
An indicator approach to assessing and predicting the quantitative state of groundwater bodies on the regional scale with a special focus on the impacts of climate change

Roland Barthel

Abstract An integrated approach for assessing the availability of groundwater under conditions of ‘global-change’ is presented. The approach is embedded in the DANUBIA system developed by the interdisciplinary GLOWA-Danube Project to simulate the interaction of natural and socio-economic processes within the Upper Danube Catchment (UDC, 77,000km² and located in parts of Germany, Austria, Switzerland and Italy). The approach enables the quantitative assessment of groundwater bodies (zones), which are delineated by intersecting surface watersheds, regional aquifers, and geomorphologic regions. The individual hydrogeological and geometrical characteristics of these zones are accounted for by defining characteristic response times and weights to describe the relative significance of changes in variables (recharge, groundwater level, groundwater discharge, river discharge) associated with different states. These changes, in each zone, are converted into indices (*GroundwaterQuantityFlags*). The motivation and particularities of regional-scale groundwater assessment and the background of GLOWA-Danube are described, along with a description of the developed methodology. The approach was applied to the UDC, where several different climate scenarios (2011–2060) were evaluated. A selection of results is presented to demonstrate the potential of the methodology. The approach was inspired by the European Water Framework Directive, yet it has a stronger focus on the evaluation of global-change impacts.

Keywords Groundwater assessment · Climate change · Integrated water resources management · Regional scale · Germany

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R. Barthel (✉)
Institute of Hydraulic Engineering,
Universitaet Stuttgart,
Pfaffenwaldring 61, 70569 Stuttgart, Germany
e-mail: roland.barthel@iws.uni-stuttgart.de
Tel.: +49-711-68566601
Fax: +49-711-68556601

Introduction

To avoid misconceptions, several terms and important concepts in the context of the presented article are explained in Table 1. Many of the definitions given in Table 1 are based on the European Water Framework Directive (WFD) (EC - Commission of The European Communities 2000). The approach presented in this article uses the WFD as a main guideline with respect to the main principles of regionally scaled, integrated assessment. In contrast to the WFD, which is foremost concerned with assessment of the past and present situation and the management of the *near* future, the approach presented here is dedicated more to the evaluation of long-term changes, namely the impact of climatic change and the comparison of long-term regional management strategies.

Motivation and problem description

Groundwater resources contribute significantly to fundamental aspects of our societal and economic communities. Assessing, planning, and managing these resources is critical, particularly as the world faces climate change. The integration of this assessment with the management of other elements of the hydrologic cycle (surface water, etc.) and across disciplines has been recognized as an important element in effective groundwater management. For example, the WFD was implemented as a political and social response to the need for integrative assessment of water resources (Quevauviller 2007). The *regional scale* plays an outstanding role in integrative assessment and management because (1) it is only at the regional scale that social, economic and ecological impacts can be integrated and balanced in a meaningful way and (2) the regional scale forms a necessary intermediate step in the usage of global models for local predictions (Varis et al. 2004, Wilbanks and Kates 1999).

The assessment of water resources in general, and of groundwater resources in particular, has been discussed extensively in literature over the last few decades. The WFD in Europe and the discussion of *global-change* impacts on the environment have accelerated efforts in science and practice. In particular, the topic of integration has received much attention recently. Reviews, discussion

Table 1 Explanation and usage of important terms in this article

Term	Explanation of usage within this article
European Water Framework Directive (WFD)	Directive 2000/60/EC of the European Parliament which commits European Union member states to achieving <i>good</i> qualitative and quantitative <i>status</i> (state) of all <i>water bodies</i> by 2015 (EC 2000). One major duty of the member states is the establishment of <i>river basin management plans</i> , which will have to be updated every 6 years. The WFD is not explicitly concerned with climate change
Regional scale	In this article, the term <i>regional scale</i> is used to describe areas of approximately 10^5 – 10^6 km ² in size. In the context of water management, areas of this size often represent medium- to large-sized river basins, i.e. the target areas of river basin management plans according to the WFD
Body of water, water body, groundwater body	A <i>groundwater body</i> as defined by the WFD refers to a distinct volume of groundwater within an aquifer or aquifers and can be understood as the smallest entity in terms of assessment and management. It should be noted that the practical definition of groundwater bodies by different EC member states differs significantly from the underlying concept as defined in the WFD and accompanying documents. Furthermore, there are huge differences in the definition of groundwater bodies in different member states (Collins et al. 2006). The use of the term groundwater body in this article therefore follows the general conceptual idea rather than any of its practical implementations in the EC
State/status, good state (of water bodies)	The term <i>state</i> relates to the term <i>status</i> (of a water body) as used in the WFD. Status is understood as a summary of the actual conditions in comparison to an assumed pristine status. In the sense of the presented approach, 'state' is measured using a weighted combination of the behaviour of <i>state variables</i> within a <i>characteristic response period</i> and in reference to a previous (good) state. It should be noted that the terms 'good' and 'bad' as used with respect to water resources, generally can only be defined in the context of a specific function (e.g., water supply or ecological functions) or in relation to a previous state
State variable	A directly measurable physical quantity (e.g. groundwater level) or a physical quantity that can be determined indirectly as the result of the evaluation of a physical process (e.g. groundwater recharge). State variables show a transient behaviour which can be directly related to changes in the state of the system.
Indicator	A pointer or a signal to show the state or the development of an object or system, often the result of a statistical evaluation or aggregation of a state variable.
Index (here: flag)	A combination, aggregation and simplification of several indicators referring to the summary of a system's state in one standardized, dimensionless value on an ordinal scale
Model parameter	A parameter used in a calculation. Contrary to state variables, model parameters can be time-invariant, do not have to be based on observations, and must not be related to any physical quantity. In the presented approach, however, model parameters are directly based on hydrogeological properties as much as possible
Characteristic (response) period	A minimum period over which a state variable has to be observed in order to reveal a significant change in a groundwater body's state. The length of the period depends on the nature of the state variable and the groundwater body type
Global-change	The sum of anticipated and ongoing environmental, social and political changes including climate change as a dominant component
Global-change scenario	A consistent description of a possible (and likely) future including all aspects of global-change
Regional scenario	A projection of a global-change scenario to the conditions in a specific region requiring a combination of the downscaling of global predictions and specific regional predictions

papers and summaries of existing approaches in the context of integrated assessment and global-change research have been presented by Dragoni and Sukhija (2008), Giupponi et al. (2006), Holman (2006), Jakeman and Letcher (2003), Loaiciga (2009), Quevauviller (2007), Rahaman and Varis (2005) and Varis et al. (2004), just to name a few. In the context of environmental assessment, indicators and indices for groundwater assessment play an important role (e.g., Webb et al. 2006). Vrba and Lipponen (2007) describe groundwater sustainability indicators which can be used on a national level. Overviews of indicators suitable for practical application on a local and regional level are given by Cameron and White (2004) and Bright et al. (1998). Sustainability and groundwater overuse, the definitions of these terms, and means of detecting these phenomena are discussed by Custodio (2002), Hiscock et al. (2002), and Sophocleous (2000).

A review of the literature in the aforementioned context reveals that assessment strategies for describing and

predicting the state of groundwater resources designed specifically for the regional scale are largely absent. Assessment strategies, indicators and thresholds are relatively well-defined on a global and national level. On such levels, there seems to be a general agreement for how *sustainability* or *groundwater overuse* can be defined. The respective definitions are often made on the basis of relatively simple budget calculations. For practical management on the regional scale, such budget-type approaches are often not suitable for defining these parameters as they neglect to a large degree the variability and heterogeneity of hydrogeological systems and the feedback loops that exist between groundwater, the environment and social systems. On the other hand, on the local scale, assessment is made on the basis of very specific characteristics present at a specific site. For the regional scale, such specific assessments are again not suitable as the results are usually not comparable or transferable between locations. Regional-scale assessment and management usually requires that advantages and

disadvantages of changes and interventions in different parts of a management area can be compared and balanced.

Furthermore, the literature review shows that the majority of groundwater resources assessment studies are concerned with resources which are already in an obviously bad state, i.e., resources that fail to meet their economic or ecological functions (see the example in Kansas, Sophocleous 2000). As a result, the definition of a *good state* and approaches for detecting and predicting when a good state changes to worse are not common, which is problematic in particular with respect to global-change research where the evaluation of impacts on 'good' situations forms a major concern.

Finally, the review of the literature shows a deficit in methodologies that integrate a wider range of observations, e.g., those that look at groundwater levels and river discharges simultaneously or strive to assess the state of the groundwater system with respect to its environmental, economic and social functions concurrently.

In summary, approaches are missing that:

- Are specifically dedicated to the regional scale, i.e., which are aggregated enough to be suitable for regional management but still respect the heterogeneously distributed characteristics of groundwater systems
- Integrate observations in different parts of the water cycle as well as ecological, economic and social aspects of assessment
- Lead to results that are directly comparable between regions, independently of local characteristics
- Are transferable from one region to another
- Can detect deterioration from good to worse state, even in regions where a bad state is so far unknown

Summary and scope of the developed approach

The approach presented here was developed to account for the deficits identified in the previous section. It allows the individual assessment of discrete groundwater zones ('groundwater bodies'; Table 1). These zones are designed to be small enough to account for the specific characteristics of hydrogeological settings in terms of hydraulic properties and geometric relationships (depth to the water table, aquifer thickness, connection to surface waters, etc.) but sufficiently large to be applicable in the regional-scale management of larger river basins. The zones employed here are delineated using an intersection of surface watersheds, regional aquifer systems (horizontal and vertical) and major geomorphologic regions to account for the hydrological, hydrogeological, and climatic conditions in a regional system. The result of the assessment for each zone is an assessment index, the so-called *GroundwaterQuantityFlag*, which can assume discrete characteristic features ranging from 1 ('very good') to 5 ('very bad'). 'Good' and 'bad' states are defined by the degree of deviation of state variables from a reference period in which conditions can be assumed to have been

good. The calculation of the *GroundwaterQuantityFlag* indices is based on the state variables groundwater recharge, groundwater level, groundwater discharge and river discharge. The concept follows the idea of communicating warnings and restrictions used in water-scarce regions (see VicWater 2009 and San Antonio Water System (2009) but extends it to regions where water scarcity is yet unknown but possible under ongoing climate change. It also makes the results transferable by accounting for particularities in local conditions.

It should be pointed out that the result of the assessment (i.e., the flags) can show spatial and temporal tendencies and can be used to identify critical conditions in space and time. However, as they are only an index (i.e., generalized values with a high level of aggregation of information, see Table 1), the flags cannot replace a detailed analysis of the underlying detailed data.

Aim of the article

The aim of this article is more to present the developed methodology and less to show the specific results derived for the case study area, the Upper Danube Catchment (UDC) in southern Germany. The case study and selected results for scenario simulations are merely used to demonstrate the potential usage of the approach. Specific results for the UDC are published in great detail in the GLOWA-Danube Global-Change Atlas (GLOWA-Danube Project 2010).

Project background

The presented approach was developed and applied within the GLOWA-Danube Project. GLOWA-Danube (www.glowa-danube.de) is one of five projects within the GLOWA program (www.glowa.org, BMBF 2008). The aim of GLOWA-Danube is to provide an integrated approach to predicting changes in the hydrological cycle due to global-change in the Upper Danube Catchment (UDC, approx. 77,000 km²; Fig. 1). Researchers from 16 different research organizations, state agencies and private companies have been contributing to the interdisciplinary integrative project, which started in 2001 and ends in October 2010.

