fig. 5, the classes provide a direct representation of common modeling concepts, e.g. *AbstractActor* as a representation of decision-making entities.

Decision-making entities (a person, an organization, or, as in the present case, a water supply company) are explicitly modeled and simulated as an *Actor* (*AbstractActor*). Different actors may have different course-of-actions as well as varying preferences, represented by their individual plans and their type-specific decision procedures. Note that since Danubia is a raster-based system with a spatial discretization of 1 × 1 km grid cells (*AbstractProxel*), an *Actor* generally represents a real person or organization in an abstract manner rather than explicitly. An *Actor* is located on one or more of these cells that in turn define the environment of this *Actor*. Within each time step of a simulation run, each *Actor* observes its environment via sensors (*Sensor*) and selects plans (*AbstractPlan*) to execute in reaction to its observations. Plan execution results in the execution of associated actions (*AbstractAction*). Actions model explicit state modifications of the simulation area. At the beginning and the end of each time step, the simulation model exchanges data with coupled simulation models according to its import and export interfaces (*DanubiaInterface*). The history of an *Actor* allows it to remember which plans were executed successfully in previous time steps.

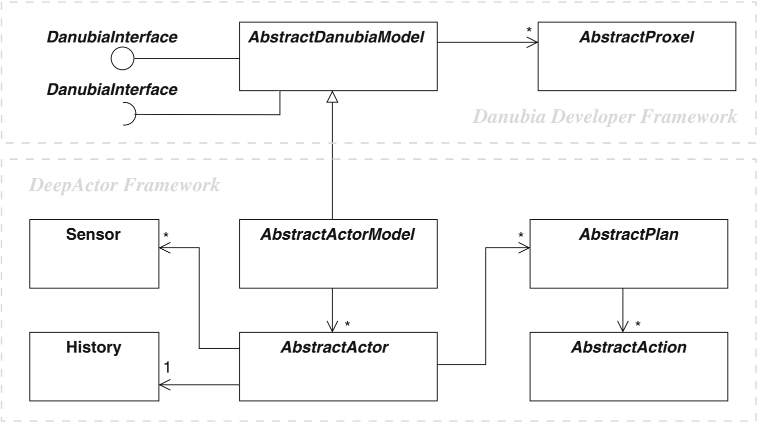

Fig. 5 Base classes for the development and integration of DeepActor models within Danubia

The framework does not restrict the implementation of type-specific decision procedures, but rather provides basic building blocks which may be used to implement arbitrary complex *Actor* types, ranging from simple reactive actors up to deliberative or adaptive actors. Which of the framework features are actually used is left to the design of the concrete DeepActor model.

The multi-actor (DeepActor) approach has the advantage that it facilitates the modelling of a flexible and realistic response to system changes. Scenarios can easily be defined by adjusting *Actor* types and preferences.

3 Model Concept and Implementation of *WaterSupply*

3.1 Point of Departure and Objectives of the *WaterSupply* Model

In the upper Danube basin, the dominant sources of drinking water are groundwater and spring water (>95%). The responsibility for water supply lies with the communities, resulting in a large number of local water supply companies (see Fig. 6). Characteristic within the upper Danube basin is a strongly decentralized, three-tier structure comprising local, community-based suppliers (well over 2,000), regional special purpose associations assuming the water supply responsibilities for a group of communities (~300), and a few supra-regional, long-distance suppliers supplying regions with little or no resources (~5) (Emmert 1999). Through this three-tier organization of water supply, a high degree of security is given, although water quality problems in particular give a growing cause for concern. Although the use of local resources is generally preferred, many communities depend upon supply from all three organizational forms for supply security. A number of group suppliers and in particular the long-distance suppliers import or export appreciable amounts of water across the boundaries of the Danube basin, which need to be accounted for in the water balance.

The development of the conceptual *WaterSupply* model was led by the following questions: (i) what is the specific purpose and role of the *WaterSupply* component within the integrated system Danubia, (ii) what are the model boundaries and which are the parameters to be exchanged with other models, (iii) which are the relevant elements and processes of the water supply system that need to be considered, (iv) which data is required to model the identified elements and processes and (v) how are the data requirements related to the actual data availability. A more detailed coverage of the questions listed is given by Barthel et al. (2005) and Nickel et al. (2005). The process of answering these questions is an iterative one. In general it can be said that data availability forms very strong constraints.

As a result of the considerations mentioned above, the following tasks were defined as necessary with respect to the overall goals of Danubia and as reasonable in view of the scale and data availability:

1. The interpretation of the quantitative and qualitative[3] state of water resources for defined spatial and temporal *Zones* according to results of the natural science models (*Groundwater*, *Rivernetwork* and *Landsurface*, see Fig. 2).

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[3] Within this article, water quality aspects are not addressed.

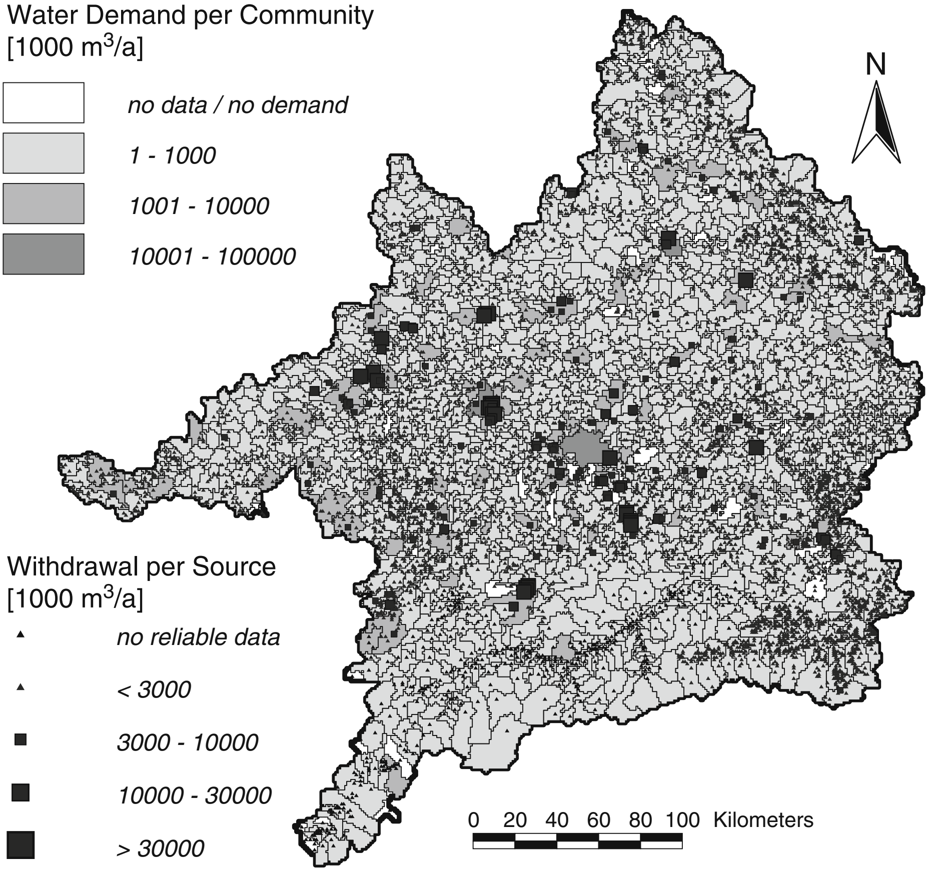

Fig. 6 Water supply in the upper Danube catchment. Note that for Austria and Switzerland no reliable data on withdrawal from wells and springs are available. Areas with no demand or demand data do either not belong to any community or represent lakes

2. The comparison of the state of water resources in relation to present water supply schemes and resource use (local, regional, long-distance) and the dynamics of user demand as calculated by the socio-economic models (*Household, Tourism, Farming* and *Economy*, see Fig. 2).
3. The optimization of the present resource use of supply companies and the identification of critical regions for which further adaptation on the supply or demand side will become necessary under changing boundary conditions, namely climate change, changes in water availability and quality and changing water demand.

As should become apparent by this list of tasks, *WaterSupply* does not model the technical infrastructure (pipe lines, treatment plants, storages and other technical equipment) of individual water supply companies in a discrete way. This would not be appropriate for the model scale, as these parts of the water supply system are

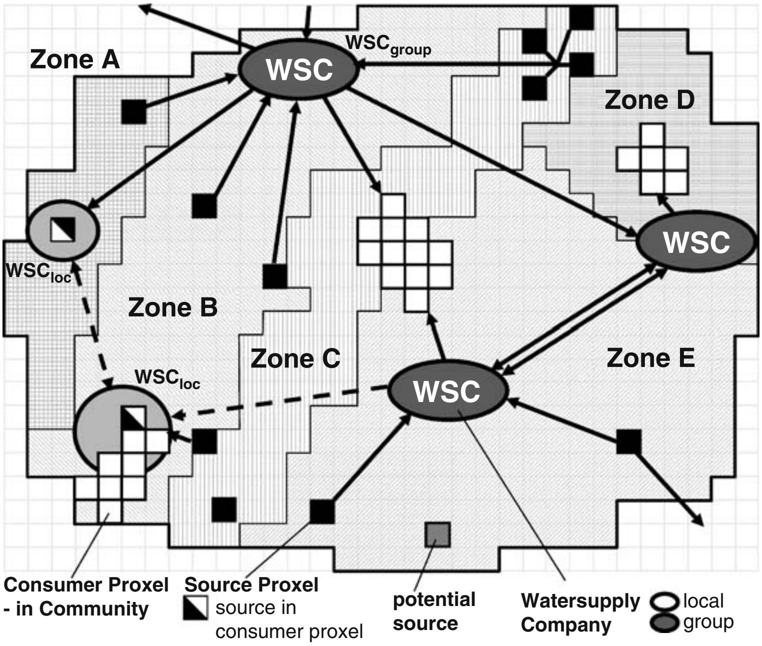

Fig. 7 Elements and spatial relations of the *WaterSupply* model

extremely complex and require company specific data which is neither available nor can be collected and processed with an affordable effort.

