Regional-scale assessment of groundwater resources quantity with respect to water supply issues and the ecological role of groundwater

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Abstract: In this paper an integrated approach to assess the availability of groundwater for human and ecological demands under conditions of climatic and socioeconomic change is presented. This approach is embedded in the DSS DANUBIA project, which was developed by the GLOWA-Danube research cooperation. DANUBIA is a fully coupled system that is comprised of 16 individual models to describe all compartments of the hydrological cycle (natural and socioeconomic) of the Upper Danube catchment (Germany, 77 000 km^2). The approach presented here allows the quantitative assessment of water availability in 405 groundwater bodies which are delineated by intersecting 150 surface watersheds and four main aquifer systems. The assessment considers the individual characteristics of the groundwater bodies and allows for the flexible definition of response times and importance of three primary indicators: groundwater recharge, groundwater level, and baseflow. After the definition of the problem, the three main aspects of the developed approach are introduced: 1) the delineation of groundwater bodies, 2) the assessment methodology and the required parameters, 3) integrating the results in socio-economic models.

Keywords: Groundwater, Climate Change, Quantitative Assessment, Groundwater Modelling, GLOWA-Danube

1. Introduction

The assessment of the status of groundwater resources covers a multitude of different aspects and can have very different objectives. Therefore the scope, objectives, and background of the assessment approach presented here are explained in some detail first. To begin with, groundwater resources assessment and the prediction of their future states is of course not a new task in hydrogeology. However, looking at the quite extensive literature that exists on that topic it can be summarized that most of the assessment approaches are:

- dedicated to the local scale and the management of smaller entities (one aquifer, one well or well field)
- looking at the present situation based on observed data
- focussing on groundwater quality
- if focussed on groundwater quantity, looking at regions where problematic situations have already been observed (a prime example is the High Plains Aquifer in Colorado, Kansas, Texas, and Nebraska (e.g. Sophocleous, 1998).
- not considering climate change

The assessment of climate change and the European Water Framework Directive WFD approach for the management of water resources however, demand a regional and integrated assessment on a river basin scale (> 10 000 km^2) in order to bridge the gap between the global effects predicted by Global Climate Models and to meet the environmental, social and economic objectives of modern water resources management. Such regional scale groundwater resources assessment, however, require completely different approaches than local ones. The widely-used hydrological assessment approaches (hydrological models, water balance approaches) on the local scales are not sufficient to describe regional groundwater systems since they neglect the vertical differentiation of the subsurface. Furthermore, in comparison to surface water systems, the state of groundwater resources is more difficult to assess because of their three-dimensional nature, the lesser defined boundaries, the limited accessibility, and the resulting lack of data. The starting point and motivation for the development of the assessment approach presented here is therefore different from the traditional ones.

Groundwater resources assessment can be divided in two branches: groundwater quantity and groundwater quality issues. Their mutual importance depends mainly on the regional climatic and socio-economic conditions. In most of the states of the European Union it seems that much more work was recently dedicated to groundwater quality issues than to quantitative aspects, leading to a lack of quantity-related approaches. A reason for this might be that the main goal of the WFD is the restoration of the natural (past) state of water bodies, i.e. a focus on minimizing human impacts (withdrawal, over-use, contamination) on water resources. Upcoming natural influences brought on by climate change are of minor concern in the WFD. However, scenario-based predictions published by the Intergovernmental Panel on Climate Change IPCC indicate that there will be severe changes to the hydrological cycle inducing, of course, changes of groundwater quantity. It is very important to remember that groundwater quantity is not only important for water supply but also plays a very important role in the ecology of rivers, wetlands, and land. The role of groundwater in ecology is most well known from cases where decreasing groundwater tables have already led to damages or destruction of wetlands, fertile land or springs. Furthermore, groundwater contributes quite often a large portion of river discharge in dry periods (baseflow or groundwater discharge). That means if groundwater quantity decreases - for whatever reason - river discharge decreases as well with all the known ecological, economic and social consequences ranging from problems with water supply and irrigation, navigation, fishery, hydropower generation, cooling water for industry and nuclear power plants to touristic attraction of regions. All of the problems just mentioned were observed in central Europe, i.e. a sub-humid to humid region, in the exceptionally dry summer of 2003. Therefore it is important to investigate whether such extreme events will occur more often and how the general climate change might influence the groundwater quantity in the future.