GLOWA-Danube considers both the influence of natural changes in the ecosystem such as climate changes, as well as social changes, e.g., changes in land use or water consumption. The central objective of GLOWA-Danube is to develop the simulation system DANUBIA, which is comprised of a total of 17 disciplinary simulation models coupled to each other dynamically during runtime. DANUBIA is a complex, modular simulation system for identifying and quantifying the joint effects of global environmental change and human activities on the water cycle. Models from the fields of meteorology, hydrology, remote sensing, groundwater and hydrogeology, plant ecology, and glaciology address the physical processes under observation. So-called *Actor models* address the

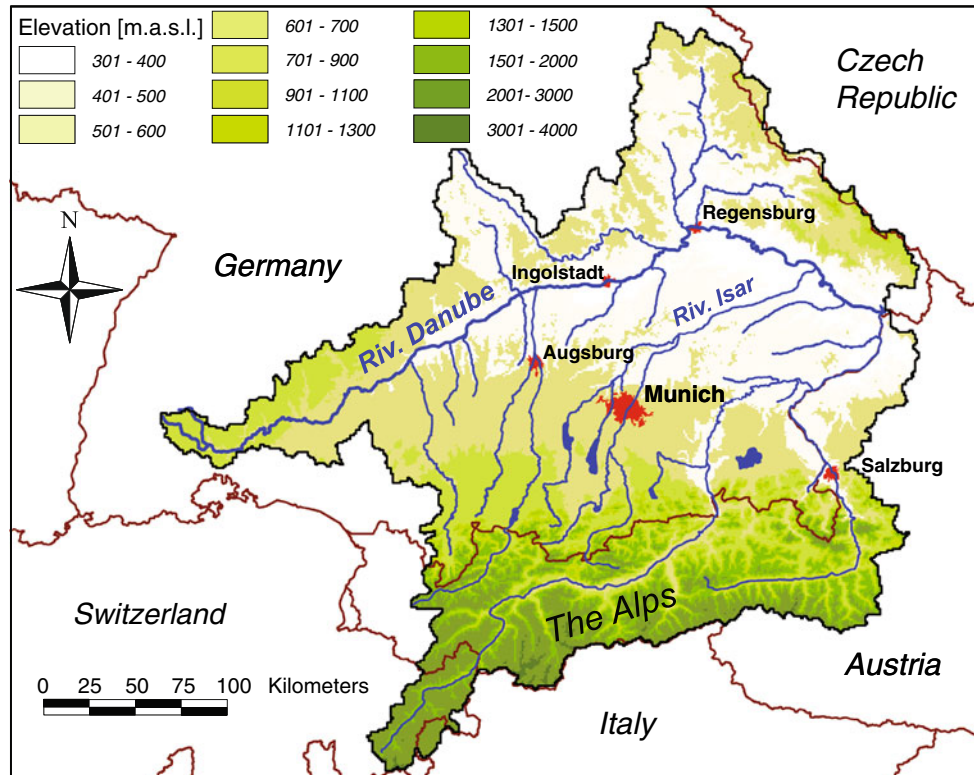


Fig. 1 The Upper Danube Catchment (UDC), the investigation area covered by GLOWA-Danube

socio-economic aspects of the water cycle from the fields of tourism, domestic water use, industry, agriculture and demography (Barthel et al. 2005b, and Barthel et al. 2008a). All of the models in DANUBIA use the same spatial discretization of 1×1 km grids but with a varying temporal resolution (see Ludwig et al. 2003). The primary application of DANUBIA is in the evaluation of the consequences of global-change scenarios on the water cycle in the UDC.

Availability and quality of water are modeled by the *Groundwater*, *LandSurface* and *RiverNetwork* components of DANUBIA. These components of DANUBIA are essential for the presented approach as they compute the main state variables used in the groundwater assessment. The *Groundwater* model is based on MODFLOW 2000 (Harbaugh et al. 2000). A detailed description of the conceptual and numerical groundwater flow model is given by Barthel et al. (2005b), (2008b) and Wolf et al. (2008). The *LandSurface* component is described in detail by Ludwig et al. (2003) and Mauser and Bach (2009). Models in DANUBIA provide groundwater recharge (daily, per 1×1 km cell), groundwater level (daily, per 1×1 km cell for four different layers) and groundwater discharge (fluxes from each groundwater flow model cell connected to a river cell and vice versa, daily, per 1×1 km cell). Details can be found in Mauser and Bach (2009), Barthel et al. (2005a), (2008b).

The UDC is a mountainous catchment, heterogeneous with respect to relief, climate, hydrogeology, landscape, land use and population density. The elevation ranges from 287 to 4,049 meters above sea level (m.a.s.l.), precipitation (P) from 650 to $>2,000$ mm/a, average

annual temperature (T) from -4.8 to $+9^\circ\text{C}$, evaporation (E) from 0 to 550 mm/a, and runoff (R) from 150 to 1,600 mm/a. The given values were spatially interpolated (T, P) and simulated (E, R) using PROMET (Mauser and Bach 2009). The total population is approximately 11.5 million. In the UDC, groundwater is the dominant source of drinking ($\sim 90\%$) and process ($\sim 60\%$) water. The hydrogeology of the UDC is defined by four major zones: the Alps, the Tertiary Molasse Basin, the Jurassic Karst, and the Crystalline Basement Complex. In the Molasse Basin north of the Alps, unconsolidated to semi-consolidated clastic sedimentary formations predominate. The basin is surrounded by sedimentary and crystalline rock formations on the northern and north-eastern boundaries. Jurassic karst dominates the hydrogeological situation in the north-western area. For a more detailed description of the hydrogeological conditions in the area, please refer to Wolf et al. (2008).

Conceptual development of the assessment approach

In the [Introduction](#), several deficits with respect to regional scale, integrated groundwater resources assessment were identified. The approach developed within GLOWA-Danube was designed to fill the identified gaps. The following enumeration lists the leading assumptions and ideas behind the development of the presented approach:

1. The magnitude and rate of change of state variables are changeable. For example, changes in groundwater level

- are strongly dependent on the local characteristics of groundwater systems (e.g., hydraulic conductivity (K), specific yield, (S_y), depth to groundwater, thickness, etc.). Therefore, changes in a state variable have to be interpreted in view of such characteristics. At the same time, local particularities may significantly differ from average regional conditions. Thus, a compromise must be found between the spatial aggregation of the assessment, the local particularities of state variable changes at a specific location, and the larger-scale behaviour of the entire aquifer. As a reasonable spatial aggregation, the 'groundwater body' in the sense of the WFD was identified.
- The state of the groundwater system at any location can be identified by analyzing the behaviour of many different state variables. Groundwater level, groundwater recharge, groundwater discharge and river discharge were identified as the most significant state variables.
 - Changes in state variables have different significance at different locations. For example, a change in river discharge has little direct significance for the state of a deep, confined aquifer. Therefore, only a weighted combination of several state variables provides a significant basis for the assessment of complex, heterogeneous, three-dimensional groundwater systems.
 - To interpret the significance of the change of a state variable for the overall state of the system, it is necessary to observe the magnitude and rate of change over a certain period in order to be able to separate 'normal' seasonal behaviour from significant changes in the state. Changes in different state variables are the result of processes with different dynamics. Characteristic response periods are therefore different at different locations and for different state variables.
 - An assessment of a groundwater resource's quantitative state is only possible on a relative and ordinal scale. The assessment must either be based on a comparison with previous conditions that are assumed to have been 'good' or be related to specific objectives (e.g., water supply). Different stakeholders (actors) can have different definitions of good and bad.
 - State variables, in particular groundwater levels, are auto-correlated and can show typical seasonal behaviour (regime). The assessment of the state in one period cannot be independent from the previous time development of the system.
 - Assessment approaches need to be simple and transparent in order to be accepted by stakeholders and to allow improvements by including external expertise from local practitioners familiar with local conditions.

Figures 2 and 3 illustrate the main concepts behind the ideas listed in the preceding, namely the concept of significance of state variables (weights) and the concept of characteristic response periods. While Fig. 2 demonstrates, in a schematic way, the influence of geometric relationships and the hydraulic properties of a groundwater system on changes in this groundwater system's state, Fig. 3 shows how such differences in changes become manifest in real situations.

Figure 2 depicts six different simplified aquifer configurations which help to illustrate the importance of assigning relative weights to state variables and considering response periods, as well as some of the main factors (properties) that can be used to determine these weights and characteristic response periods. The main explanatory factors are the depth to groundwater (i.e., the thickness of the unsaturated zone d_{UZ}), the hydraulic conductivity of the unsaturated zone K_{UZ} , the existence of a connection to a river, the thickness of the aquifer T and finally the

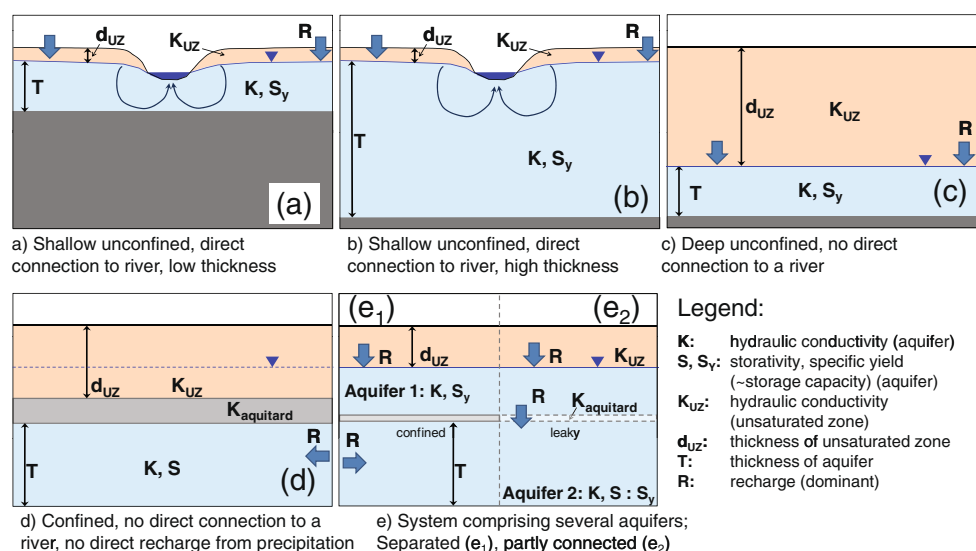


Fig. 2 Six simplified examples of groundwater system configurations. The scenarios depicted in a–e lead to different magnitudes in and rates of response to variations in recharge from precipitation and show the significance of the different state variables to the overall state of a groundwater body. Any horizontal characteristics (limits, connections, etc.) have been ignored

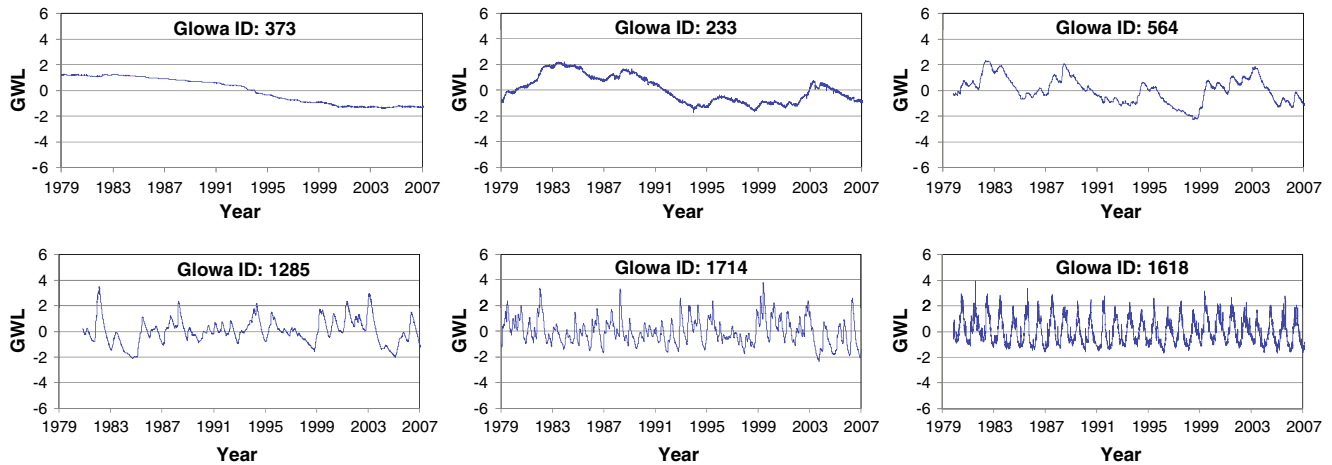


Fig. 3 Examples of groundwater level (GWL [m.a.s.l.]) time series from selected observation wells in the case study area intended to demonstrate the significance of different responses of groundwater levels to precipitation. All time series have been normalized (mean=0, standard deviation=1). From left to right and beginning in the top row, seasonality becomes more and more dominant while the magnitude of long-term changes decreases. Thus, the rate and magnitude of changes must be interpreted differently in each example. The location of the observation wells has been depicted in Fig. 9. Major characteristics of the selected observation wells are summarized in Table 2

hydraulic properties determining the permeability and storage capacity of the aquifer (K , S , S_y).