3.2 Model Structure and Concept

3.2.1 Model Elements

Figure 7 shows the main elements of the *WaterSupply* model and their dependencies in a schematic map. As the spatial discretisation of *WaterSupply* matches the *Proxel*-concept[4] of Danubia, model elements are represented by at least one *Proxel* (i.e. a model cell of 1 × 1 km, see Section 1.2). Model elements can also be formed by continuous or non-continuous groups of *Proxels*. *WSC* are defined both by the *Proxels* they withdraw water from (*Source Proxels*) and by the *Proxels* that they supply water to (*Consumer Proxels*).

The model elements and terms used in Fig. 7 are described in more detail in Table 1, which also summarizes and explains the main function of the model elements. Table 1 also lists the main static properties (set at initialization and kept constant during a simulation) and the dynamic properties (changed during a simulation) of the model elements. Beginning with the '*Zones*' and the '*Flag*' concepts, which lie at the core of the *WaterSupply* model, the elements and their attributes will be explained in following sections.

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[4] PROXEL: process pixel, model cell on whichcomputation takes place.

Table 1 Characterization of the main elements of the *WaterSupply* model (Fig. 7)

Element	Number	Static attributes[a]	Dynamic attributes[a]	Role/comment
Water supply company (*WSC*)	1,720	*Source Proxels*, *Potential Source Proxels,* collaborators	*drinkingWaterQuantityFlag*, Used capacity, target capacity, necessary expansion	4 types summarized to *locWSC, locWSC with collaborators* and *regWSC* (Fig. 8)
Source	5,152	Location, initial capacity, WSC	Capacity	A Source (Proxel) represents all known wells or withdrawal points located in a Proxel
Potential Source	387	Location, initial capacity, WSC	Capacity	Location to build a new well. Can be used if demands exceed existing capacity, existing capacity cannot be increased and status of the Zone is at least good
Community (*COM*)	2,095	*WSC*1, *WSC*2, *Consumer Proxels*	Water price, demand, supply, deficit	Consist of one to several 100 *Proxels*; all *Consumers* in one *COM* are supplied by one *WSC*, demands are calculated on *COM* level
Consumer	76,213	Location	See community	A consumer Proxel represents all households within a Proxel. Consumers are represented by their COM
Zone	405	Location, size, aquifer, sub-catchment, hydraulic properties, geometric properties	*groundwaterQuantityFlag*, Groundwater recharge, -level, baseflow	Represents a groundwater resource that reacts uniformly to changes of boundary conditions

[a] Attributes will be explained in detail in the remainder of Section 3.2 and in Section 3.3

3.2.2 Zones

A *Zone* (see Fig. 7, Table 1) is defined as a group of *Proxels* (continuous or non-continuous) that belong to the same surface watershed and the same major aquifer (groundwater body). Within *WaterSupply*, the 'state' of these *Zones* is determined using results from the natural science models (*Groundwater*, *Rivernetwork* and *Soil*, see Fig. 2) and expressed in the form of '*groundwaterQuantityFlags*' (*GQF*, see Fig. 11) on a scale of 1 (very good) to 5 (very poor). 155 surface sub-catchments within the upper Danube catchment, for which continuous discharge measurements exist, and 4 major aquifers (i.e. the four layers of the groundwater flow model used in DANUBIA (see Barthel et al. 2005) lead to 405 individual *Zones* (∅ 200 km^2). A *Zone* represents the portion of a surface water catchment in which a certain layer of the groundwater model forms the 'main' (in many cases the uppermost active[5]) aquifer. The delineation is based on the assumption that all model cells located in a *Zone* react similarly to changes of boundary conditions (recharge, withdrawal) and that they contribute similarly to the surface water discharge at the respective gauge (baseflow).

For these 405 *Zones*, the state of groundwater resources, meaning their quantity and quality, is calculated for each time step based on *GroundwaterRecharge*, *GroundwaterLevel* and *InExfiltration* (baseflow) (see Fig. 3, Fig. 11). If the state is 'bad', less groundwater is available in storage in comparison to a reference period or the quality of groundwater has decreased. The determination and interpretation of the state and its use by *WSC* within the *WaterSupply* models is explained in the following section.

3.2.3 Flag Calculation—Assessment of the State of Resources

Whereas the quantitative state of groundwater resources is expressed by the *GQF*, other *Flags* are calculated in *WaterSupply* as well. One example is the *drinkingwaterQuantityFlag (DQF)*[6] with values from 1 to 4, which summarizes the state of all resources a *WSC* uses. The concept of *Flags* follows the idea of warning and restriction levels which are applied in some water scarce regions of the world (e.g. Victorian Water Industry Ass. Inc. (2005), San Antonio Water System (2009)). Although in the past situations requiring such a warning system were not common in the water rich upper Danube catchment, recent climatic events (the dry summer of 2003, see BAYSTMUGV 2003) and the anticipated climatic change display the necessity for such assessment and information tools. Tables 2 and 3 explain what the *Flag* values mean and how *Flags* can be interpreted by *Actors* within the partner models.

To understand the interaction between different *Actors*, e.g. the *WSC Actor* and the *Household Actor* (the *Actor* in the *Household* model, see Fig. 2) it is important to note that the interpretation of a *Flag* and the subsequent reactions to it are different for different *Actor* Types (a *Farming Actor* interprets *Flag*s differently than the *Household Actor*). For example, *Household Actor* types have different ecological and social sensitivities and therefore react differently to public appeals to save water. A more detailed description is given by Barthel et al. (2008a).

3.2.4 Water Supply Companies—WSC

In *WaterSupply*, the deciding entity, i.e. the *Actor*, are the *WSC* (see Fig. 7, Table 1). These can draw upon water from *Zones* or from surface water bodies via *Sources* which are limited initial extraction capacities and the *groundwaterQuantityFlag*. The

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[5] 'active' here refers to the active cells of the MODFLOW based *GroundwaterFlow* model (see Fig. 2: The main components of the coupled simulation system DANUBIA).

[6] Other such Flags in use within Danubia are '*riverwaterQuantityFlags*', '*groundwaterQualityFlags*' and '*riverwaterQualityFlags*'. These *Flags* are not addressed in this article.

Table 2 General meaning of the *groundwaterQuantityFlag (GQF)*

GQF value	General interpretation by *Household Actors*	Interpretation/reaction by *WSC Actor*[a]
1	Very good status, groundwater recharge, baseflow and groundwater levels at or above long term averages within a significant period	No specific reaction, business as usual
2	Good status, groundwater recharge, baseflow and groundwater levels only slightly below long term averages within a significant period	No specific reaction, business as usual; under strict ecological regulations, withdrawal might be slightly reduced
3	Warning stage, groundwater recharge, baseflow and groundwater levels significantly below long term averages within a significant period	Includes Reactions to *Flag 2* No further increasing of capacity of sources, tapping of new sources restricted, reduce withdrawals to a specified percentage etc.; Warnings (and restrictions) are issued to *Consumers* (information level)
4	Critical status, groundwater recharge, baseflow and groundwater levels significantly below long term averages over a long period. Ecological damages and water scarcity (water supply) occur frequently but locally	Includes Reactions to *Flag 3* Strong reduction of withdrawal, crisis management (legal level)
5	Catastrophic status: Severe ecological damages and water scarcity (water supply) on a regional level	Includes Reactions to *Flag 4* Stop withdrawal

[a] How and to what extent a *WSC Actor* reacts is part of the scenario definition. In a sustainability oriented scenario, *WSC* will pay more attention to warnings and react stronger and earlier than in a liberalization scenario (see Section 4.2)

WSC deliver drinking water on a local, regional or long-distance scale to affiliated communities (*COM*). Two types of *WSC* are currently represented in the model: local and regional types (Figs. 7 and 8).