In order to do this, it is necessary to 1) evaluate the actual state of a groundwater resource in connection to neighbouring systems (i.e. surface water bodies, wetlands) and 2) predict possible future changes as a consequence of changing boundary conditions (climate – groundwater recharge, river discharge)

Accordingly, the scope of the presented assessment approach can be summarized as:

1. it is meant to be applied on the regional scale
2. it is dedicated to the assessment of long term changes, with a special focus on the investigation of impacts of climate change within the next 100 years
3. it is based on model results as input values rather than on observed values (follows from 2.)
4. is mainly focuses on quantitative aspects of groundwater resources (storage, groundwater levels, fluxes, availability, sustainability, reliability)[1]

2. General aspects of groundwater resources assessment (quantity) on the regional scale

A meaningful approach to assess the stable quantity of a resource must be based on four essential requirements, which need to be carefully adapted to the specific objectives of the assessment in any specific case:

1. The definition and delineation or separation of the object which will be assessed (in the present case: a groundwater body) from adjacent objects of the same type and/or from objects of other types which interact with the object in question (here: e.g. rivers)
2. The definition of primary indicators, which allow for an integral assessment of the object state with respect to the objectives of the analysis.
3. The definition of a strategy to convert the primary indicators in assessment categories of practical use in decision making (good – bad in the simplest case). This is a rather crucial aspect in all cases where the primary indicators are not intuitively meaningful for the end user or decision maker (e.g. in the case of groundwater levels, see below). More complex strategies are necessary if a judgment can only be made on the basis of two or more primary indicators.
4. The definition of rules for the use and the interpretation of the assessment results. In the case of complex assessment strategies, it might be necessary to even define specific course of actions.

It is obvious, that these general requirements for resources assessment are especially hard to fulfil in the case of groundwater resources assessment (quantity) since

- groundwater resources can not easily be delineated and

[1] An approach to assess groundwater quality on the regional scale under conditions of climate and socio-economic changes is under development and not presented here

- indicators for the quantitative status of groundwater resources can either be measured only point wise (in boreholes/wells) or can be indirectly determined (baseflow, recharge)

The delineation of groundwater bodies on the regional scale has received a lot of attention in practice through the requirements of the WFD during the last years. A scientifically consistent approach is however not available, mainly due to the differences in the separation of aquifers that is highly dependent on the characteristics of the location and the problem context and is therefore hard to generalize.

Furthermore, indicators for groundwater assessment have become a main research topic in the recent years world-wide, not only in practice, but also in science (see e.g. Vrba and Lipponen, 2007, Webb et al. 2006). Depending on the objectives and the spatial scale of the assessment, very different parameters are used as indicators. It can be roughly distinguished between mere 'physical' indicators and socio-economically influenced indicators (e.g. withdrawal per area or per capita). Socio economically oriented indicators are mainly used on political levels (country, district) and are in most cases not applicable to investigations on the impacts of climate change on physically defined specific groundwater resources. According to the literature and following from relatively simple consideration, the following physically-based indicators can be used for the predictive assessment of groundwater availability in specific aquifers or aquifer systems on the regional scale:

- groundwater level
- groundwater recharge
- discharge, baseflow

There are other physically-based indicators such as plant water stress in groundwater dependent ecosystem, but these are difficult to model and hardly meaningful on a regional scale.

Table 2 summarizes the main characteristics of these indicators with respect to the assessment of groundwater resources. The aspects raised here will not be discussed in detail. Related discussions can be found in Scanlon et al. (2002). Conceptual problems of the relation between groundwater recharge, baseflow and groundwater storage are described in Barthel (2006).

Table 1: Determinability, meaning and significance of important groundwater indicators

Indicator	Determinability *	meaning and significance *
Groundwater Level	Directly measurable; meaningful for specific aquifers, difficult to interpolate / regionalize	Shows direct, explicit reactions to changes of boundary conditions (withdrawal, recharge, discharge). Is a direct indicator for dynamics and trend of storage changes, but without any volumetric evidence, local effects dominate
Groundwater Recharge;	Not directly measurable, very different methods for determination, difficult to relate to a specific aquifer;	Shows direct, often explicit reactions to climate and land use changes; direct volumetric meaning; is not significant for dynamic and future behaviour (trend) of the groundwater resource; significance depends strongly on the estimation approach
Groundwater Discharge / Baseflow	Not directly measurable; Temporal-spatial relation to specific aquifers difficult. Highly conceptual.	Shows reactions to longer term changes (climate, groundwater levels), cause and effect mechanism ambiguous; only meaningful if clear connections between aquifer and river exist; very good yet difficult to interpret indicator
Discharge	Directly measurable, integral; Temporal-spatial relation to specific aquifers difficult.	Shows mainly short term reactions to climatic changes, the groundwater related fraction is difficult to determine (see: baseflow in this table)