Figure 2a (scenario/system a) represents a system that responds quickly to changes. Several, here highly correlated, state variables can be used to assess the state of the system: groundwater level, groundwater recharge, river discharge (or level), and groundwater discharge. Groundwater level, however, should be assigned the highest weight (significance), as the other variables can be influenced by factors that are not directly related to the groundwater system (e.g., river discharge might be affected by upstream conditions). The main differences between this scenario and the scenario shown in Fig. 2b (scenario/system b) are the greater depth to groundwater, which leads to longer response times, and the greater thickness of the aquifer. An equal change in the groundwater level in scenarios a and b could lead to different results: the groundwater in system a might be entirely depleted while system b would still store large volumes of water. The interpretation of these results would depend on the objective of the assessment. If the target was assessment of a groundwater body with respect to its ecological role in a riparian system, the groundwater level change would have the same effect on both systems, whereas if the target was assessment with respect to water supply, the state of system a would worsen more quickly than that of system b.

The main difference between the two scenarios already described and scenario c (Fig. 2c) is the larger depth to groundwater, which leads to longer delay of responses, and the absence of a connected river. Here, climatic signals will be delayed and dampened, and any change in the aquifer (groundwater level) will manifest itself only after some time and be less pronounced. River discharge and groundwater discharge cannot be used for an assessment of the state in this scenario.

In scenario d (Fig. 2d), neither groundwater recharge (from precipitation) nor river discharge nor groundwater

discharge can be used for the assessment of the state: groundwater level is the only state variable of significance. Groundwater level must be observed over a longer period of time in order to detect significant changes of state in this scenario.

Scenarios e_1 and e_2 , shown in Fig. 2e, represent situations with more complex behaviour. Firstly, a distinction can be made between the assessments of the upper aquifer (aquifer 1) and the lower aquifer (aquifer 2). Whether such a distinction is possible and necessary depends on the available information and the purpose of the assessment. In scenario e_1 , the situation is similar to scenario c for the upper aquifer and similar to scenario d for the lower. Scenario e_2 shows a situation which can be treated differently dependent on data availability and objectives. Ideally, a detailed analysis based on observed time series should be carried out.

Note that all of the situations shown in Fig. 2 represent highly idealized and significantly simplified conceptual models. As with many conceptual models, they may not occur in nature at all, and if they do, they are most certainly not so simple. Many contributing factors have been excluded. The main purpose of the figure is to illustrate some of the ideas underlying the presented approach.

Figure 3, along with the information shown in Table 2, demonstrates how aquifers located at different depths respond differently to changing boundary conditions, namely with different rates of change (differences in magnitudes of change have been ignored here as the data have been normalized). It should be noted that the selected examples show 'ideal' situations where actual behaviour is quite close to the expected behaviour. It should also be noted that the transition from low to high rates of change in these examples is continuous, yet not linearly proportional in any way. A large number of factors, and not only the depth to groundwater or the distinction between a confined and unconfined aquifer, determine the responses shown.

Table 2 Major characteristics of the groundwater observation wells referred to in Fig. 3

Well ID	Formation age	Aquifer geology	Well screen (upper to lower level; below land surface[m])	Confined/unconfined
373	Triassic	Sandstone, fractured	142–174	Confined
233	Cretaceous	Sandstone, porous, fractured	4–177	Confined
564	Jurassic	Limestone (karstic)	74–88	Unconfined
1285	Tertiary	Weakly consolidated gravel and sand	10–16	Unconfined
1714	Quaternary	Gravel and sand	13–31	Unconfined
1618	Quaternary	Gravel and sand	4–6	Unconfined

The aforementioned considerations presented lead to five basic requirements for a regional integrated assessment approach:

1. Delineation of groundwater bodies of appropriate size and reasonably similar characteristics
2. Assignment of a weight to each state variable in each groundwater body for the purpose of designating the variable's significance as determined by groundwater system characteristics
3. Definition of characteristic response periods for each state variable in each groundwater body
4. Definition of a reference time series for each state variable in each groundwater body for the purpose of determining any deviation of the current scenario from a reference state
5. A methodology that accounts for the fact that the assessment of a groundwater body's current state cannot be independent of its previous state

The following section describes the implementation of the conceptual ideas that have been presented in this section.

Implementation of the approach in the Upper Danube Catchment

The calculations described in the following are typically performed as part of a coupled DANUBIA simulation which is run in a repeated cycle. The calculations in a coupled DANUBIA simulation are performed repeatedly for each time step. The general operational sequence within one DANUBIA cycle is *getData* (read input data from partner models), *compute* (perform calculations), and *provide* (export data to partner models). The first cycle is started with an *'init'* (assignment of static model parameters and starting values). Details on the controlling and timing in the coupled system are provided by Barth et al. (2004) and Hennicker and Ludwig (2006). The presented approach is in fact just one out of several calculations performed by the DANUBIA model *WaterSupply* (see Barthel et al. 2010). It is very important to note that within the DANUBIA system, the assessment process is carried out during a coupled simulation process. This allows for feedbacks: between, state, demand, withdrawal and again state of groundwater resources. For details on these feedbacks please refer to Barthel et al. (2008a) and (2010).

It should be pointed out that despite apparent dependency on DANUBIA, the calculations presented here can also be carried out independently of the simulation system, even using no more than a simple spreadsheet. The only requirement is the existence of simulated or measured time series for each of the state variables in the catchment zones which are to be assessed. Theoretically, the approach could even be successfully applied to just a single zone and using just one state variable. Table 3 explains the steps involved in the calculations carried out within one simulation cycle.

In the following, the actions listed in Table 3 are explained in more detail along with their mathematical formulation.

Preparatory steps

Preparatory step A: delineation of groundwater bodies (zones)

In the approach presented, the term 'groundwater zones' has been used instead of 'groundwater bodies', as the latter term is often used ambiguously in Europe and can therefore easily be misinterpreted (see Table 1). The zones developed for the UDC were designed such that the hydrogeological characteristics within a zone can assumed to be 'reasonably similar' and that any change in boundary conditions leads to a reasonably similar response at any location in the zone. Similarity in the context of properties (hydrogeological characteristics) and responses (time series of observations) can be defined formally using a metric such as the Euclidian Distance in a multi-dimensional set of descriptors, where descriptors can be hydraulic or geometric properties of aquifers or (statistical) shape parameters derived from the analysis of time series. A comprehensive discussion of similarity in the context of hydrology is given by Wagener et al. (2007). In the presented study, the designation of similar properties was simply based on the classification and grouping of the geometric and hydraulic properties of zones using a combination of simple hierarchical cluster analysis and refinement using expert hydrogeological knowledge. Among the properties used for grouping were depth to the water table, hydraulic conductivity of the unsaturated zone, and aquifer thickness. It should be mentioned that a strict formal classification is difficult as many of the properties used are only very roughly known.

Zones in the UDC have been delineated by the intersection of surface catchments (155 gauges with continuous discharge measurements available for the period between 1960 and 2006) and the uppermost active layer of the groundwater model used in DANUBIA (see Wolf et al. (2008)). To account for supra-regional geological and geomorphological differences, the zones were also intersected with six major geological/geomorphological regions. A total of 405 zones were delineated in this way. As a result, each catchment is subdivided into zones in which different aquifers

‘dominate’. The dominant aquifer formation can be understood as the aquifer which:

- Covers the highest percentage of the surface area and/or
- Is predominantly tapped for groundwater withdrawal in the area and/or
- Receives direct recharge through precipitation and/or
- Is directly connected to the surface water drainage system

These four attributes are not mutually exclusive and therefore may lead to ambiguous definitions. Additional

Table 3 Sequence of actions performed during the flag calculations. The superscripts and subscripts used are: t current time step of simulation [month]; i state variable (groundwater level; gwl groundwater recharge; gwr groundwater discharge; gwd river discharge; rd). S state variable; P characteristic response period; Z zone; C model cell; I indicator; F index or ‘flag’. See Table 1 for an explanation of the aforementioned terms). Several actions are addressed in more detail in the text

Action/step	Results and symbols used	Explanation/comments
Preparatory steps		
A: Groundwater body delineation	Zones: Z	Each model cell is assigned to a zone; zones can be discontinuous and vertically overlapping
B: Derivation of reference values for each state variable and zone		Determined using measured data from a reference period as input for the simulation of state variables
C: Definition of model parameters for each zone and state variable: Weights W , characteristic response periods P , vulnerability factors k , and threshold values T		Done on the basis of aggregated values of geometric and hydraulic properties (see Table 4). Threshold values must be defined for the classification of state variable deviation from normal on the basis of past critical states, if possible
0 Initialization (<i>init</i>)		
0.1: Initialization of zone objects	Zones: Z	The zone geometry is specified upon initialization and can be configured for each simulation run, but will usually not be modified
0.2: Assignment of reference values	$S_{Z_{ref_i}}^{P_i}$	Can be configured for each simulation run
0.3: Assignment of model parameters for each state variable and each zone	W_Z, P_Z, K_Z	Weight: Degree of significance a change in this state variable has for the overall assessment of a zone. Period: Characteristic period that needs to be evaluated in order to detect significant changes of a state variable in a zone
0.4: Assignment of initial flags	$F_{Z_{init}}$	Initial state at beginning of simulation
0.5: Assignment of threshold values	T_i	Thresholds for classification of state variable deviations
1 Import of state variables (<i>getData</i>)		
Import of state variable scenario values from partner models or read from files	Sc_i^t	Partner models calculate state variables for each model cell and day and provide them as monthly aggregated values at month-end
2 Main calculations (<i>compute</i>)		
2.1: Aggregation of state variables to one value for each zone	$S_{Z_i}^t$	Sum, average or maximum value per zone, depending on the state variable (gwl, gwr, gwd, rd)
2.2: Calculation of scenario value averages for gwl, gwr, gwd , and rd for each zone and state variable	$S_{Z_i}^{P_i}$	2.2–2.4: For the analysis of a scenario, state variable values for each zone are aggregated over a moving window which has a length equal to that of the characteristic period, P (per zone and state variable). The results are compared to the moving average calculated for the reference period over the same window length. Detailed explanations and justification for the concept of moving average comparisons of scenario and reference values are given in the text
2.3: Calculation of reference values for the equivalent period length	$S_{Z_{ref_i}}^{P_i}$	
2.4: Calculation of the deviation of scenario values from the corresponding reference values for each zone, time step and state variable	$\Delta S_{Z_i}^t$	
2.5: Categorization of state variable deviations into an indicator (flag) for each variable	$F_{Z_i}^t$	Percentage deviations are converted to yield values between 1 and 5 using the T_i values
2.6: Weighted combination of the indicators derived for each state variable	$F_{Z_i}^{t_{weighted}}$	Weighted sums calculated according to the weights defined for each of the state variables in a zone
2.7: Postprocessing of the $F_{Z_i}^{t_{weighted}}$ values	F_Z^t	Several minor modifications to remove unwanted numerical effects from the final <i>GroundwaterQuantityFlag</i>
3 Export to partner models (<i>provide</i>)		
Export of the F_Z^t values to partner models or to a visualization for direct use		In DANUBIA, flag values have an influence on water and land use and therefore have an influence on the state variables utilized in the next time step
1 Import of state variable (<i>getData</i>)- Repetition of actions 1–3 for the next time step (t increased by an increment of 1 month)		