Table 3 Interpretation of *DQF* values in the *Household* model

DQF value	Interpretation by *Household Actors* (general examples)[a]	Individual interpretation/reaction	
		Hedonistic actor type	Post-materialist type
1	No problems reported	No specific reaction—water use habits	
2	Multiple reports in the local newspaper about potential water supply problems	No specific reaction	Increased activation; water saving technology
3	Public appeal to save water issued by the mayor	Ignore	e.g. reduced shower frequency
4	Official restrictions for water use	Ignore (if possible)	Obey

A DQF is considered to be a formal (legal restriction) or informal (press article) information on the state of the water supply

[a] Farming or industrial actors may have different interpretations

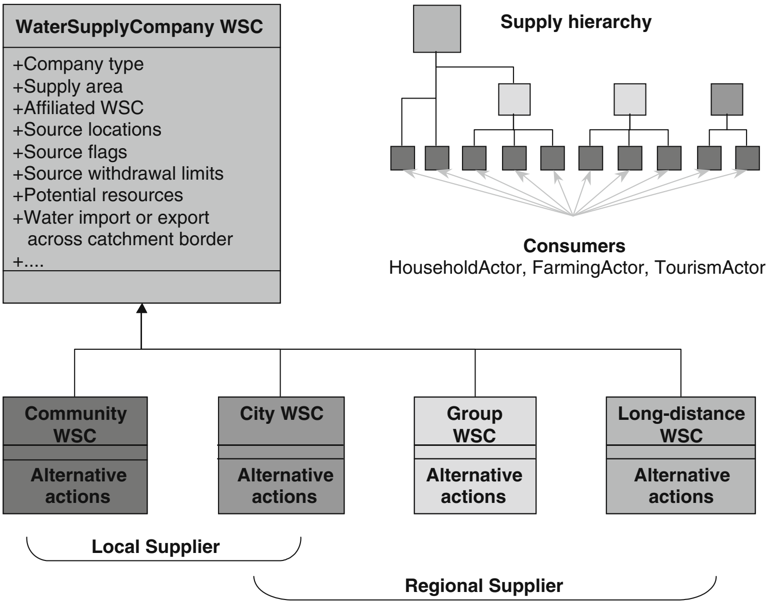

Fig. 8 Hierarchy of the water supply system in the upper Danube catchment and its abstract representation in the *WaterSupply* model

The *WSC* compare the demands to the state of the resources on the supply side. Depending on the ratio between demand and the *WSC* water extraction capacities, the state of its resources, its type (local, regional) and location, a *WSC* chooses from four plans (responses) ranging from ‘business as usual’ to ‘crisis management’ (Fig. 10). For example, a *WSC* might increase its capacity in view of increasing demands—if the *groundwaterQuantityFlag* allows.

3.2.5 Communities—COM

Communities (*COM*) form the link between the *Consumer* and the *WSC*. A *COM* consists of all *Proxels* within the administrative boundaries of a politically independent community. At each time step (here: 1 month), the *COM* aggregates the *Consumer* demand of the *Actor* models (*Household, Tourism, Farming* and *Economy*, Fig. 2) and communicates the demand sequentially to the affiliated *WSC*. Each *COM* can be supplied by a local supplier, a regional supplier, or both. Resource limitations (need for demand-side management measures) are communicated to the *COM* by means of company-specific ‘*drinkingWaterQuantityFlags*’ (*DQF*). Furthermore, the *COM* calculate both the drinking water price on a yearly basis and community-specific *DQF*, and relay this information to the *Consumers*. These, in turn, interpret the *DQF* as warnings or use restrictions (demand-side management). Table 3 offers a brief example of how Consumers, in this case domestic water users, may interpret the *DQF*.

3.3 Implementation and Computation

3.3.1 Utilization of the DeepActor Framework

The implementation of the concept and structure described in the previous section and its integration into the Danubia simulation framework makes use of the DeepActor framework (see Section 2). *WaterSupply* implements the *Actor* type water supply company (*WSC*), distinguishing between local and regional *WSC* (see Section 3.2, Fig. 7, Table 1). In the object-oriented model structure used, both *WSC* and *COM* are represented by their own class (Fig. 9). Both classes have a limited view and knowledge of their environment. A *COM* knows where and how much water is consumed and from which *WSC* it is served. A *WSC* possesses information regarding extraction sites and water rights, (capacity, raw water quality etc.) and potential collaborating *WSCs*.

Due to the high level of supply security of the water supply system in Germany and the generally good water availability in the upper Danube catchment, it can be assumed that capacity problems will only occur under extreme climatic conditions. The extremely hot and dry summer of 2003 can serve as an example. To do justice to this situation, the model comprises two units: a 'flat' unit that deals with all the cases where the demand can easily be met and a 'deep' unit that deals with all cases in which demand cannot be met or a critical demand/capacity ratio is reached. The flat unit of the model, shown on the left and center of Fig. 9, is equation based. The deep unit shown on the right is *Actor* based. The model implementation in two units was done for performance reasons as the deep calculations require more computational resources. The flat *WaterSupply* unit was described in detail in Barthel et al. (2005).

The *Actor*-based (deep) unit allows a *WSC* to perform actions that are different from 'business as usual'; 'business as usual' means that the quantitative and qualitative needs of the *Consumers* can be satisfied without using extraordinary measures. Figure 10 shows a summary of plans and actions that can be taken by the *WSC Actor* and how these are represented within the DeepActor framework.

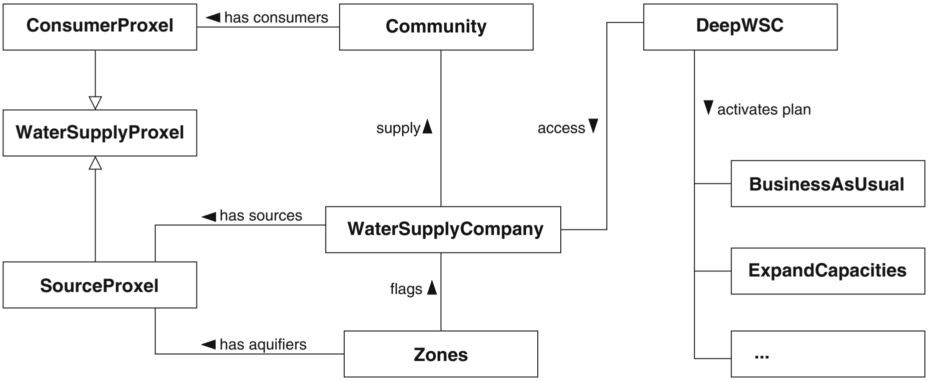

Fig. 9 The object-oriented model structure derived from the conceptual view in Fig. 7. The flat unit of the model is shown on the *left* and *center*, whereas the deep unit is shown on the *right*

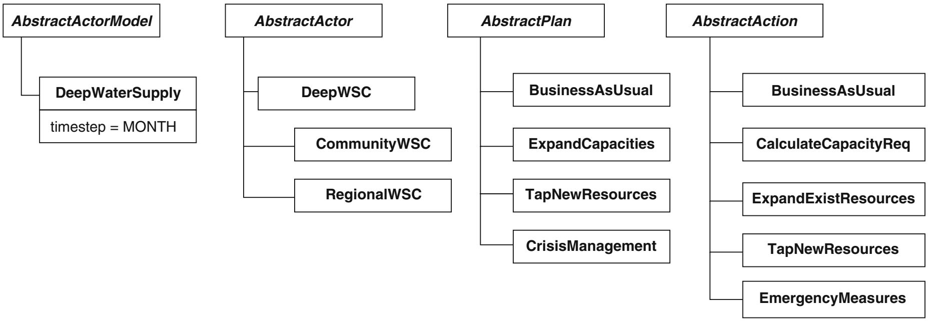

Fig. 10 The implementation of *WaterSupply* based on the DEEPACTOR framework (see Section 2) and summary of the plans and actions the *WSC Actor* can chose from

The calculations carried out by *WaterSupply* are based on two main steps:

1. *Consumer* demands aggregated by the *COM* and sent to a *WSC* are accumulated and compared to supply capacity to determine the degree of sufficiency,
2. If the supply capacity is insufficient, a solution to the problem is sought, i.e. the deep model unit is activated (see Fig. 9). At the same time, the *WSC* inform the *COM* about the resources state using *Flags* (see Table 3).

In the deep model unit of *WaterSupply* (Fig. 10), only those calculations are carried out that lead to a change of *WSC* attributes or to a behavioral change. Such changes aim to secure a full supply of all drinking water demands. The necessity for change arises either from growing demands, which surpass the present capacity, or from a quantitative degradation of one or more of the present *Sources* in use, which leads to a capacity reduction. The parameters necessary for plan and action selection are the following:

1. The type of the *WSC* (local, regional—see Fig. 8),
2. The existence of collaborators (affiliated *WSC* able to supply water in case of insufficient supply),
3. The usable capacity,
4. The state of the resources the *WSC* draws upon, as stated by the *Flag* values of groundwater *Zones* and river reaches and the number of *Sources* with a good quantitative status ($GQF = 1$ or 2),
5. The number of *Potential Sources*.

The plans and actions are summarized in Table 4. This overview includes a description of the situations which trigger one of the four plans. Each plan draws upon a different combination of actions.