*Statements are related to the river *basin* scale only

The general dependence of groundwater level on the climatic situation (assuming that precipitaion and recharge are strongly correlated) is shown in Fig. 1. The highly schematic illustrations are meant to show that the significance of groundwater levels and their changes with time is highly dependent on the local characteristics of the aquifer. Therefore, general interpretations (as sometimes found in the literature) are not possible. The particularities of groundwater systems, namely the long-lasting and complex storage effects and delayed reactions to changes of the boundary conditions are frequently not considered.

Whereas Fig. 1 shows the principle of the relation between groundwater recharge through precipitation and groundwater levels for different hydrogeological settings schematically, Fig. 2 demonstrates the same relation by means of measured groundwater level time series. Two time series of observation wells in the south western part of Germany, both located in alluvial aquifers, both showing the same period have completely different characteristics with respect to the dynamics of groundwater level changes as a result of different hydrogeological conditions in the vicinity of the observation well (e.g. for example the distance to the river).

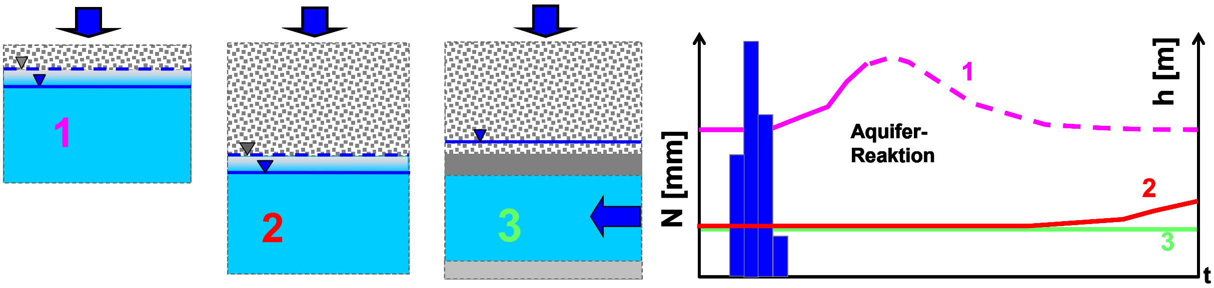

Fig. 1**:** Relation between groundwater recharge from precipitation and groundwater level - schematic. Aquifer 1 is unconfined and shallow, 2 is unconfined and deep, 3 is confined and deep. P: Precipitation, h: groundwater head.

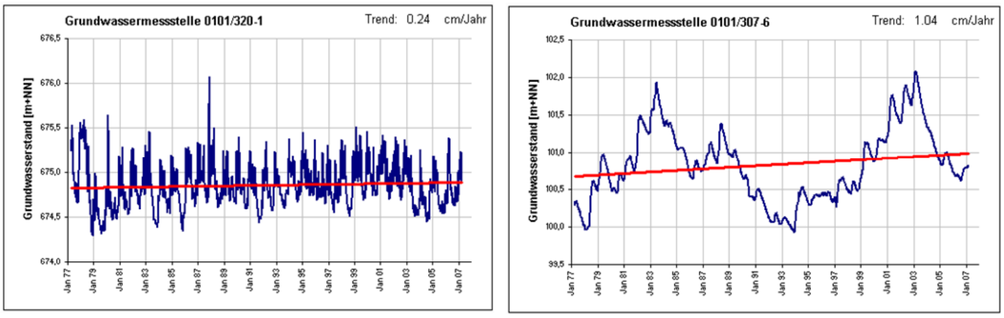

Fig. 2: Groundwater level time series (1977-2007) for two observation wells, both located in quaternary alluvial aquifers (unconfined). Left Danube valley, filtered depth unknown, Right Rhine valley, filtered depth of 7.1-9.1 m (LUBW, 2007).