complications are that (1) aquifer formations are often not clearly separated, (2) water supply wells tap more than one formation, and (3) the groundwater/ surface-water interaction regime can vary over short distances. It must be pointed out that any groundwater body or aquifer delineation approach is a compromise between available information, size of zones and the context in which the delineation is carried out. To account for the fact that there is no unique delineation concept for all scales and all purposes, the delineation used here is flexible, for example in order to account for situations where water is being withdrawn from deeper aquifers or when different vertical aquifers are 'dominant' at one location. In general, the zone concept used here represents a compromise between a simple two-dimensional-delineation approach based on surface watersheds and a full three-dimensional-delineation approach. The first approach neglects important features of groundwater systems, while the latter is difficult to realize as it requires information that is usually not fully available.

Preparatory step B: derivation of reference values for each state variable and zone

An important step in the calculation of flags is the derivation of reference values for each state variable that can be used as a basis for comparison. Such reference values can be determined in various ways, e.g., by interpolating measured data from a period in the past which is characterized by known good conditions, or simply by making assumptions about good states and correspondingly defining the reference state variables synthetically. The most consistent way to create reference values that are directly comparable to values calculated in a scenario simulation is to derive the reference values from a simulation which uses the same models with observed climatic data as input. This is done within DANUBIA by performing a simulation run with the DANUBIA partner models using measured climatic data from the past as input. Models are run using the meteorological input for the period between 1960 and

2006 (measured station data, see Mauser et al. 2007, and Mauser and Bach 2009) and an identical parameterization. The resulting state variables are then aggregated for each zone and averaged for each month of the year (i.e., average values are calculated for January, then February, etc.).

Figure 4 shows the results of this process for the groundwater level and groundwater recharge state variables in three zones (the same zones are used in the section [Application in the Upper Danube Catchment: selection of exemplary results](#)). While groundwater recharge shows approximately the same behaviour in all zones, the responses in groundwater level are delayed or dampened when compared to one another.

Preparatory step C and initialization: assignment of characteristic parameters to groundwater zones

The response of a zone is quantified by the analysis of four different state variables: groundwater recharge, groundwater level, groundwater discharge and river discharge. Groundwater and surface water withdrawal are indirectly involved in the evaluation as they form boundary conditions for the hydrological models in GLOWA-Danube and, therefore, influence groundwater levels and river discharge. The most important aspect of the assessment approach is to ascertain how fast and to what degree the state variables affect changes in the groundwater bodies' quantitative states (see section [Project background](#)). This is done via the determination of three model parameters: the period, P (characteristic response time), which is used in the evaluation of the three state variables; the weight, W , which characterizes the influence a particular state variable has on the total assessment of a zone; and k , the vulnerability factor, which accounts for the extent (thickness, area) of a groundwater zone. The model parameters, which are explained further in Table 4, are mainly determined using the average hydraulic and geometric (static) properties of the dominant aquifer (e.g., depth to the water table or hydraulic conductivity) in unsaturated

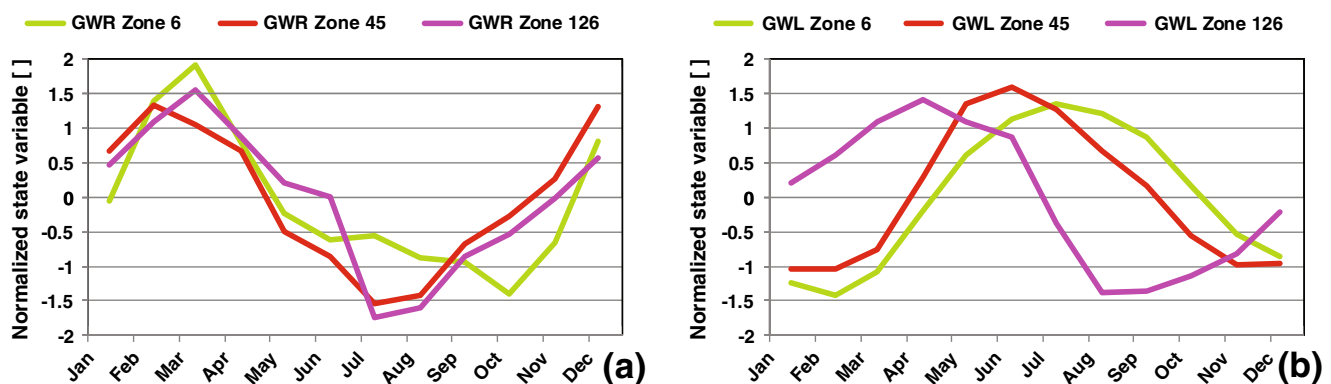


Fig. 4 Simulated state-variable values (normalized) for **a** groundwater recharge (GWR) and **b** groundwater level (GWL), in three selected zones based on observed climate data for the period 1960–2006. All values have been normalized (mean=0, standard deviation=1) for better comparability

Table 4 Parameters used in the calculation of flags and symbols used in the respective equations (Initialization – step 0)

Model parameter	[Unit]/range	Meaning	Is derived from
Characteristic reaction period, P , defined for each zone and state variable	[month]/1–12	The length of time a state variable must be 'monitored' in order to indicate a significant change of the groundwater quantity in a specific zone	Depth to the groundwater Transmissivity of the unsaturated zone Hydraulic diffusivity ($D=T/S$) of the aquifer
Weight, W , defined for each zone and state variable	[-]/0–1	The relevance of a state variable in a specific zone, or the degree of significance a state variable has to the quantitative state of a groundwater resource	Hydraulic connection to surface waters present/not present Thickness and stratification of the unsaturated zone
Long-term average magnitude of groundwater recharge k , defined for each zone	[-]/0–1	The factor k acts as a buffer: the larger the total efficient storage volume of an aquifer, the less vulnerable the system is against worsening conditions	Aquifer type and geometric properties: transmissivity, thickness, depth, porosity, specific yield, storativity
Categorization threshold value T	[%]	Thresholds for the categorization of a state variables deviation from normal into categorical values from 1 to 5	Analysis of past critical situations, expert knowledge, assumptions on potential impacts
F_{init} , defined for each zone	[-]/1–5	The initial flag value at simulation start	The state of a groundwater system always depends on its previous state (autocorrelation). Therefore, an initial value has to be provided

parts of a zone. They are consistent with the parameters used in the numerical groundwater flow model employed in DANUBIA and mainly derived from (1) measured data, if available, (2) calibration of the flow model, and (3) expert knowledge (as communicated by professionals from the area or via literature and reports).

Step 1: import of state variables

The import of state variable values from partner models is managed by the DANUBIA framework and the DANUBIA time controller (Barth et al. 2004; Hennicker and Ludwig 2006).

Step 2: main calculations

Step 2.1: aggregation of state variables

At each time step, t (1 month) the state variable values, Sc_i^t imported from the partner models are aggregated for each zone, Z to form the zone average value, $S_{Z_i}^t$. A distinction must be made between Eqs. (1), (2) and (3) because the volumetric flux parameters (gwr , gwd) are expressed in [m^3/s] and need to be summed to form a zone value, while the mean for the gwl parameter, expressed in units of length [m], must also be determined. For river discharge, rd , the aggregated value per zone is represented by the cell with the maximum discharge in each zone (i.e., the cell corresponding to the location of the gauge at the catchment outlet). Note that not all zones include a river; in these cases rd and gwd are not considered in the assessment.

$$S_{Z_i}^t = \sum_{c=1}^{C_z} Sc_i^t; \quad \text{where : } i=(gwr, gwd) \quad (1)$$

and:

$$S_{Z_i}^t = \frac{1}{C_z} \sum_{c=1}^{C_z} Sc_i^t; \quad \text{where : } i=(gwl) \quad (2)$$

and:

$$S_{Z_i}^t = \text{Max}\{Sc_i^t(Z)\}; \quad \text{where : } i=(rd) \quad (3)$$

with:

- gwr State variable value of groundwater recharge [m^3/s]
- gwl State variable value of groundwater level/piezometric head [m.a.s.l.]
- gwd State variable value of groundwater discharge [m^3/s]
- rd State variable value of river discharge [m^3/s]
- c Cell index for zone Z
- C_z Number of cells in zone Z
- t Current month of the simulation [$1-T$], (model time step=1 month)
- Sc_i^t State variable value in cell c at time step t (input value from partner models aggregated to 1 month)

Step 2.2: calculation of scenario value averages of the state variables

In this step, the zone state variable values, $S_{Z_i}^t$ are aggregated over the characteristic period, P_{Z_i} in order to obtain the aggregated state variable value, $S_{Z_i}^{P_i}$ for the characteristic response period. Step 2.2 can only be performed if t is larger than the largest of the characteristic periods in the zone— $t > \text{Max}\{P_{Z_i}, i=(gwr, gwl, gwd, rd)\}$. Otherwise, the flag values are set to $F_{Z_{init}}$ (Table 4). In most cases, the largest period, P_{Z_i} in a zone, Z is defined

for the *gwl* parameter by the groundwater level showing the longest response time:

$$S_{Z_i}^{P_{Z_i}} = \frac{1}{P_{Z_i}} \sum_{t=P_{Z_i}}^t S_{Z_i}^t; \quad \text{where : } i=(gwl, gwr, gwd, rd)$$

(4)

with:

P_{Z_i} Characteristic period length for each i (= *gwl*, *gwr*, *gwd*, *rd*) in a zone Z [month]

Step 2.3: calculation of reference values for equivalent period length

In order to assess changes in the calculated aggregated state variable values, $S_{Z_i}^{P_{Z_i}}$, they are compared with reference values, $S_{Z_{ref_i}}^{P_{Z_i}}$ that describe the long-term condition of the state variable in a zone, Z and refer to the same characteristic response period, P_{Z_i} . These reference values are obtained by aggregating monthly long-term mean values of the state variables $S_{Z_{longterm_i}}^{month^t}$ (see preparatory step B):

$$S_{Z_{ref_i}}^{P_{Z_i}} = \sum_{t=P_{Z_i}}^t S_{Z_{longterm_i}}^{month^t}; \quad \text{where : } i=(gwr, gwl, gwd, rd)$$

(5)

with:

$S_{Z_{ref_i}}^{P_{Z_i}}$ Reference value for the state variable S in zone Z equivalent to the average value obtained for the reference period (here, 1960–2006)