3.3.2 Assessment of the State of Resources—Flag Calculation

At each time step, each *WSC* aggregates the usable capacities of its individual *Source Proxels* to get a total usable capacity. Whereas the capacity of each source is initially defined by its assigned water rights and technical constraints, the usable capacity depends on the quantitative state (*Flag*) of the *Zones* the source is located in. *Flags* are calculated at each time step. The *Flag* calculation relies on the results of the

Table 4 Plans and actions that can be selected by the model

Plan/action number	Name	Explanation, trigger
Plan 1	Business as usual	No change is necessary; all demands can be met with the present usable capacity of the *WSC*
Plan 2	Expand *WSC* capacity	Not all demands can be met. The capacity of one or more presently used *Sources*, initially determined by the water right, must be expanded to fulfill demands. Only *Sources* with a *GQF* value of a certain value (usually 1 and 2) can be expanded. The *GQF* values and the factor by which capacity can be expanded can be specified in the scenario definition (see also Section 4.2) e.g. to express a more or less environmentally oriented behavior
Plan 3	Tap new *Source*	Not all demands can be met. A *Potential Source* must be tapped to secure supply. If a potential source is available and if it can be used depends again on the state of the resource and threshold values specified in the scenario definitions (see previous row)
Plan 4	Crisis management	Not all demands can be met. Crisis management measures, e.g. delivery of water from outside the catchment via tank vehicles, are necessary to meet demands. Crisis management options are not explicitly defined deliberately
Action 1	Business as usual	No changes are initiated; all *WSC* attributes remain the same
Action 2	Calculate new capacity need	The difference between present capacity and desired capacity is calculated
Action 3	Expand *WSC* capacity	The capacity of one or more existing *Sources* is raised
Action 4	Tap new *Source*	A *Potential Source* is changed to a source and assigned needed capacity or its maximal usable capacity
Action 5	Crisis management	Drinking water is supplied by a fictitious supplier in the current time step, however consumer are informed about water scarcity in the next time step

A plan may include more than one action

Danubia models *Soil*, *Rivernetwork* and *Groundwater* (Fig. 2). It is based on a backward analysis of the changes in groundwater recharge, groundwater level and baseflow and a comparison with long term averages:

1. For each *Zone* (see Fig. 7), the indicators groundwater recharge, groundwater level and baseflow as calculated by the partner models are aggregated to one value per *Zone* and time step (1 month).
2. Starting from the current time step, the backward mean of a period P is calculated for each indicator, whereby P is the 'characteristic reaction period' for each

indicator and each *Zone*. The length of P depends on the hydrogeological characteristics of each *Zone*, e.g. shallow aquifers have a short reaction time and accordingly a shorter P.

3. The mean calculated in step 2 is then compared with the mean for the same calendar month of a reference period (in this specific case 1960–2006). For example, if the current simulation time step is May 2025 and the characteristic reaction period for the specific *Zone* and indicator is 9 months, then the mean from September 2024 to May 2025 from the simulation run is compared to the mean of all months September to May from the reference period. The relative deviations are classified according to classes defined individually for each indicator and *Zone* based on the hydrogeological characteristics. The thresholds can therefore differ over a larger range. The classified values are called 'indicator *Flags*' and range from 1 (very good) to 5 (very bad). The threshold values are defined individually for each *Zone* and indicator.
4. The indicator *Flags* calculated in step 3 are then combined to the 'weighted *Flag*' by calculating the weighted mean (each indicator has a different weight for each *Zone*) of all parameters. As above, *Flag* values range from 1 to 5.

3.3.3 WSC Reaction to Flag Values—Decision Process

How the *WSC* actually interprets the *GQF* must be defined in the scenario definition of a simulation (see Sections 1.3 and 4.2). For example, in the socio-economic scenario 'business as usual' a 'normal behavior' of *WSC* is assumed. This means that the capacity of the *Sources* remains unchanged if the value of the *GQF* is 1 or 2 (good status). At 3, the capacity is reduced to 75%, at 4 to 50% and at 5 (very bad status) to 25% of the original capacity (see also Table 2). The usable capacity is compared to the total drinking water demand, which is sent by the affiliated *COM*, to calculate an initial demand/supply ratio. This ratio, together with specific *WSC* attributes, triggers one of four plans (see plans and actions Table 4) which all aim at fulfilling *COM* demands. As a result, all demands are finally met in the present time step, yet warnings and restrictions are sent to the *Consumers* with the aim to limit demands in future time steps. The values and percentages listed in this paragraph are just examples from one scenario—they can be defined to meet the assumptions made in the overall scenario definition of a Danubia simulation.

Within the model, all *Consumer* needs are satisfied, if necessary using unspecified 'crisis management actions'. These are necessary to close the overall water balance, as the water used by *Consumers* is ultimately discharged into the rivers as waste water. Of interest to the model use is the identification of regions and conditions under which actions beyond business as usual become necessary. These must then be further analyzed using the in-depth information of all 16 Danubia model results. *WaterSupply* seeks a solution for the problem by choosing one of the available plans. The chosen plan should not be viewed as a proposed optimal solution but as an indication of the severity of necessary changes to the present system of water supply. The aim of *WaterSupply* lies not in planning but in evaluating possibilities.

As there are always misunderstandings regarding the terms 'water demand' (what is needed) and 'water consumption' (what is actually used or can be used) it should be noted that *WaterSupply* makes no differentiation between the two. Any demand is satisfied in the current time step to close the water balance, yet for the next time step restrictions may be set. This means: *Consumers* can be prompted to reduce their demands. It then depends on the *Consumer* preferences and behavior if they comply (see also Table 3).

The individual *Source Proxels* of the *WSC* are debited a portion of the total supply in accordance with their *GQF* value. The usable capacity of 'healthier' *Sources* (*Sources* with a good state, *GQF* 1 or 2) is maximized first, so that 'unhealthy' *Sources* receive less strain. The *GQF* values are one main factor for the choice of a plan by a *WSC*, since they determine if the capacity of existing *Sources* can be expanded or if *Potential Sources* can be tapped. In addition to that, they play an important role in the decision making process of the other *Actor* models, e.g. the *Household* model (see above) or the *Farming* model, in which irrigation from groundwater is restricted to *Sources* with a good state.

3.3.4 Communication with Other Actors in Danubia—Drinking Water Quantity Flag

Within Danubia, the *GQF* is used foremost by the *WaterSupply* model as information on the quantitative state of groundwater resources. The domestic users (the *Household Actors*) also base their decisions on the state of the resources. In contrary to the *WSC Actor,* a *Household Actor* (i.e. an individual *Consumer*) is not directly interested in the state of a groundwater resource. The *Household Actor* is more interested in the overall state of the water supply systems he is supplied by (the degree of interest varies according to *Household Actor* type, see Table 3). Usually a *COM* (which is the representation of a group of *Household Actors* in the *WaterSupply* model) is served by more than one *WSC*, which in turn draw upon different *Sources*. In the view of the *Household Actor,* the state of the water supply system is therefore an averaged value of the states of all *Sources* he is connected to through one or more *WSC*. To acknowledge this, the '*drinkingWaterQuantityFlag*' (*DQF*) is calculated and passed to the *COM*. The *DQF* values range from 1 to 4. The *DQF* is the weighted average of all *GQF*s that add to the total supply of one *COM* (Fig. 11).

The rules for interpreting *Flags* (see e.g. Table 3) are set for each simulation as a part of the scenario definition (see Section 4.2).

3.3.5 Detailed Description of the Decision Process and Model User Options

Before describing the decision process in detail it should be mentioned that all threshold values (percentage of capacity, *Flag* values considered 'good' or 'bad') can easily be changed and are part of the scenario definition (see also Section 4.2). Therefore, if the model user decides to run a more sustainability-oriented or a more economically-oriented scenario, he can do this by changing the threshold values. The following description should therefore be regarded as an example of how the decision process takes place. It should also be noted that the object-oriented model structure allows for a very easy adaptation of the model to different user needs, be it the number and nature of plans, *WSC* characteristics or regulations. The UML activity diagram in Fig. 12 is a graphical representation of the decision-making process which is then described in the following:

The choice of a plan is dependent upon the type of *WSC* (see Figs. 7 and 8), the demand sent to the *WSC* and the state of its *Sources*. The following example explains

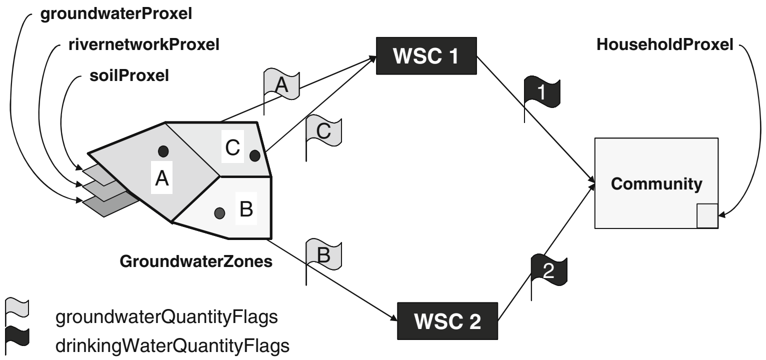

Fig. 11 Information exchange between the natural science models *Groundwater*, *Rivernetwork* and *Landsurface (Soil)*, the deep unit of the *WaterSupply* model and the *Consumers* (*Actors* models) based on *Flags*

the decision process. Again the values and percentages used in this paragraph are just exemplarily and can be defined together with the general scenario definitions and other assumptions:

A local water supply company (*locWSC*) can have one or no collaborators. If a collaborator exists, than the *locWSC* is not required to meet the total demand of its affiliated *COM* representing the *Consumers*. In this case, the *locWSC* is simply interested in maintaining the status quo, i.e. the total usable capacity should equal the total initial capacity determined through the water rights. As long as this applies, Plan 1 is followed. When this is no longer the case, the *locWSC* will choose Plan 2 ‘Expand *WSC* capacity’, as long as at least one of its *Sources* has a good quantitative status