The problem of the determinability and significance of groundwater quantity indicators (see Fig. 1, Fig. 2, Table 2) can be summarized as follows: Firstly the groundwater level, as the only directly measurable primary indicator, is point information which is highly dependent on the local geological and geomorphologic characteristics. For the integral assessment of a groundwater body it is therefore necessary to make an aquifer-specific temporal and spatial aggregation of measured point data. Secondly, groundwater level, groundwater recharge, and baseflow must be integrated, since one primary indicator alone does not reveal how the actual state is related to the changes of boundary conditions in the past and which future development is to be expected. Only if the correct spatial and temporal relation between two indicators (see recharge and gw-level in Fig. 1) is known, are predictions for the future behaviour of the system possible. Thirdly, a detailed knowledge of the site and aquifer characteristics (aquifer geometry, hydraulic properties, properties of the hydrogeological systems as a whole) is necessary. That also means that local expert knowledge is required to interpret groundwater indicators meaningfully.

3. The Integrated Assessment Approach of the GLOWA-Danube project

In this paper an integrated approach to assess groundwater availability for water supply purposes as well as for ecological demands under conditions of climatic and socioeconomic change is presented. This approach is embedded in the DSS DANUBIA which was developed by the interdisciplinary GLOWA-Danube research cooperation during the past six years. DANUBIA is a fully coupled system that is comprised of 16 individual models to describe all compartments of the hydrological cycle (natural and socioeconomic) of the Upper Danube catchment (Germany, 77 000 km^2). All models use

the same spatial discretisation of 1 x 1 km grids. The Institute of Hydraulic Engineering at the University of Stuttgart develops a groundwater flow and transport model as well as a model to simulate the water supply system of the catchment. For further details on GLOWA-Danube in general see Mauser and Strasser (2005), for details on DANUBIA see Barth et al. (2004). The groundwater flow model is described by Barthel et al. (2005a), the water supply model by Barthel et al. (2005b).
One important aspect of DANUBIA is the representation of socio-economic 'processes' that is achieved by so-called 'actor-models'. An actor model within DANUBIA (agent based model is an almost synonymous term) describes water related socio-economic processes as the sum of the individual activities of a multitude of individual actors[2]. An actor represents an entity ('object'), which is capable of reacting to systems changes in an individual way, i.e. it is capable of making decisions. The individuality is thereby achieved by individual properties and preferences of each actor object. Fig. 3 demonstrated schematically how the individual properties and preferences are assigned. The basic principles of the DANUBIA actors modelling approach are described in detail in Janisch et al.[3] whereas the concrete implementation of the multi-actors approach for the WaterSupply model is demonstrated in detail in Barthel et al. [4].

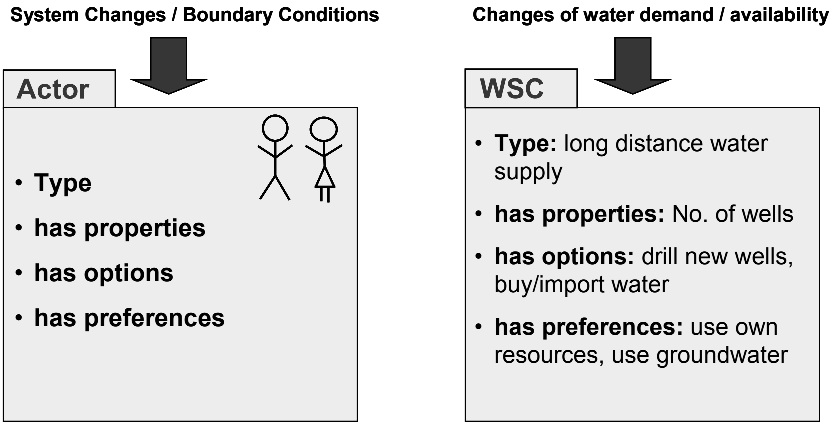

Fig. 3: Schematic diagram of an actor: Left: abstract actor, right: a specific water supply company (WSC) actor as used in the DANUBIA model 'WaterSupply'. The specific actor will react to system changes (e.g. changes of groundwater available[5] for extraction) in a specific way depending on its properties, options and preferences.

In the context of the present article it is mainly important to determine how system changes – in that case any relevant changes of the groundwater resources – can be made available to the actors – in the present case the water supply companies –. For that purpose two principal possibilities exist:

1. The direct determination and communication of the actual available groundwater quantity (volume, per time unit)
2. The determination and communication of indicators or of situations where the values of such indicators reach or exceed certain limits.