$S_{Z_{longterm_i}}^{month^t}$ Long-term monthly average value for state variable S in zone Z for each month of the year month: month of the year [1–12]

If the characteristic period, P_Z is a multiple of 12 months, the long-term mean for each variable (i.e., the variable's average over the entire reference period) and zone, $S_{Z_{ref_i}}$ is used (see Eq. 4). The definition of periods which are not multiples of 12 but where $P > 12$ (e.g., $P=18$ or 32) is not justified by hydrogeological knowledge.

$$\text{if } P_Z = (12, 24, \dots) \Rightarrow S_{Z_{ref_i}}^{P_{Z_i}} = S_{Z_{ref_i}} \quad (6)$$

$S_{Z_{ref_i}}$ Mean value of the reference state variable for parameter i in zone Z (i.e., the long-term average over the entire reference period)

Step 2.4: deviation of scenario values from corresponding reference values

In this step, the state variable values from the scenario period are compared to the state variable values for the reference period. The difference is expressed as the percentage deviation, $\Delta S_{Z_i}^t$ obtained from Eq. (5):

$$\Delta S_{Z_i}^t = \left(1 - \frac{S_{Z_i}^{P_{Z_i}}}{S_{Z_{ref_i}}^{P_{Z_i}}} \right) \times 100; \quad (7)$$

where : $i = (gwr, gwd, rd)$

For the groundwater level (*gwl*), effects of different elevations (above the common datum sea level) and different groundwater level dynamics are removed by normalizing to the maximum range of groundwater level changes observed during the reference period:

$$\Delta S_{Z_i}^t = (-1) \left(\frac{S_{Z_i}^{P_{Z_i}} - S_{Z_{ref_i}}^{P_{Z_i}}}{\max S_{Z_{longterm_i}}^{P_{Z_i}} - \min S_{Z_{longterm_i}}^{P_{Z_i}}} \right) \times 100; \quad (8)$$

where : $i = (gwl)$

$\min S_{Z_{longterm_i}}^{P_{Z_i}}$ Minimum value of the average groundwater level in a zone during the reference period

$\max S_{Z_{longterm_i}}^{P_{Z_i}}$ Maximum value of the average groundwater level in a zone during the reference period

Steps 2.2 to 2.4: concept of equivalent periods and moving window calculations

Figure 5 exemplifies the comparison of simulation values from the current scenario with reference values. The figure shows the annual distribution of monthly values of an arbitrary state variable calculated in a 2-year-long scenario simulation (according to step 2.2) and the long-term averages of this state variable during a reference period (according to step 2.3). For better visualization, values are normalized such that the maximum monthly value equals 1 ($S_{norm} = S/S_{max}$). For the purpose of demonstration, the annual average during the reference period and the annual averages determined for each of the two scenario years were set equal to a value of 0.23. The seasonal distribution of the state variable in an average year during the reference period shows bi-modal behaviour with a pronounced maximum in the spring and a second maximum in autumn. The behaviour of the state variable in the two scenario years deviates significantly

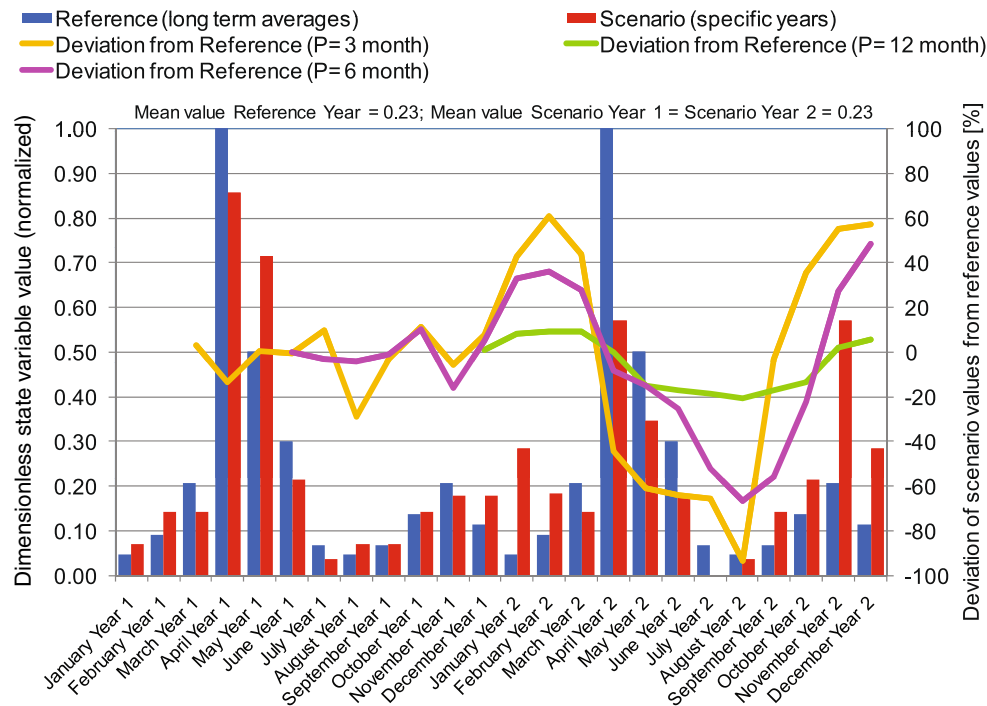


Fig. 5 Example, demonstrating both the significance of different period lengths and a moving window comparison for the assessment of changes in state variables

from the average behaviour of this state variable during the reference period.

With respect to the discrepancies between the two scenario years and the average reference situation, an assessment of the situation shown in Fig. 5 can be carried out in various ways:

1. By comparison on a month-by-month basis
2. By comparison on a year-by-year basis
3. By a flexible comparison where the periods being compared are adjusted according to the buffer capacity and response times of the state variable in a zone

A *comparison on a month-by-month basis* would not yield a meaningful assessment as seasonal climate variations are usually relatively large and most, if not all, regionally scaled aquifers have the capacity to buffer one or two dryer-than-average months. One dryer-than-average month is not enough to indicate a significant change in the state of a groundwater body in the context of regional, integrated assessment.

A *comparison on a year-by-year basis* would more appropriately account for the inter-annual variability of the climate and for the buffer capacity of regional aquifers. However, as with all climates which show a pronounced *seasonality*, the generalizations resulting from a year-by-year comparison would be too strong for aquifers with a low buffer capacity. In the case shown in Fig. 5, an assessment made on the basis of annual averages would show that the scenario years do not differ from the average and would therefore not be negative. However, depending on the buffer capacity, the nature of the state variable, and the use of the water, such a result could be misleading as it would not account for the dry spring and summer of

scenario year 2. An aquifer with a low buffer capacity or an aquifer which is intensively used in the summer might in fact be under severe stress in such a situation.

For these reasons, a *flexible comparison* which is adjusted to the known behaviour and properties of the aquifer (zone) should be undertaken. Figure 5 demonstrates the ideas underlying such a comparison. The lines show the deviation of monthly scenario values (aggregated over the characteristic period length) from reference values for characteristic periods of 3, 9 and 12 months. The values are calculated as moving averages using a window size equal to the specified characteristic response period length, P_{Z_i} , Equation (4). The same distribution of the state variable for two different scenario years leads to different deviations and therefore different assessments. An aquifer with a small characteristic response period ($P=3$ months) will quickly begin to experience a state that differs severely from the 'normal' state in the dry spring of year 2, while an aquifer which responds more slowly ($P=9$ or 12 months) would be able to buffer effects of the dry spring and thus not show any severe deviations from 'normal'.

Step 2.5: translation of deviations into an indicator (flag) for each variable

A comparison of scenario values and reference values results in a deviation which is expressed as a percentage. The percentage deviation of each individual state variable is then assigned an ordinal value according to Eq. (7) to obtain a universal *indicator* parameter, $F_{Z_i}^{\dagger}$. The higher the

deviation of the indicator values from the reference values, the higher the ordinal number assigned to indicate the degradation of resource conditions. The threshold values used for this classification are shown after Eq. (7) and explained in Table 4. To account for different horizontal groundwater body extents, each threshold value is multiplied with a vulnerability factor, k_z [0–1]. The smaller this factor, the lower the resulting threshold, i.e., the smaller the deviations which will result in a higher (worse) indicator value. This measure was introduced to allow for the fact that in zones with similar hydrogeological properties but of differing sizes, changes in state variables will result in greater overall changes in the smaller zone than in the larger zone (see Table 4).

$$\Delta S_{Z_i}^t < \text{Max}\{ |T_i \times k_z|, i = (gwr, gwl, gwd, rd) \} \Rightarrow F_{Z_i}^t \quad (9)$$

- T_i Threshold values for the classification of the flags ($i=gwl, gwr, gwd$)
- $F_{Z_i}^t$ Indicator for each state variable, S and zone, Z in time step, t
- k_z Vulnerability factor, summarizing the extent of a zone in order to reflect its resistance to change [0–1]

Threshold values T_i for each state variable $i=(gwr, gwl, gwd, rd)$ are listed in Table 5.

Step 2.6: weighted combination of the indicators derived for each state variable

Since different indicators have different degrees of importance in the evaluation of the final zone state, the flags are weighted according to Table 4:

$$F_{Z_{\text{weighted}}}^t = \sum_i F_{Z_i}^t \times W_{Z_i}; \text{ where } : \sum W_{Z_i} = 1 \quad (10)$$

- W_{Z_i} Weight (importance of influence) of each state variable, i in each zone, Z
- $F_{Z_{\text{weighted}}}^t$ Weighted flag for each zone, Z at time step, t

Step 2.7: post-processing of weighted flag values

As a final step of the flag calculation, the weighted flags, $F_{Z_{\text{weighted}}}^t$ are modified to yield the final flag, F_Z^t (the *GroundwaterQuantityFlag*, *GQF*). These minor modifica-

Table 5 Threshold values T_i for each state variable $i=(gwr, gwl, gwd, rd)$ used in Eq. (9)

T_i			F_{Z_i}
$i=gwr$	$i=gwl$	$i=gwd=rd$	
30	15	30	1
60	25	60	2
90	40	90	3
120	60	120	4
>120	>60	>120	5

tions are made to account for numerical effects that can result from the ‘crisp’ classifications made in step 2.6. A fuzzy rule-based classification would lead to smoother and sometimes more reasonable results but was not used in order to keep the approach as transparent as possible. In particular, step 2.7 is taken to avoid too frequent and too sudden changes in the final flag values.

Step 3: Export to partner models

After the internal calculations of the individual models in the coupled system DANUBIA are completed all calculated values (here: the flag values) are made available to the partner models. Examples of how the flag values are used by other models in DANUBIA are shown in Barthel et al. (2008a)

Application in the Upper Danube Catchment: selection of exemplary results

The overall objective of the described approach for assessing the quantitative state of groundwater resources on a regional scale is to provide directly applicable information for decision-making in integrated (ground) water-resources assessment on a regional scale. The scope and objective of the developed approach is to determine how, when and where changes of climatic, social and economic conditions (e.g., agricultural policies) may have negative impacts on the quantity of groundwater resources available in a large catchment and the potential impacts these changes might have on water usage. With respect to groundwater quantity, a critical situation would be one in which the water-supply system failed to meet demands or in which sustainability rules were violated and ecological or economic damage occurred. Changes of the *GQF* from lower to higher values indicate that problems are occurring but they do not directly indicate the nature and origin of these problems. In order to discern these, results of other DANUBIA models have to be analyzed as well. For example, it could be determined whether a decrease in groundwater level is the result of increased withdrawal or a result of decreasing recharge, or, to give another example, if decreasing groundwater recharge is the result of changes in temperature and precipitation or the result of a change in land use.