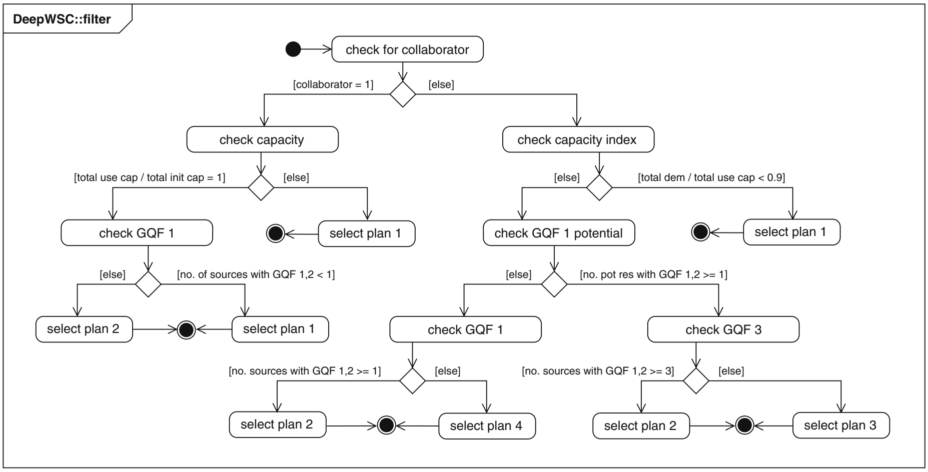

Fig. 12 UML activity diagram of the plan selection in the deep model unit of *WaterSupply*

(*GQF* = 1 or 2). The capacity is expanded so that the total usable capacity/total initial capacity ratio is once again equal to 1. In the event, however, that Plan 2 fails, no alternative plan is carried out, as this is not an emergency situation. If no collaborator exits, the *locWSC* is alone responsible for supplying its affiliated *COM*. In this case, the *locWSC* is interested in maintaining a usable capacity which surpasses the total drinking water demand within a margin of safety. As long as the total demand/total usable capacity ratio is below (for example) 90%, Plan 1 is followed. When the total demand/total usable capacity ratio rises above 90%, the *locWSC* attempts to carry out Plan 2. If Plan 2 is successful (depending on the state of its *Sources*), the capacities of the *Sources* with good quantitative status are raised so that the total demand/total usable capacity ratio equals 65%. When Plan 2 fails, Plan 4 is chosen to meet the demand.

Potential *Sources* are available to all *WSC*—yet no *WSC* can use a *Source* outside its defined area of influence. This is of course a limitation which excludes the possibility to let the water market in the model grow freely. This limitation was specifically made for the upper Danube catchment model implementation for two reasons: a) water supply in Germany is highly regulated and is the responsibility of the communities; there is an implicit priority rule saying that each *Potential Source* is foremost at the disposal of the community it is located in; b) allowing all or some *WSC* access to *Potential Sources* all over the model domain or larger parts of it leads quickly to an unrealistic evolution of the system, as large infrastructural changes in reality are based on political decisions and rely on economic considerations. Such decisions are difficult or impossible to include in the simulation process. Thus, if a model user would be interested to see the effect of, for example, one *regWSC* growing very large, this would have to be done by directly changing the specific parameters in the model. As such simulations are not in the centre of focus of GLOWA-Danube, no concrete interfaces to do this have been implemented.

A regional water supplier (*regWSC*) may have access to one or more *Potential Sources*, but has no information regarding collaborators.[7] The *regWSC* is therefore always interested in maintaining a safety margin, analogous the *locWSC* without a collaborator. Plan 1 is followed as long as the safety margin is maintained. When the total demand/total usable capacity ratio equals 90% or more, the *regWSC* must choose from among the Plans 2–4. If the *regWSC* has at least one *Potential Source* with good quantitative status (*GQF* = 1 or 2), and the number of presently used *Sources* with a good quantitative status is less than 3, one of these *Potential Sources* is tapped, becoming a usable *Source*. If the number of presently used *Sources* with good quantitative status is greater than or equal to 3, the capacity of these *Sources* is raised. In both cases, the final total demand/total usable capacity ratio should equal 65%. If the *regWSC* has no *Potential Source* but at least one presently used *Source* with good quantitative status, the *Source* capacity is expanded (Plan 2) so that the total demand/total usable capacity ratio equals 65%. If both Plans 2 and 3 fail, Plan 4 is chosen.

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[7] i.e. a local WSC can get water from a regional WSC but not vice versa; to model this, as well as the potential cooperation of two or more regional WSC would raise the level of complexity very much and would involve many economical considerations and unknowns.

4 Modelling Results

4.1 Overview and General Description of Potential Results

In order to be able to fully judge the meaning and validity of the results of the *WaterSupply* model, it would be necessary to discuss the results of the DANUBIA System and the 16 simulation models (see Fig. 2) as a whole, as all the partner models influence the *WaterSupply* results. It would also be necessary to discuss the results along with the underlying scenario assumptions and of course in view of the specific situation in the modeled catchment. The scope of this paper does not allow a discussion of this breadth. Results presented here are reduced to the *WaterSupply* model. An extensive overview of DANUBIA results is available through the GLOWA-Danube online Atlas at http://www.glowa-danube.de/atlas/atlas.php (Print version: GLOWA-Danube 2008), though currently only available in German.

According to the principle aims of GLOWA-Danube, the objective of *WaterSupply* is to identify and visualize water supply related tendencies and developments in the upper Danube catchment under conditions of Global Change, based on scenario calculations (~2011–2060). The main aims are to demonstrate spatially variable changes in the water supply situation (good, reliable and stable or endangered, unstable, unsafe), to identify regions that might experience a critical situation in the future given defined climatic conditions, and to pinpoint water overuse that could entail ecological risks.

The following outputs of *WaterSupply* can be used for further analysis:

- The *groundwaterQuantityFlag* (*GQF*): A change of this parameter from better to worse indicates that ecological constraints or sustainability criteria are endangered. Changes of the *GQF* point to problems on the resource side of the hydrological cycle, which can be the result of overexploitation (‘man-made’) or changes in water availability (e.g. due to decrease of precipitation) or a combination of both. In combination with output parameters of other DANUBIA models (e.g. groundwater level, river discharge, water demand, evapotranspiration), these problems can be specified more clearly.
- The *drinkingWaterQuantityFlag* (*DQF*): A change of this parameter from better to worse shows that the supply situation has worsened in the respective regions. The *DQF* are a direct function of the *GQF* (see above) but also contain an evaluation of the demand side and include the specific characteristics of each *WSC*. They therefore summarize all possible causes (infrastructural, climatic, and ecological) for a decreasing supply security of the water supply systems on a regional and a local scale. High values (3, 4) of the *DQF* indicate problems with the water supply system in the respective region, yet an analysis of the causes requires the evaluation of the results of other DANUBIA models.
- Choice of plans and actions to be taken (see Fig. 10) of the *WaterSupply Actor* (*WSC*): An evaluation of the choice of plans made by the *WSC Actor* can help identify the source of the problem and provide a first indication of how the problem might be solved.

In general the choice of plans and the *DQF* are based on the characteristics of the specific water supply company and can therefore be interpreted to solve infrastructural problems. As stated by other authors (e.g. Haakh 2007), it seems, for example, that in the upper Danube catchment in particular those *WSC* are vulnerable with respect to climate change which rely on one single, spatially limited resource.

4.2 Description of the Scenario Assumptions

The scenarios used to create the results described in the following sections have two components: (1) climate scenarios consisting of time series of hourly climate data values (temperature, precipitation, humidity and wind speed) for the period 2011 to 2060 (50 years) and (2) assumptions on the behavior of the *WSC Actors*.

The climate scenarios were developed using a stochastic climate generator (details in Mauser et al. 2007; Mauser and Bach 2009, manuscript submitted). This climate generator uses measured historical meteorological time series and produces a likely realization of the future climate. It generates future climate data through a rearrangement of the historical meteorological data set. The method is based on the assumption that the annual course of climate can be decomposed into weeks which are characterized by an average temperature, a precipitation sum and the covariance between the two. Weekly average temperatures, rainfall and the covariance matrix are fed into a coupled random number generator which generates two dependent normally distributed random numbers for each week in the scenario period. These numbers are transformed into random average temperature and rainfall values based on averages of temperature and rainfall for the considered week. Then the historical data set is analyzed to determine the most similar week in terms of average temperature and rainfall. This selected week is added to the generated data set. Adding the temperature and precipitation trends as given in the IPCC-A1B scenario to the random number generation creates an IPCC-A1B climate development on the basis of physically consistent measurements. The procedure is based on the assumption that the general statistical relations among climate parameters will not change significantly during the scenario period. Several scenarios were defined in the GLOWA-Danube project according to a number of criteria which are not addressed here in detail (see Mauser et al., in preparation). To create a broad spectrum of climate scenarios that reflect the current uncertainty of GCM and regionalization methods, three different assumptions regarding the future trend of temperature and precipitation in the upper Danube were used. For each of these general climate trends, four subsets were defined which contain ‘critical’ events. Table 5 explains the trends and their subsets.

Figure 13 shows the future climate development as defined by the resulting 12 climate scenarios (combination of three trends and four subsets) along with the measured climate of the past in an overview.

Since groundwater is the main source of water supply in the upper Danube catchment, the effects of climate change on the groundwater resources are of particular interest. Steep temperature increases and slightly decreasing precipitation lead to a reduction of groundwater recharge and subsequently to falling groundwater levels (Fig. 14).