The determination of the available groundwater volume (1) is conceptually difficult and numerically demanding. A more detailed discussion of the related aspects can be found in Maimone (2004), Alley and Leake (2004), Kalf and Wooley (2005) or Custodio (2002), Devlin and Sophocleous (2005).
A clear distinction has to be made between technical limits (e.g. drawdown exceeds saturated thickness) and aspects of sustainability of groundwater. The latter requires the inclusion of social, ethical, ecological and economic aspects in the determination of groundwater available for extraction. Since there are no common objective rules for the integration of such aspects, their implementation in a numerical scheme is difficult, at least conceptually. The next general problem is the problem of

[2] therefore called 'multi-actor-approach'
[3] submitted to Environmental Modelling and Software, November 2006, currently under review
[4] submitted to Water Resources Management, August 2006, currently under review
[5] Where ‚availability' can be defined in different ways (technically available, sustainable)

groundwater body delineation (see section 2), i.e. how to fix the resources boundaries and how to consider variable boundaries. A major problem is the fact, that the boundaries of the system are dependent on the groundwater withdrawal (volume and duration) itself. If the radius of influence of a well increases with time it may for example reach adjacent aquifers, surface water bodies or neighbouring wells in the same aquifer. Additionally the available amount of groundwater can not be expressed as a volume (L^3) but only as a rate (L^3/T).To determine the actual available amount of groundwater correctly under such conditions leads to an optimisation problem which can not realistically be solved in a regional integrated model as it would be conceptually difficult and too computational demanding.

The second option is to communicate indicators to the actor model or to decision makers. This is the option which is commonly used in practice. As shown before (section 2) one indicator (e.g. groundwater level) for one observation well is meaningless if it's spatial and temporal relation to other quantitative indicators (groundwater recharge) is unknown and if the local characteristics of the observation site are not acknowledged. Therefore it does not make sense to tell a decision maker what the actual groundwater level at a certain point of time is, without telling him what exactly this *means*. What it means is always depending on the site characteristics but also on the history, i.e. climatic and hydrological conditions and withdrawal rates in the past. This means, even if critical limits of groundwater levels were already defined, it still makes a difference if these limits were reached quickly or slowly or if the decrease is mainly a result of climatic or of withdrawal conditions.

The concept which was developed in DANUBIA is based on the second option. But, instead of communicating indicator values, it directly aggregates and converts them in several ways:

1. Indicators are aggregated spatially for hydrogeological response units (see below)
2. Indicators are temporally aggregated over a longer period of time which is individually defined for each indicator and each response unit
3. Three indicators are combined and weighted to form a general indicator the so-called 'flag'. The weights for each indicator are individually defined for each response unit.

The flags can assume discrete values from 1 to 5, where 1 is very good and 5 very bad. They include the full integral description of the actual state of a groundwater body using all available information in condensed form. In the context of actor modelling in DANUBIA, the flags are convenient means to convey system changes to the decision making entities (the actors). Again, for each actor, individual reactions to flag values can be defined. In the case of Water Supply Company (WSC) actors for example, an individual WSC can be very sensitive to the flag values, e.g. change its management mode as flags change from 2 to 3 or it can ignore flags and carry on with business as usual until flags reach untenable values. In the present paper, only the flags that indicate the quantitative situation ('groundwaterQuantityFlags') are described, the quality indicators are currently in preparation. In addition, flags are used in DANUBIA to express different risks (flood, draughts.) but also as a simple quantitative description of a resource (surface water, groundwater). Groundwater Quantity Flags are used by all actors that have direct access to groundwater, whereas other actors, e.g. households only have access to groundwater through a water supply network and therefore used Drinking Water Quantity Flags for decision making (see Barthel et al., submitted)

The approach presented here allows the assessment of 405 groundwater bodies (hydrogeological response units) within the Danube catchment which are delineated by intersecting 150 surface watersheds and four main aquifer systems. The assessment results in a classification of each groundwater body in five status categories (from very good (1) to very bad (5)) which are called "Groundwater Quantity Flags". Those flags are mainly used by the six socio-economic models (Household, Tourism, Economy, WaterSupply, Farming, Demography) contained in DANUBIA, which are based on a common multi-actor approach. The individual actors can interpret and use the flag values according to their attributes and preferences in order to simulate decisions. The groundwater quantity flags are calculated monthly, based on three exchange variables: groundwater recharge, groundwater level and infiltration from groundwater to surface water ("baseflow") provided by two natural science models in DANUBIA. The calculation includes the individual characteristics of the groundwater bodies by using a combination of response times and weights for each exchange variable.