Furthermore, the approach is designed to be used for evaluation of the benefits or dangers created by specific management measures (interventions, e.g., building a reservoir). It is therefore important that results for different locations are directly comparable, and thus that results are spatially and temporally explicit.

As mentioned earlier, the flags, i.e., the results of the presented approach, are only one out of several results the DANUBIA model *WaterSupply* provides (see Barthel et al. 2010). The model *WaterSupply* in turn is just one out of 17 models included in DANUBIA. The DANUBIA system provides hundreds of output parameters which can be analyzed, visualized and used in various ways. The brief

presentation of exemplary results in the following section provides only a glimpse into how the results of the presented approach might be used. It does not present a full-scale evaluation of the impacts of climatic change in the UDC. The GLOWA-Danube interactive online Atlas (GLOWA-Danube Project 2010) provides a platform for those interested in a wider selection of results.

Flag computation results

As pointed out earlier on, the definitions of good, bad, better and worse with respect to groundwater resources cannot be made in a general or absolute way without being put into a specific context. The *GQF* are values on an ordinal scale, i.e., 1 is better than 2. At the same time, a value of 3 in one zone shows that the conditions in this zone are better than in other zones which have values of 4 and 5 and worse than in zones which have values of 1 and 2. In general, ‘good’ and ‘bad’ states are always relative, because good for one purpose can mean bad for another, different stakeholders (or actors) can have different interpretations of good and bad, a good natural state of a groundwater system does not necessarily mean that conditions are good for water supply or to support groundwater dependent ecosystems, etc.

Table 6 gives an example of how *GQF* values can be generally interpreted and how they might be used by a specific stakeholder, a water supply company (WSC). In the case of DANUBIA, a WSC is represented as an object within the computer model *WaterSupply*, but the values shown could be used in the same way by a water-supply company in the real world. Note that a stakeholder’s usage of flag values may not only depend on his individual preferences but also on existing legal and political frameworks (see Barthel et al. 2008a and Barthel et al. 2010 for a full-scale discussion).

Global-change scenarios used

The development of consistent global-change scenarios in GLOWA-Danube required enormous interdisciplinary efforts and was an iterative process conducted over many years. Its presentation and discussion is beyond the scope of this paper. It should be pointed out that difficulties in deriving regional scenarios from global predictions still seem to be widely underestimated, particularly within the field of groundwater research.

In GLOWA-Danube, regional global-change scenarios were defined for the period between 2011 and 2060 based on global climate-change scenarios of the A1B type (according to the Intergovernmental Panel on Climate Change (IPCC); see IPCC 2007 and Bates et al. 2008) in combination with socio-economic mega-trend scenarios. The societal scenarios consider three paths along which society may be assumed to evolve. The baseline trend describes a continuation of the present societal conditions while the Open competition and public welfare trends make more or less opposing assumptions about the development of society towards a more free-market liberal orientation in the former case and an orientation centred more around collective responsibility in the latter.

Within DANUBIA, downscaling of global climate predictions to regional conditions can be done by regional climate modelling or by using a stochastic weather-generator approach. The results presented here were generated using the latter method as it provides more stable results, particularly in the high alpine parts of the catchment. The climate scenarios use the regional (European) trends of the A1B scenarios and the input values were derived from a statistical analysis of 46 years of observed climate data. Details of the procedure are explained in Marke (2008) and Mauser and Bach (2009).

The results presented were derived using a relatively warm and dry climate scenario combined with the baseline

Table 6 General meaning of the *GroundwaterQuantityFlag (GQF)*

<i>GQF</i> (flag) value	General meaning for the groundwater state within a zone	Interpretation/reaction by a WSC ^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, withdrawals reduced 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 damage and water scarcity (water-supply shortages) 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 shortages) on a regional level	Includes reactions to flag 4. Withdrawal stopped

^a *WSC* water supply company. How and to what extent a WSC reacts to flag values is part of the scenario definition. In a sustainability oriented scenario, a WSC will pay more attention to warnings and react more strongly and earlier than in a scenario oriented around producing economic profit

societal trend. In the selected scenario, strong temperature increases and slightly decreasing precipitation lead to a significant reduction in groundwater recharge and subsequently to falling groundwater levels (Fig. 6). To demonstrate the rate and the magnitude of the selected scenario, the future situation (2011–2060; Fig. 6b and d) is compared to the reference data set (1960–2006; Fig. 6a and c). The values shown were calculated using the same methods for both the reference and the scenario periods. For the reference period, climate data for 270 stations were spatially and temporally interpolated and input into the hydrological models of DANUBIA to calculate state variables. For the scenario period, scenario data sets were generated for the same 270 climate stations, interpolated and used as input for a simulation of the scenario groundwater recharge and groundwater levels (see Marke 2008 for details).

The groundwater recharge and groundwater levels shown in Fig. 6 together with groundwater discharge and river discharge (not shown) form the input to the flag calculations shown in the following figures. Figure 7 shows the temporal development in the *GQF* for the selected scenario over all 405 zones of the UDC. For each time step (1 month), the percentage of zones that received each flag (from 1 to 5) is shown. Because all zones in this simulation were initialized with a flag value of 1 (assuming that the state of all zones was very good at the beginning of the scenario), no flag values greater than 1 appear at the beginning of the simulation period ($N(1)=100\%$). The first appearance of values greater than 1

occurs when the zones with the shortest reaction periods, P_{Z_i} (Table 4), begin to influence the averaged results. In the first two decades of the scenario, conditions remain relatively stable because the regional groundwater systems generally have the capacity to buffer the effects of a few relatively dry years. The dry years of 2011 and 2017 cause about 25% of the zones to change from 1 (very good) to 2 (good), but fewer than 3% of the zones eventually change from 2 to 3 (early warning state). The extremely dry year 2029 marks the beginning of a trend towards a more rapid increase in flag values (Fig. 6). From 2030 on, even a sequence of relatively wet years does not lead to recovery of the system. This is mainly due to the groundwater level state variable, which expresses increasingly depleted storage.

The spatially aggregated, temporally explicit presentation of results gives a good first overview of the general tendency of a climate scenario's impact and forms the starting point for the development of further scenarios, e.g., intervention scenarios where in addition to a climate scenario, management measures can be defined for certain regions and specific periods. It can also be used for the definition of 'what if' type or 'worse/worst case' scenarios, e.g., duplication of extremely dry years.

While Fig. 4 shows scenario results averaged over the entire catchment, Fig. 8 shows three particular zones selected because of their contrasting hydrogeological properties. Although the changes in boundary conditions (precipitation, temperature) are almost identical for the three zones, the responses of the groundwater system are very different; thus, demonstrating the important role

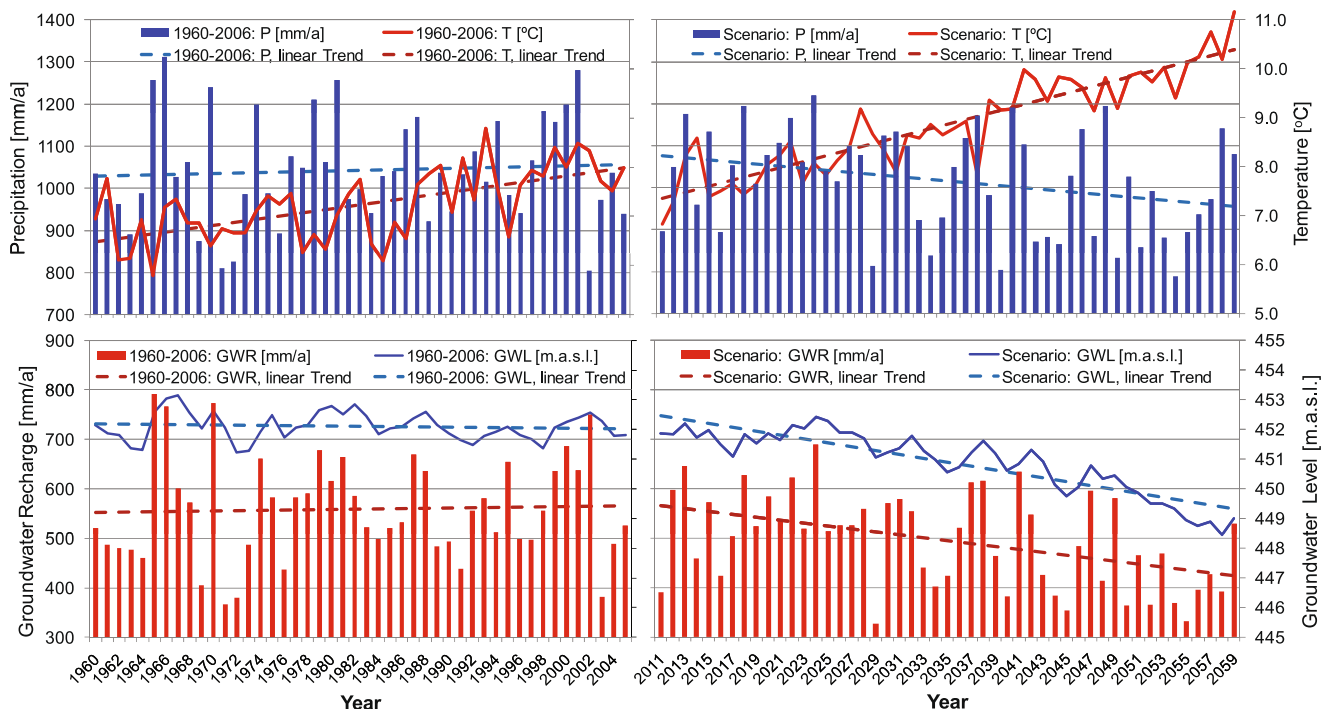


Fig. 6 Mean annual values of precipitation, temperature, simulated groundwater recharge and groundwater levels averaged over the entire catchment. The diagrams on the *left panel* (a and c) show results based on measured climate data from 270 climate stations for the period from 1960 to 2006. The diagrams on the *right panel* (b and d) show results based on climate data derived from a regional climate scenario. All values are averaged per year over the entire catchment

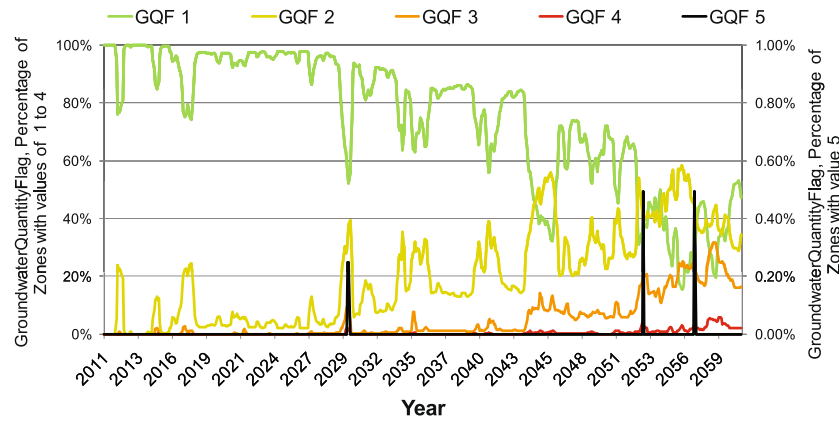


Fig. 7 The temporal development of GQF values expressed as the percentage of zones that assume a specific flag value per time step in the selected climate scenario (Fig. 6). The flag value of 5 occurs only rarely and is therefore shown separately on the *right* y-axis

geometric and hydraulic properties play in the meaningful assessment of the future state of a groundwater zone.