In addition to the climate scenarios described above, the socio-economic *Actors* models require that certain basic assumptions on the behavior of *Actors* are specified. This is done in DANUBIA by specifying so-called societal trends. To date, three different sets of societal trends have been defined (see Table 5). For the

Table 5 Scenario definitions used in DANUBIA

Climate trend (CT)	Climate variant (CV)	Societal mega-trend (SMT)	Interventions
CT1: IPCC-Regional (trends derived from the regional IPCC report)	CV1: Baseline (average conditions)	SMT1: Baseline (*Actor* behavior assumed to be as at the moment)	Not specified here, e.g. building of a large reservoir
CT2: REMO-UBA (trends derived from the regional climate model REMO based on ECHAM4 GCM)	CV2: five warm winters[a]	SMT2: Liberalization (economically oriented behavior of *Actors*)	
CT3: Measurements (trends derived from measured climate data 1960–2006)	CV3: five hot summers[a]	SMT3: Sustainability (ecologically oriented behavior of *Actors*)	
	CV4: five dry years[a]		

[a] Successive

WaterSupply model and the *WSC Actor* the scenarios have the following meaning (roughly summarized): In the ‘business as usual’ scenario, the *WSC* behave as they do now, i.e. resources are utilized respecting ecological criteria and sustainability yet also considering economic aspects. In the ‘sustainability’ scenario, *WSC* react very sensitively and early to changes of the state of resources by reducing withdrawal and

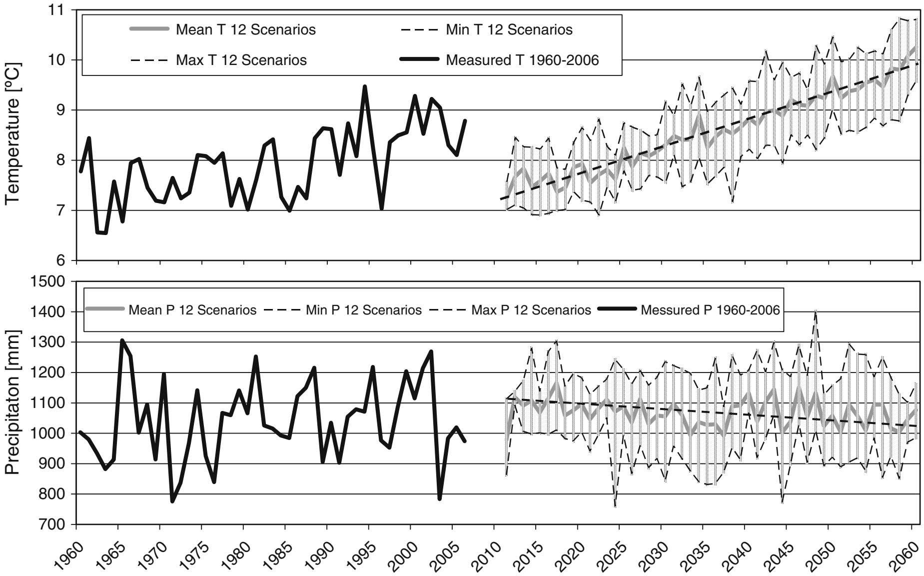

Fig. 13 Temperature and precipitation for 12 climate scenarios (mean and range of all scenarios) and the measured climate in the reference period (1960–2006). Note that climate scenarios start approximately with the trend values at the end of the 1960–1990 period

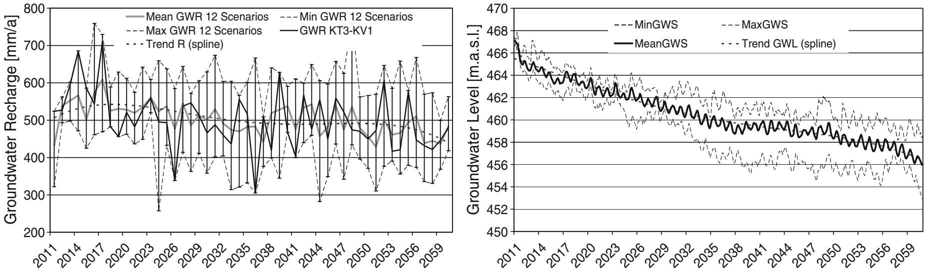

Fig. 14 Simulated groundwater recharge (*GWR*) and groundwater levels (*GWL*) for 12 climate scenarios (see Table 5, Fig. 13), yearly and monthly GWL averages for the entire upper Danube catchment. The results stem from the *Landsurface* and *Groundwater* components of DANUBIA (see Fig. 2)

imposing restrictions on the *Consumers*. In the 'liberalization' scenario, *WSC* use their water resources up to the limits of technical capacities while ignoring the state of resources until they are completely depleted.

4.3 *WaterSupply* Scenario Results

As stated above, the *GQF* and *DQF* values comprise an assessment of water resources available for water supply. Figure 15 shows the spatial and temporal development of the *GQF* and *DQF* for one selected climate scenario (CT1-CV3, see Table 5) in combination with the three societal mega-trends (SMT1…3 see Table 5). The selected scenario is a relatively dry one (see Fig. 14), with a steady decrease of groundwater recharge. Over the scenario period of 50 years, this leads to a significant degradation of the state of the groundwater resources (see Table 2) expressed in the *GQF* (upper box in Fig. 15). It is notable that the societal component of the scenario has an influence on the state of the groundwater resources as well, as it determines the consumption of groundwater water and subsequently the groundwater levels. However, the influence of climate is stronger than of social impacts. This does not take into account that under a warmer and dryer climate regime, irrigation will become increasingly more common than it is at present. As this is a political issue being debated at this moment, it is not included in the scenarios presented here. The boxes below the *GQF* in Fig. 15 show three different realizations of the *DQF* for the three different SMT (Table 5). The 'sustainability' scenario (SMT3) leads to a strong decrease of *DQF* values, i.e. to a decreasing state of the water supply system (see Table 3). In comparison, under scenario assumptions of the 'liberalization' scenario (SMT2), the *DQF* values hardly change at all: They remain 'very good' and 'good' until the end of the simulation period. The differences can be explained by the different ways *WSC* use the *GQF* values: In SMT2, *WSC* largely ignore the *Flag*s and withdraw water up to the technical limits, whereas in SMT3 any sign of a worsening of the resources state would lead to a reduction of withdrawal. SMT3 and SMT2 represent two extremes of social development and were to explore the maximum breadth of possible changes. A more likely development is represented by the 'baseline' scenario (SMT1), which lies in between (Table 5). Under assumptions of SMT1, we see a moderate degradation of the state of the water supply system.

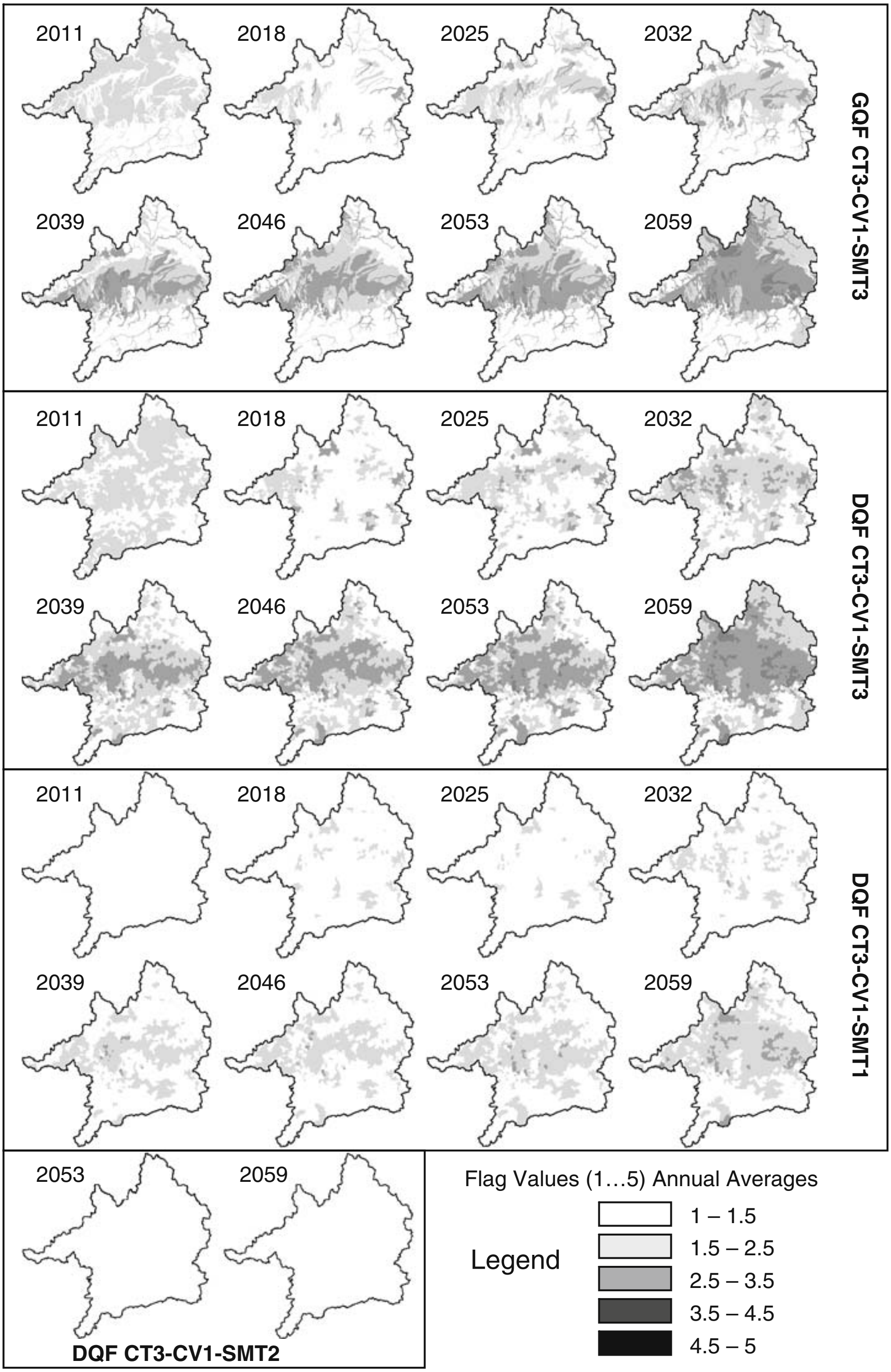

Fig. 15 Changes of the *Flag* values (Table 2, Table 3) under different scenario assumptions (see Table 5)