4. Flag Computation

In this section the basic principles of flag computation (Groundwater Quantity Flags) are briefly introduced. A full description of all steps is not possible in this paper. Results are presented without extensive discussion, because it would require a more detailed description of the geological and hydrological characteristics of the area.

The first basic step of the groundwater resources assessment approach used in DANUBIA is the delineation of 'groundwater bodies[6]' which are here simply called 'zones'. The definition of zones is based on an intersection of 155 surface watersheds for which continuous discharge measurements exist with the four layers of the groundwater flow model used in DANUBIA. This way, a zone represents the portion of a surface water catchment in which a certain layer of the groundwater model forms the 'main' (in most cases the uppermost active) aquifer. In the Upper Danube catchment 405 zones resulted from this intersection. 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). The way a zone reacts is determined mainly by three parameters which are explained in Table 2. The conceptual meaning of the parameters with respect to the indicators can be deduced from Fig. 1. The indicators used in the assessment approach are described in Table 3. Indicators are calculated by DANUBIA models, the parameters are determined from a) measured data, as far as available, but mainly b) from a knowledge based approach (i.e. derived from the knowledge of experts). From this it will become obvious that a certain degree of subjectivity is inherent in the approach. This issue will be discussed in the conclusions.

Table 2: Parameters used in the flag calculation

Parameter	**Unit / range**	**meaning**	**Is derived from**
Characteristic reaction period n	[month] / 1..12	How long must an indicator* be monitored to show a significant change of the groundwater storage and level in a specific zone?	• depth to the groundwater • Transmissivity of the unsaturated zone [m^2/s] • hydraulic diffusivity* $D=T/S$ [m^2/s] of the aquifer
Weight w	[-] / 0..1	What is the relevance of an indicator* in a specific zone?	• hydraulic connection to surface waters / rivers • thickness and stratification of the unsaturated zone
initial flag	[-] / 1..5	Initial assessment of the aquifer properties describing the static properties of an aquifer which are independent from changes of the boundary conditions	• aquifer type and properties: T, thickness, depth

* see Table 3

Table 3: Groundwater quantity Indicators used for the flag calculation (compare with Table 1)

Indicator	Determined by	Spatial and temporal resolution / [unit]	Spatial and temporal aggregation
Groundwater Level	DANUBIA GroundwaterFlow model	Per aquifer cell (1x1 km); daily / [m]	Mean per zone, monthly
Groundwater Recharge;	DANUBIA LandSurface component / Soil model	Per aquifer cell (1x1 km); hourly / [m^3/s]	Sum per zone, monthly
Baseflow	DANUBIA GroundwaterFlow model	Per river cell (1x1 km); daily / [m^3/s]	Sum per zone, monthly
Discharge*	DANUBIA RiverNetwork model	Per river cell (1x1 km); daily / [m^3/s]	Sum per zone, monthly Requires upstream discharges to be subtracted

*optional, currently not used

[6] „Groundwater bodies“ is the term used in the European Water Framework directive. It is however not an exactly defined term and can be used in many ways.

The methodology for the calculation of flags is rather simple and transparent:

1. For each zone the indicators as calculated by the partner models are aggregated to 1 value per zone and time step (1 month) according to Table 3.
2. Starting from the current time step (month) the mean of the n-previous month is calculated for each indicator where n is the characteristic period (see Table 2) for each indicator and each zone.
3. The mean calculated in step 2. is then compared with the mean for the same month of a reference period (in the specific case 1970-2003). For example, if the current time step is May 2025[7] and the characteristic reaction period for the specific zone and indicator is 9 month, then the mean from September 2024 to May 2025 from the simulation run is compared to the mean of all month September to May from the reference period. The relative deviations are classified according to classes defined for each indicator (e.g. 10% less recharge than in the reference period is still very good). The classified values are called 'indicator flags' and range from 1 (very good) to 5 (very bad).
4. The indicator flags calculated in step 3. are then now combined to the 'weighted flag' by calculating the weighted mean (weights see Table 2) of all parameters .
5. The weighted flags (step 4) are post processed in order to check their feasibility and to remove unwanted effects such as sudden changes; inclusion of the initial flag value and the 'final flag' is formed