Zone 45 is an aquifer typical of alluvial river valleys: a shallow, unconfined system dominated by coarse sand and gravel deposits stretching alongside the River Isar. The hydrogeological properties of the system (hydraulic conductivity and storage capacity) are very good, and it responds quickly to changes in climatic input. The aquifer is, however, relatively resistant to long-term changes and its ‘memory’ for ‘bad conditions’ is not pronounced, as evidenced by its quick recovery at the end of the simulation period.

Zone 6 can also be characterized as an unconfined system of Quaternary age and alluvial origin, but it has slightly worse hydrogeological properties in comparison with zone 45. Here, the average depth to the water table is higher and the zone’s area does not strongly correspond to the area through which the river flows. Therefore over much of the zone, the distance to the river is large and connections between the zone and the river do not dominate. Seasonal fluctuations are also less pronounced than in zone 45. The system responds more slowly than zone 45 and it can buffer the effects of single dry years more effectively. However, its ‘memory’ for dry years is also better, and, thus, storage losses in the system add up significantly.

Zone 126 is an unconsolidated aquifer of Tertiary age, dominated by partly consolidated clastic sediments (sand) with medium storage capacity and hydraulic conductivity. The water table is deep and no connected river is present in the zone. The system responds very slowly and seasonal effects are not recognizable. Table 7 summarizes some of the key characteristics of the zones presented in Fig. 8. The location of the zones is shown in Fig. 9.

Only temporal aspects, i.e. the development of the state variable with time, have been discussed thus far. However, the approach under discussion also provides detailed spatial information. Figure 9d shows the spatial development of the GQF in the selected scenario. To indicate the spatial resolution, zone geometry is shown in Fig. 9a. The geology is shown in Fig. 9b, while Fig. 9c depicts the difference in recharge for the climate scenario used

relative to the reference period. The flag values shown are annual mean values. A steady decrease in groundwater recharge results in decreasing groundwater levels over the 50-year period which leads to an increase of the GQF values. It can be observed that conditions remain stable throughout the first two decades of the scenario. Only at the northern border of the Alps do circumstances first begin to deteriorate due to the combination of decreasing precipitation in this area (a situation which has also been observed in past measurements) and unfavorable hydrogeological conditions (moraines). This spatial trend develops even further towards the end of the simulation period.

The flag values, the final result of the approach being presented here, can be depicted and evaluated via various methods of spatial and temporal aggregation. As pointed out earlier, the flag values are just one of many results the underlying models provide. A wider range of results related to the flags are provided in Barthel et al. (2008a), (2010) as well as in the GLOWA-Danube Atlas (GLOWA-Danube Project 2010).

Validation

With respect to the validation of the GQF in the UDC, a problem lies in the fact that over the past three to four decades, significant groundwater-quantity problems in the region were almost unheard of. There is, therefore, little opportunity to directly validate the GQF results with observed data.

In general, however, GQF results observed in model simulations where the assessment approach was applied to climatic conditions for the reference period 1960-2006 are in agreement with the observations made during this period: The state determined for the reference period is very good to good with very few exceptions. There are good and reasonable reactions to known climatic extremes such as the hot and dry summer of 2003 and the exceptionally warm year of 2006. Figure 10 shows both the reference recharge calculated for the entire catchment and for one selected zone (zone 5), along with the respective calculated GQF values. A significant decrease

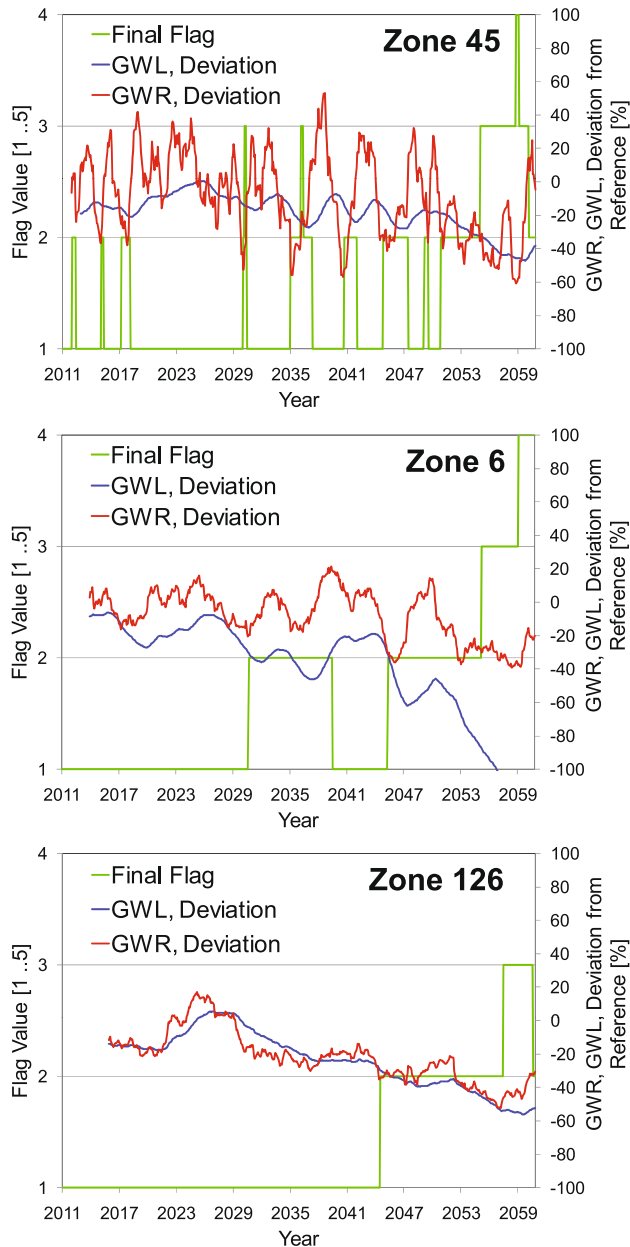


Fig. 8 Comparison of GQF values for three zones with different weight and period parameters (see Table 4): **a** zone 45, **b** zone 6, and **c** zone 126

in groundwater recharge in 2003 leads to a general deterioration of *GQF* values. In zone 5, this effect on *GQF* values is even more pronounced because the zone was assigned a high weight for groundwater recharge values and a short characteristic response period for the *gwr* state variable (6 months). In 2006, twelve consecutive months were much warmer than the long-term average and were preceded by 2 years of lower-than-average recharge, leading to a strong increase in zone 5 but only a minor response of the entire catchment. Those short-term events, however, did not have any long-term regional effects and the state improved quickly after several wetter-than-usual months which followed.

Discussion of the methodology

The following section discusses issues related to the feasibility, potential applications and users, transferability validation, and uncertainty of the presented approach.

Fields of application

The presented approach was specifically designed to meet the requirements of integrated assessment, planning and management on a regional scale. Two points should therefore be taken into consideration when determining its applicability:

1. Regional, integrated management is a task that necessitates the application of considerable human and technical resources. To be done effectively, experts from different fields have to be involved, large amounts of data must be collected, and complex models have to be set up. Regional, integrated assessment and management should thus be carried out by a high-level organization.
2. The flag approach presented in this article represents a compromise between the size and the complexity of heterogeneous natural systems, the high degree of uncertainty inherent to operating on a regional scale and the need to realistically and reliably assess the impacts of global-change and regional-scale management measures on the environment.

Table 7 Properties and model parameters of the zones shown in Fig. 8

Selected attributes	Zone 6	Zone 45	Zone 126
Area [km ²]	957	455	173
Ave. depth to groundwater [m]	43.8	18.3	83.7
Type	Unconfined	Unconfined	Unconfined
Geology (dominant)	Quaternary	Quaternary	Tertiary
Storage capacity	Medium	High	High
Residence time	Medium	Low	Very high
Hydraulic Conductivity	High	Very high	Medium to high
Characteristic periods: <i>gwl</i> , <i>gwr</i> , <i>gwd</i> , <i>rd</i>	36, 36, 12, 12	24, 9, 6, 6,	60, 60, 0, 0
Weights <i>gwl</i> , <i>gwr</i> , <i>gwd</i> , <i>rd</i>	0.35, 0.45, 0.1, 0.1	0.3, 0.3, 0.2, 0.2	0.6, 0.4
Vulnerability factor, <i>k</i>	0.95	0.95	0.95

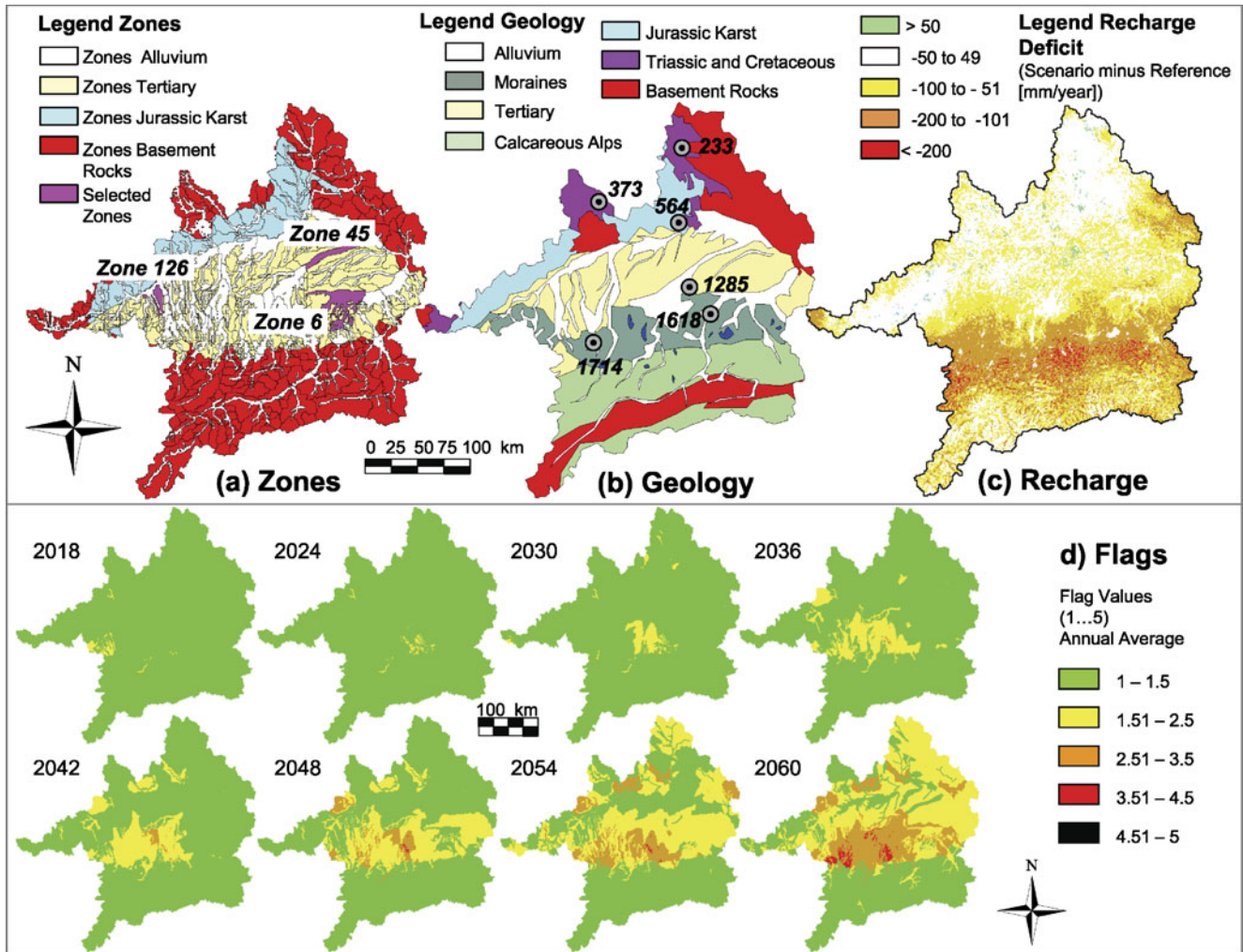


Fig. 9 Maps of **a** zone geometry, **b** major geological formations and **c** the difference in recharge for the climate scenario used relative to the reference period, and **d** the spatial changes in the *GroundwaterQuantityFlag* between years 2018 and 2060 for the selected scenario. *Circles* in part **b** indicate the location of observation used in Fig. 3 to show different temporal behaviour of groundwater levels