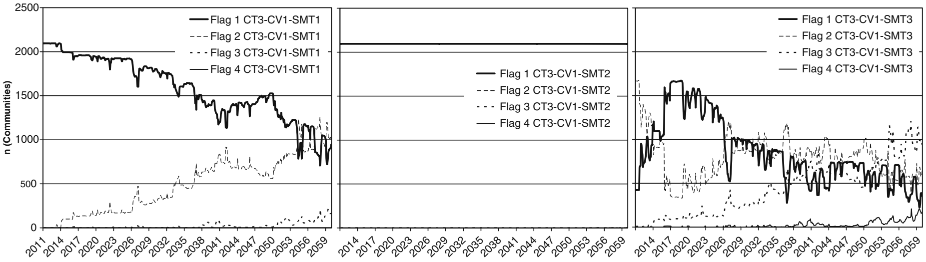

Fig. 16 Number of communities that received *drinkingWaterQuantityFlags* of the categories 1, 2, 3, 4 for CT3-CV1 climate scenario combined with the societal trends SMT1–3 (see Table 5). Total number of communities: 2,095

That the degradation is moderate in view of the relatively strong deterioration of groundwater resources (*GQF*) can be attributed to the highly developed water supply system in the upper Danube catchment which can buffer most of the climate change impacts over a long period of time.

Figure 16 shows the number of communities that received *drinkingWaterQuantityFlags* of the four different categories. Obviously, in the 'liberalization' scenario (SMT2), the consumers are not at all informed about any changes on the resources side and the *WSC* find ways to satisfy all demands by using their resources regardless of their (ecological) state. In the 'sustainability' scenario (SMT3), in contrast, the number of communities receiving a *Flag* value of one decreases rapidly, while *Flags* of higher values increase. In the last decade, up to 200 communities even receive a 'highly critical' *Flag* value of 4, which implies water scarcity, restrictions and crisis management (see Tables 3 and 4). As can be expected from the scenario definition (see Table 5) the results of the 'baseline' scenario (SMT1) lies between both extremes.

In general, values within the first 6 years of the scenario simulation period should not be regarded as reliable model output, as the coupled simulation system Danubia needs some time to adjust to the changing boundary conditions.

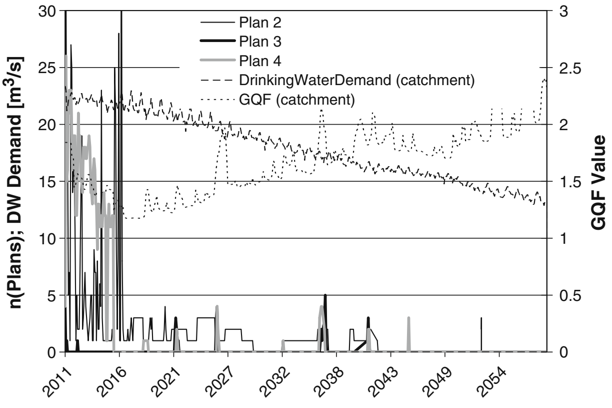

Fig. 17 Dependencies of plan execution (Table 4), *GQF* values (Table 2) and *Consumer* demands for the entire upper Danube catchment for one selected *WSC* for the CT3-CV1 climate scenarios combined with the societal trend SMT3 (see Table 5)

Figure 17 shows the number of *WSC* that executed the Plans 2 to 4, thereby deviating from business as usual (see Table 4). Plan 4, crisis management, is an unspecified plan that can be chosen if the demand cannot be met, but the deficits are relatively small (e.g. delivery of water by trucks). The diagram reveals some interesting aspects. First, the peak execution of Plans 2 to 4 takes place in the initial 5 to 10 years of the simulation. This has several reasons: the assignment of *Sources* and *Consumers* to *WSC* and *COM* and the initial *Source* capacity at model initialization are obviously not realistic for approximately 20 to 30 *WSC*. These adjust their capacity during the first decade. Secondly, many of the 16 models coupled in DANUBIA need some time to adjust to the set boundary conditions. Currently, the GLOWA-Danube strategy is rather to skip the first 5 to 10 years of results than to invest more effort in defining the ideal starting conditions for the scenarios and models.

The second interesting aspect is the interaction between the different *Actors* on the demand side (*Farming*, *Household*, *Tourism*, *Economy*, and *Demography*) and the supply side (*WaterSupply*). In SMT3 all parties react very 'sustainably', leading to the consequence that demands decrease strongly as a reaction to the dryer climate and the warnings and restrictions issued by the *WSC Actor*. In the present case, the decreasing demands almost fully compensate the changes on the resources side. Consequently, *WSC* do not have to increase capacity or tap new sources, even if the state of their existing resources deteriorates.

Figure 18 shows exemplarily for one *WSC* the dependencies of *Flags*, plans and water demand of *Consumers* for the same scenario assumptions (CT3-CV1-SMT3). It can be seen that this *WSC* has to adjust its source capacity and tap new sources in response to the changes of the resources state several times. A significant reduction of demands takes place in the second half of the simulation period.

Figure 19 finally shows a summary of important input and output parameters or *WaterSupply* for the whole catchment compared for the CT3-CV1 climate scenarios with two different societal scenario assumptions (SMT2, 3). In both realizations,

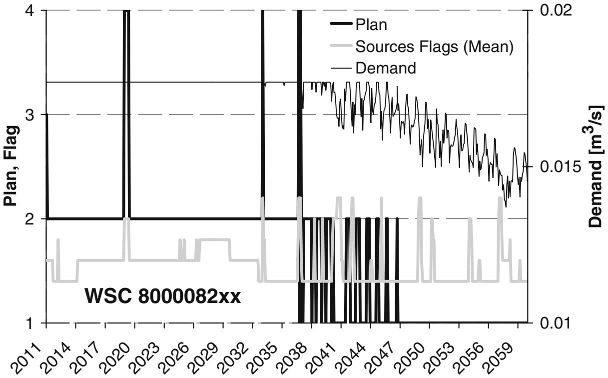

Fig. 18 Dependencies of plan execution (Table 4), *GQF* values (Table 2) and *Consumer* demands for one selected *WSC* for the CT3-CV1 climate scenario combined with the societal trend SMT3 (see Table 5). It should be noted that demands calculated by the *Household* partner model (Fig. 2) are not only a function of *Flag* values but also depend on climate directly and on social learning of *Household Actors* (see Schwarz and Ernst 2009). The *Sources Flags* are the calculated un-weighted average for all *Sources* of the *WSC*

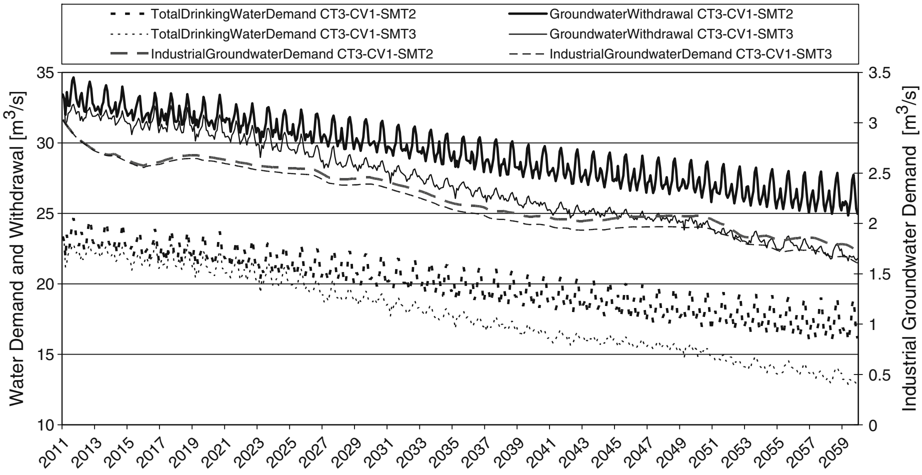

Fig. 19 Water demand and groundwater withdrawal under different scenario assumptions. Industry maintains it own groundwater sources which cover a portion of its demand and are not part of the public drinking water supply system ('drinking water')

the demands and subsequently the withdrawal decrease due to the dryer climatic conditions causing *Consumers* to utilize less water (irrigation is not considered here) and water suppliers to withdraw less. The effect is stronger in the SMT3 scenario. To fully interpret the results on the demand side it would be necessary to describe the concept, assumptions and parameterization of the responsible models *Household*, *Economy*, *Demography*, *Farming* and *Tourism,* which goes far beyond the scope of this article.