The flag calculation algorithm as well as the definition of zones (groundwater bodies) of the approach presented here are relatively simple. This aspect is discussed in more detail in section 6. The reason is that the conceptual basis of the approach is neither deterministic nor empirically based. In contrary, it is founded principally on a (subjective) knowledge-based system. The concept can hardly be improved by measured data, at least not in a region like the Upper Danube catchment. The last point requires a more detailed discussion. As previously mentioned, the flag calculation algorithm as well as the definition of zones (groundwater bodies) of the approach presented here are relatively simple. The reason is that the conceptual basis of the approach is neither deterministic nor empirically based. In contrary, it is mainly founded on (subjective) expert knowledge. The concept can hardly be improved by measured data at least not in a region like the Upper Danube catchment where the following conditions can be found:

a) it is a water-rich region in general
b) water scarce areas are supplied from water rich areas through an highly developed water supply infrastructure

Therefore, on a regional scale[8], it is currently unknown when, where and how climatic changes as predicted by the IPCC (IPCC, 2001) might have negative impacts on the groundwater system. Conditions which would correspond to "bad" or "very bad" or even "critical" (flag values of 4, 5 and 3 respectively) in the sense of the assessment approach presented here are almost unknown in the region[9].

5. Results

The planned results of the GLOWA-Danube are the identification and visualisation of regions and periods in the future, where under conditions of Global change (climate, land use, demography) critical situations can be expected to occur. For that purpose, DANUBIA provides many output variables. Here only the Groundwater Quantity Flags, which indicate the quantitative status of groundwater resources, are presented. With respect to groundwater quantity a critical situation would be one where the water supply system fails to meet demands, and all situations where sustainability rules are violated and ecological or economic damage occurs. Changes of the Groundwater Quantity Flag from lower to higher values indicate that problems occur but they don't indicate directly the nature and origin of the problem. For that purpose the results of other DANUBIA models have to be

[7] The approach is mainly used for future predictions based on climate scenarios
[8] the situation is different on a local scale since problems can be defined more specifically in a local context
[9] Exceptions are the hot and dry years 1976 and 2003, where 1976 is hardly comparable to the present situation and 2003 generated only very local effects

analysed as well. But the flags are not intended to describe the process but instead to be transparent and easily understandable tools for decision makers to recognise critical regions.
Fig. 4 shows results from a DANUBIA simulation run which is based on a very dry climate scenario which led to a dramatically decreased groundwater recharge. It must be pointed out, that this scenario is even dryer than the most pessimistic scenario simulations of IPCC. As pointed out previously, the Upper Danube Catchment is quite water-rich. Therefore drastic scenarios have to be defined to get visible reactions. The results displayed here are mainly of demonstration character and should not be misinterpreted as predictions. In that context it must also be mentioned that the total uncertainty of the results is a multiplication of the uncertainties contained on the input climate (scenario) data, model's uncertainty and the flag calculation uncertainty. Starting from the climate scenario input, over the individual models which provide the indicators (see Table 3) to the definition of zones and parameters a wide range of uncertain values is introduced in the calculation. However regional scale reliability is increased by the spatial and temporal aggregation as well as by the use of relative values and trends rather than absolute values of the indicators. In turn it becomes immediately clear that predictions on the local scale can not be obtained simply by downscaling of the obtained results.