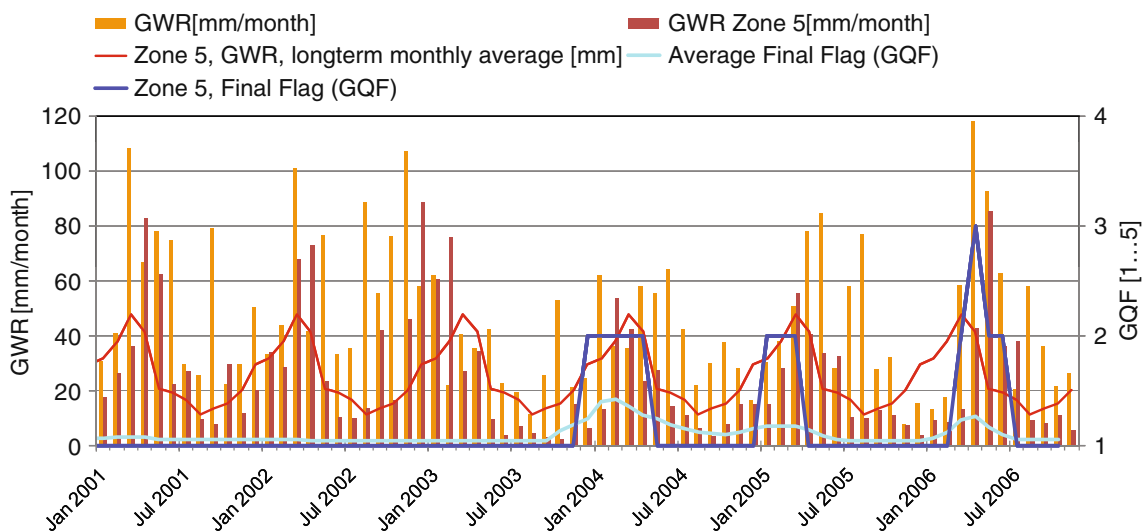


Fig. 10 Groundwater recharge (GWR) reference and GQF assessment values in 2001–2006 for the entire catchment and a selected zone with short reaction periods (zone 5). Zones with medium and long response times show no specific reaction to the exceptionally dry summer of 2003

The application of the presented approach in smaller case study areas and/or in a less integrated context is technically feasible but would not make much sense as more appropriate tools already exist for assessing and managing groundwater-specific problems on the local scale. The most important application of the presented approach is in the evaluation of the impacts of climate change on the regional scale. As pointed out by different authors (see [Introduction](#)), analyses made on a regional scale form a necessary link between global climate-change projections and local predictions. Regional analyses can form the framework for more specific analyses conducted on a local level.

Another important application involves regional integrated planning for larger-scale interventions in river basins (with or without considerations related to climate change), e.g., efforts to support the implementation of a river-basin management plan according to the WFD. Fundamental to this application is the proposal of ‘what if’-type management questions meant to evoke possible outcomes in different scenarios. To give a typical and very real example related to the presented case study area, a discussion has recently begun amongst high-level politicians in the UDC regarding whether or not irrigation in the area can and should be extended (currently less than 1% of the cultivated area is irrigated). According to German law, any groundwater withdrawal requires permission, and therefore a political decision that involves many ecological, economic and social considerations. Unlike in other countries, this decision would be made in an attempt to avoid damages before they occur rather than to try to manage the extent of existing damages.

Transferability and use outside DANUBIA

The approach as it is presented here depends on the coupled simulation system DANUBIA and its implementation in the UDC. Despite this, it would be possible to adapt the presented concept for use in a different context and a different region without making any drastic modifications to it, though any application would necessitate the availability of spatially and temporally distributed state variables. Interpolated data derived from past measurements could be used for an assessment of the current state or to describe past developments, but because the intended application is the evaluation of possible future scenarios, models for the simulation of state variables should be available as well. In many cases, it may be possible to do without one or two of the state variables used here, or to use different ones. Also as mentioned earlier, it is not necessary to perform the required calculations in a fully coupled system such as DANUBIA. Calculations could in fact be done with a simple spreadsheet, though it should be noted that only a fully coupled system allows for the analysis of feedback and dependencies and the provision of the large number of output variables necessary for deeper insight into system behaviour. The entire DANUBIA system will be available under an Open Source license from October 2010.

Uncertainty

The uncertainty of predictions is a major issue in modeling and deserves careful attention, in particular with respect to long-term predictions of complex, non-linear, coupled systems (Bogardi and Kundzewicz 2002, Krysanova et al. 2007). In the context of the presented methodology, the following uncertainty-related issues should be considered:

1. Working on larger (regional) scales usually means accommodating a wider range of properties and conditions, requires coarser discretization and aggregation in models, and involves lower data availability than when working on more specific, local problems.
2. Problems related to error propagation, inconsistencies in model concepts and exchanges across model boundaries are inherent to integration and model coupling.
3. Global climate models and the emission scenarios underlying global climatic-change predictions are still highly uncertain, as evidenced by the huge differences in the assumptions and results presented in IPCC reports.
4. When viewed in the context of a global model, regional catchments cover only a few model cells. Disaggregation of (downscaling) global model results to describe regional conditions is a highly challenging and uncertain task, particularly in mountainous regions.
5. All models used in an integrated assessment come with inherent inaccuracies emerging from uncertainty in observed data and structural errors.

One could argue that the sum of the uncertainties resulting from the issues outlined in the preceding is so large that any prediction made on a regional scale is meaningless and any effort made based on these predictions is therefore useless. Most scientists, and hopefully practitioners and policy makers as well, will agree that this point of view is not particularly helpful with regard to managing the future of coming generations. Those not yet convinced may want to consider some thoughts presented by Voss (2005) in his editorial to a special issue of this journal entitled *The Future of Hydrology*:

Hydrogeology is far from being a typical quantitative science. There is rarely any proof of hydrogeological hypotheses. Each model and each prediction is a hypothesis and there are rarely true tests of these predictions...In other words, hydrogeologists (concerned with space and time scales larger than the immediate neighborhood of a production well) ‘believe’ that their approach is a meaningful and useful way to proceed, but cannot prove it objectively.

Regional, integrated modelling and assessment is still a relatively new field and only a few hydrogeologists have begun work in this context. The quality of investigations made on a regional scale cannot be measured using the same standards as those made on a local scale.

Within the presented approach, the reliability of regional-scale assessments and predictions is increased and uncertainty is reduced by:

- Looking at trends and differences in comparison with reference situations rather than evaluating simulated values on an absolute scale
- Comparing simulated scenario values to simulated values obtained using the same models in reference scenarios in order to get to a consistent description of deviations
- Aggregating to larger spatial and temporal units (zones, month) to reduce the influence of local, short-term heterogeneities

The most important means for the validation and improvement of any concept is of course discussion of the results with experts, i.e., a consideration of the opinions and experiences of water-supply company managers, local water authorities, and so forth.

Objectiveness

Models which simulate environmental processes are ideally based on measurable properties (e.g., hydraulic conductivity), but instead often exploit mere calibration parameters (values without any physical meaning used to achieve best fit). The presented approach relies to a large degree on parameters that lie somewhere in between (see Table 4): they are not measurable but are directly related to hydrogeological properties and cannot assume values outside a reasonably narrow range. On the other hand, these parameters cannot be determined through calibration as no measured results are available for comparison.

There are two ways to derive the aforementioned parameters:

1. Via analysis of observed system responses and known properties (semi-quantitatively)
2. Via soft data, e.g., the experiences of local experts

The first quantitative approach is often difficult to carry out as observed data are limited and properties are not well-enough known (attestation to the fact that hydrogeological systems often respond very differently than expected). The determination of parameters thus becomes a stepwise, iterative process. An initial estimate is made based on a semi-quantitative assessment. Next, the results of an assessment based on the initial assumptions are discussed with experts (when possible) and refined. A certain degree of subjectivity is, however, implicit. Again, the thoughts presented by Voss (2005) should be considered.

Summary and conclusions

The present article introduces an approach to assess the quantity of groundwater sources. It is designed for use on

a regional (large) scale and in an integrated context. Prime areas of application are in the evaluation of the impacts of climate change, and regional management. Potential users of the approach are higher-level administrations and interest groups. The European WFD and its goals formed major guidelines in the development of the presented approach, which was created based on an analysis of the requirements of and pre-existing strategies for regional-scale groundwater assessment. With respect to the latter, large deficits and the need for new strategies were identified. In particular, it was found that strategies which lead to a comparable and transferable assessment concept are missing. The appropriate delineation of groundwater bodies (here called zones) was identified as a crucial development aspect.

The approach developed in response to the identified deficits relies on the assumption that a set of various state variables can be used to assess a groundwater body's state. The influence of each state variable has to be weighted according to system characteristics, and the response time and buffer capacity of the system must also be accounted for. Local particularities and local characteristics of groundwater systems were implicitly considered.

The resulting methodology is a compromise between the following factors: the large diversity and heterogeneity inherent to regional-scale systems, the uneven spatial distribution of available data and general data scarcity, and the need to provide spatially and temporally explicit as well as reliable results to allow for meaningful regional management. The aggregation to results by zone keeps the number of individual assessment results reasonably small and balances the uncertainty in the underlying model results, which are calculated in much finer resolution.

The presented assessment approach relies on data, models and expert knowledge and is not intended as a substitute for these. Its objective is to aggregate, integrate and interpret existing information available from a variety of sources and in various forms to allow for sound assessment and to support management decisions. It is meant to make complex information more easily understandable in the local context. The reliability and usability of the approach rely on the quality of the available information. The approach is not applicable to 'un-gauged basins' i.e., in regions where data, models and expert knowledge are not available. It requires considerable human resources and is not meant to be applied on the local level.

The methodology has several disadvantages:

- The output flag values (indices of groundwater quantity) cannot be validated for all situations which are more extreme than those that have been observed in the past.
- Subjective categorizations have to be made when assigning model parameters.
- Uncertainty is high because the level of uncertainty implicit in regional-scale approaches, as well as uncertainty about future scenarios, is combined with a degree of uncertainty emerging from coupled (integrated) modelling.

The approach also offers significant advantages:

- Parameters used in the assessment (groundwater level, groundwater recharge, etc.) do not need to be very accurate on an absolute scale since only relative changes are evaluated.
- The assessment algorithm is straightforward, based on easy-to-understand, very simple mathematics, and relies on parameters with a comprehensible physical meaning.
- The assessment strategy is flexible and can easily be configured with respect to data availability, required data, and the desired spatial resolution of results.
- It provides output that can be used directly by users or inputted into other models. The results have proven well-suited for discussion with local experts and stakeholders.
- The flag concept, despite being relatively simple, goes far beyond water-balance estimates as they have traditionally been used in integrated regional assessment and management.

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