5 Discussion and Conclusions

In this section the attempt is made to address a number of questions and issues that need to be discussed for most simulation models:

(a) the specific validity and applicability of the scenario simulation results in the upper Danube catchment,
(b) the applicability and transferability of the model to other catchments worldwide, the advantages and disadvantages of the model and an overall assessment.

5.1 Validation and Applicability of the Model Results

Results of a concrete deterministic physical model implementation are usually not discussed without a sound description of the specific conditions in the model domain (here: the catchment) and a thorough discussion of the input data. To discuss these conditions and input data is difficult in the present case, as the model domain and data basis are large and heterogeneous. Therefore this chapter on validation is reduced to some general aspects of validating the model and does not go into concrete details of the water supply system within the upper Danube catchment.

Generally, within fully integrated and multidisciplinary systems such as DANUBIA, the objective of validation cannot be the validation of single models or even single process descriptions, but more the validation of the coupled simulation system as a whole. For the socio-economic models within the *Actor* component (Fig. 2), data that can be used for validation is generally less accurate, meaningful and reliable than equivalent data that can be used in the natural science sector. Typical socio-economic model output variables are for example domestic water consumption (model *Household*) and groundwater withdrawal (*WaterSupply*). For these output parameters, statistical data on a community level exist for most parts of the catchment. A comparison of calculated and observed statistical data for the communities usually yields quite good results. Such a comparison is however not very relevant, since problems with water quantity have only played a marginal role during the last two–three decades. Water suppliers have mainly carried out business as usual behavior, i.e. they have mainly distributed water from source to consumer according to the initial configuration of the system (see Section 3.3). Therefore it is not surprising that the model results are close to the observed situation since the observed values were used to initialize the model.

Much more interesting is the comparison of the *Flag* values or the choice of different plans to observed values. Unfortunately, observed data appropriate for validating the results of the *Flags* (*DQF*, *GQF*) or plan execution is rare. Little is known about the 'behavior' of water supply companies under conditions of Global Change. It is therefore very difficult to validate the respective model results in a traditional way. As a result, many important outputs of *WaterSupply* cannot be validated in the classical sense on the basis of measured data. The only means for validation is to include expert knowledge, e.g. the judgment from water supply company managers, local water authorities or consumer opinions collected using questionnaires (see e.g. Dow et al. 2007).

In its current phase, the research consortium of GLOWA-Danube is carrying out an intensive stakeholder dialogue to discuss the model concepts, model parameters and scenario assumptions with stakeholders from administration, water supply companies, consultants and NGOs dealing with water-related questions in the upper Danube catchment. Through this discussion process, which comprises round table discussions, individual interviews, scenario workshops and regional conferences, the quality and reliability of the model concept and assumptions can be increased. However, the simulation results have proven difficult to judge even for local experts.

5.2 Transferability and Applicability in Other Catchments

The object-oriented structure of *WaterSupply* makes it relatively easy to transfer the models concept and structure to other regions of the world. However, depending on the size and heterogeneity of the simulation area, parameterization and validation of the model may prove tedious. The present implementation in the upper Danube catchment comprises roughly 2,100 communities, 1,700 water supply companies, 5,000 water extraction sites (representing 11,000 wells in reality). It is obvious that the data requirements to parameterize these objects are enormous. The size of the model domain is decisive for the implementation of spatially explicit, process-oriented model concepts. This is obviously not a specific characteristic of *WaterSupply* and DANUBIA. In general, the higher the spatial and temporal resolution and accuracy of the available data, the more meaningful the results will be. However, model applications based on rather limited information may nevertheless produce results that give valuable insights in a water supply system and its vulnerable parts.

A general requirement to apply the *WaterSupply* model sensibly is the existence of a working and well structured water supply system. This limits the application to industrialized countries. Also, a minimum of information on the water supply system must be available to parameterize the model. It is obvious that it doesn't make sense to model a water supply system in a region where such a system does not exist or where the system is chaotic and its elements and their parameters unknown.

As mentioned before, *WaterSupply* as presented here is part of the DANUBIA simulation system. Within DANUBIA it is linked to partner models that provide information on the resource and the demand sides (water demand, groundwater recharge, groundwater levels, baseflow, etc.). *WaterSupply* is reliant upon such input data (see Fig. 3), but not on these specific partner models.

Within the runtime environment of DANUBIA, *WaterSupply* can also be executed stand-alone, importing pre-processed data (demand, groundwater data) from files. A number of data formats can be used for this purpose. DANUBIA, *WaterSupply* and all other model components will be made available to the scientific community under an open source license for further development and application by the end of the third project phase (April 2010). Nevertheless, even if *WaterSupply* can be executed stand-alone, its main field of application will be as a part of an integrated modeling system.

5.3 Potential Fields of Application of *WaterSupply*/DANUBIA

The simulation system DANUBIA and the *WaterSupply* approach presented in this article are a compromise between the size and the complexity of heterogeneous natural systems in large catchments, the complexity of human behavior, the high degree of inherent uncertainty both in natural systems and human society and the need to realistically and meaningfully evaluate the impact of Global Change on the environment and human welfare. The aim of DANUBIA is to describe the water cycle and its physical and socio-economic components *as a whole* and not so much to describe individual sectoral processes. Experts from different disciplines may therefore find the representation of their discipline and the specific results oversimplified. DANUBIA was developed for use on a very high administrative level (governmental institutions on state, country or river basin level), where knowledge, data and financial resources to set up and run the required models are available. It was developed as a generic system that is transferable and reusable but not necessarily scalable. It can be applied everywhere (see Section 5.2), but an application must be based on a high-level political decision and respective financial resources to allow its implementation, since the volume of data and financial resources needed to parameterize the individual models are quite extensive. An application to smaller scale case studies is technically feasible but largely meaningless since it contradicts the regional scope of the approach.

The main fields of application that the model developers have foreseen and which are now being refined in a stakeholder dialogue will be in the evaluation of worst case scenarios of climate change, the regional planning of large scale interventions and political decisions (e.g. on the use of irrigation in agriculture or building of large reservoirs to overcome water scarcity in the summer).

5.4 Conclusions

A water supply model is an essential requirement for any fully-coupled integrated water management system (see Fig. 4). The water demands of consumers must be routed to the distinct water extraction sites (springs, wells, surface water) or larger scale resources (aquifers, water bodies). This is the only way to guarantee that a certain demand-driven withdrawal actually affects the resource side, e.g. through a corresponding drawdown or discharge change. As a result of these considerations, water supply companies, communities and extraction sites with their aforementioned attributes were found to be these essential components.

The *WaterSupply* model integrated in DANUBIA is novel in both its aim and approach. Its regional, river basin scope, full integration in a coupled simulation system, and ability to respond to changing boundary conditions on the supply and demand side attest to this. Models from the field of water supply traditionally look at one distinct water supply company or network, and aim at optimizing this system according to costs, security, and capacity requirements. Often technical parameters (e.g. energy requirements, etc.) are in the center of focus. A large quantity of relevant literature exists pertaining to such models (see Section 1.4). Following a converse approach, Tillmann et al. (1999) or Davis (2000), for example, look at the water supply system from a much broader perspective, focusing on the hydrological cycle while not attempting a run-time comparison of resource availability and consumption patterns under changing climatic conditions.

Regarding the model concept, socio-economic and technological change can only be considered by means of specifying respective scenarios that include such changes. The model will not develop new technologies for water treatment or define new ecological or economical goals. Such changes can be included using certain plug points and by specifying certain model parameters (e.g. the threshold values for the use of a resource). However, the water supply system is generally conservative in the sense that technological development (and implementation) is rather slow and that social and political changes will affect mainly two issues: (a) water pricing (b) appreciation of sustainability. For both aspects plug points exist.

Increasing the capacity of a water supplier is only possible within certain limits. These limits are either of technical (existing infrastructure) nature or depend on the resources state, but can also be the result of political, ecological and economical considerations, rules and constraints. Solely the resources state is modeled explicitly within DANUBIA. The socio-economic, political and technical rules must be defined as part of the scenarios used to run the simulations (see also Section 4.2).

One great advantage and achievement of *WaterSupply* is its ability to set developments on the supply (natural resources) and demand side in relationship to one another for long-term planning purposes. It offers an easily adjustable and extendable (see Section 5.2) tool for testing the results of different response mechanisms both on behalf of water suppliers and, in conjunction with the affiliated *Actor* models, of water users. The multiactor approach used to represent the real-world decision makers and the implementation of decisions in the form of plans and actions which can be edited and extended with ease render the tool user friendly. In essence, *WaterSupply* is one of the central 'adjusting screws' of DANUBIA for defining water management scenarios and comparing varying outcomes. *WaterSupply* should not be mistaken as an optimization tool or as a planning tool for designing future water supply systems. It provides insights into the critical sites of water supply systems and indicates where, how and to what extent adjustments and interventions may become necessary.

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