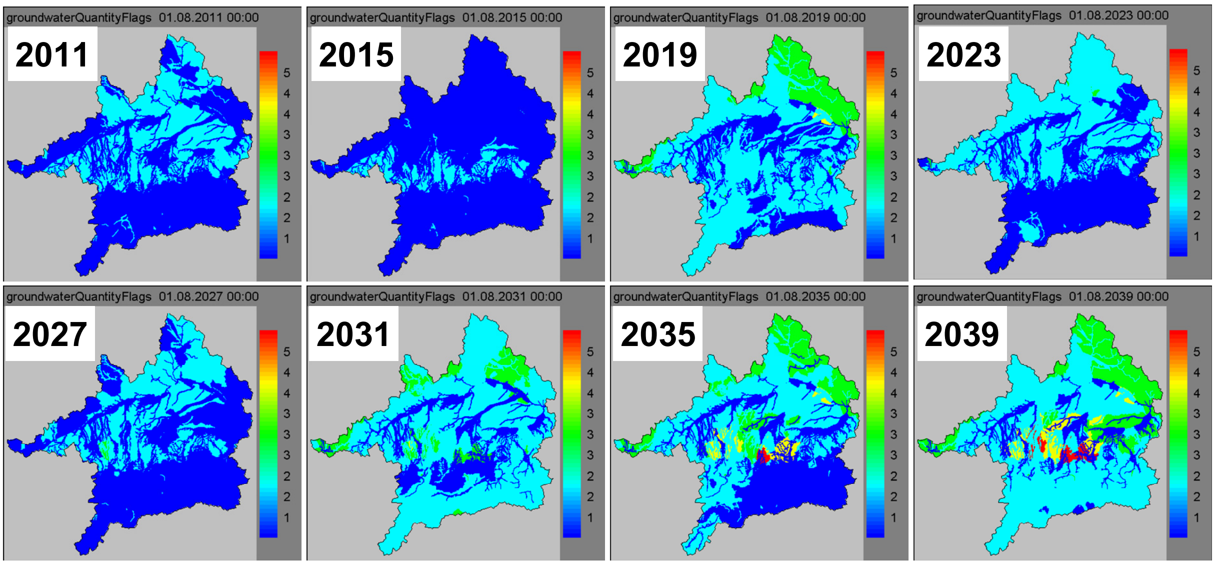

Fig. 4: Spatial changes of the groundwater Quantity Flag (quantitative status of 405 defined groundwater bodies in the Upper Danube catchment) for an extremely dry scenario. Flag values: 1 - very good statues … 5 very bad status

6. Conclusions and outlook

The present article cannot describe the groundwater resources assessment approach developed in DANUBIA and its results in detail. For that purpose it would be necessary to describe the hydrological and hydrogeological conditions as well as the water supply infrastructure in the catchment in a comprehensive way. Instead, an attempt was made to describe the problem of quantitative groundwater resources assessment at first in a more general way. From this general problem description the requirements of an appropriate and meaningful assessment approach applicable in scenario simulations (predictions) were deduced. These requirements can be summarized as follows. The assessment approach:

- must be adapted carefully to the hydrogeological conditions of the area, i.e. the hydrogeological characteristics of the aquifers and the surrounding geological formations must be considered
- should be based on a delineation of groundwater bodies, which is appropriate with respect to the objectives of the assessment, the scale, the data availability and the complexity of the region. This might be the most crucial aspect for many regions.
- should be based on at least two different indicators which need to be weighted according to their importance for the specific groundwater body

- must consider the uncertainties of underlying models and scenarios by applying a high level of aggregation and by looking at trends rather than absolute values.
- should be simple enough to be validated using external expert knowledge

Since groundwater quantity problems in the Upper Danube Catchment during the last 3-4 decades are more or less unknown and problems known from earlier periods cannot be compared to the current situation there is no possibility to validate the results in the classical sense. That means, the assessment approach presented here cannot be validated on the basis of past experiences or measured data. The only means to validate and improve the concept is to include more expert knowledge, i.e. the judgment and experiences from water supply company managers, local water authorities and so forth. In any case: In order to use such experiences from other experts, it is necessary to make the concept transparent and intuitively understandable. If this requirement is fulfilled, the quite subjective and uncertain parameters of the calculation (see Table 2) can be meaningfully discussed and adjusted according to the advice of local experts.

Finally it needs to be pointed out, that the assessment approach presented here was first and foremost developed for the use within DANUBIA. Nevertheless, it would be possible, without drastic modifications to adapt the concept for other regions and to use in a different context and a different region. In the case of DANUBIA the flag values are used by Actors models to simulate decision making. However, the flag values can also be regarded as final results that can be used in "real" decision making. To transfer the concept to another region, it must be assured that the required input parameters (see Table 3) are available all over the area in a spatially distributed way. It is thereby not important whether these data sets are the results of model simulations or the result of interpolated measured values. The most crucial aspects are, to define the groundwater bodies (zones) and the parameters needed for the calculation (Table 2) on the basis of hydrogeological expert knowledge. The concept presented here was successfully implemented in the DANUBIA framework and provides results which are considered to be plausible in view of the hydrogeological conditions of the Upper Danube Catchment. The next step however is to discuss the results carefully with external experts and stakeholders and to adjust the parameters accordingly.

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