Potential Climate Change Impacts on the Groundwater Resources in the Upper Danube Watershed - a Scenario Case Study using the DANUBIA Decision Support System

[1]Roland BARTHEL, [2]Wolfram MAUSER, [2]Ulrich STRASSER, [3]Ralf LUDWIG, [4]Winfried WILLEMS, [5]Barbara FRUEH

[1]Institute of Hydraulic Engineering, Universitaet Stuttgart, Germany (roland.barthel@iws.uni-stuttgart.de),
[2]Faculty for Geosciences, Ludwig-Maximilians University (LMU), Luisenstr. 37, D-80333,
[3]Institute for Geography, University of Kiel, Germany,
[4]Institute for Applied Water Resources Management and Geoinformatics IAWG, Ottobrunn, Germany,
[5]Institute for Meteorology and Climate Research, University of Karlsruhe, Germany

Abstract: Within the GLOWA-Danube project the physically-based Global Change decision support system DANUBIA was developed with the aim to minimize external calibration and thereby maximize predictive capabilities. Among other modules, DANUBIA couples physically-based hydrological, hydraulic and groundwater flow models with a stochastic procedure to derive a long-term time series of synthetic future climate data from measured historical records. The stochastic climate generator was applied to the 77 000 km² Upper Danube catchment (Germany, Austria, Switzerland; gauge Passau). DANUBIA calculates the energy- and water balances as well as discharge, groundwater recharge and groundwater levels with a temporal resolution of 1d and a spatial resolution of 1 km. Results show that the increase of temperature and decrease of precipitation is accompanied by an increase of radiation and evapotranspiration and a corresponding decrease of groundwater recharge and stream flow.

Keywords: climate change, groundwater recharge, groundwater model, hydrological model, Danube river basin, DANUBIA

1. Introduction

To understand and predict the potential effects of climate change on water resources in general and in particular, on stream flow, groundwater discharge, groundwater levels and wetland ecology, it is necessary to be aware of the complexity of the interactions between climate, the land surface and the subsurface, and to consider the influence of the scale on which these interactions are investigated. In mountainous watersheds and their forelands, the hydrological situation is particularly complex because of lateral flows, which are of considerable importance. To be able to realistically simulate the impact of different scenarios of future climate change on the water cycle, physically-based hydrologic models with high predictive ability are necessary.

The objective of 'GLOWA-Danube', which began in 2001 and is now in its third phase lasting until 2010, is the investigation of the sustainability of future water resources management alternatives, using integrative techniques and strategies for identifying and quantifying regional effects of Global Environmental Change coupled with human activities (water and land use) on the water cycle (see Mauser and Strasser, 2005; Ludwig et al., 2003, Barthel et al., 2005, Barthel et al., 2007). For that purpose the physically-based Global Change decision support system DANUBIA was developed. DANUBIA comprises a total of 16 precisely defined disciplinary models from the fields of meteorology, hydrology, remote sensing, groundwater and hydrogeology, plant ecology, and glaciology and so-called '*Actor*' models cover economy, agricultural economy, tourism, environmental psychology, and water supply. A primary scope of DANUBIA is to evaluate consequences of IPCC derived climate scenarios (IPCC, 2001) for the coming 100 years.

DANUBIA has been applied to the Upper Danube catchment (Figure 1; 77 000 km^2 until the gauge at Passau) in which groundwater is the main source of drinking water (with a share of roughly 90 percent) and contributes more than 50% to industrial water use. Groundwater discharge is also the main source of river discharge in dry summer periods – which, according to recent IPCC predictions, will become even longer and dryer in the near future.

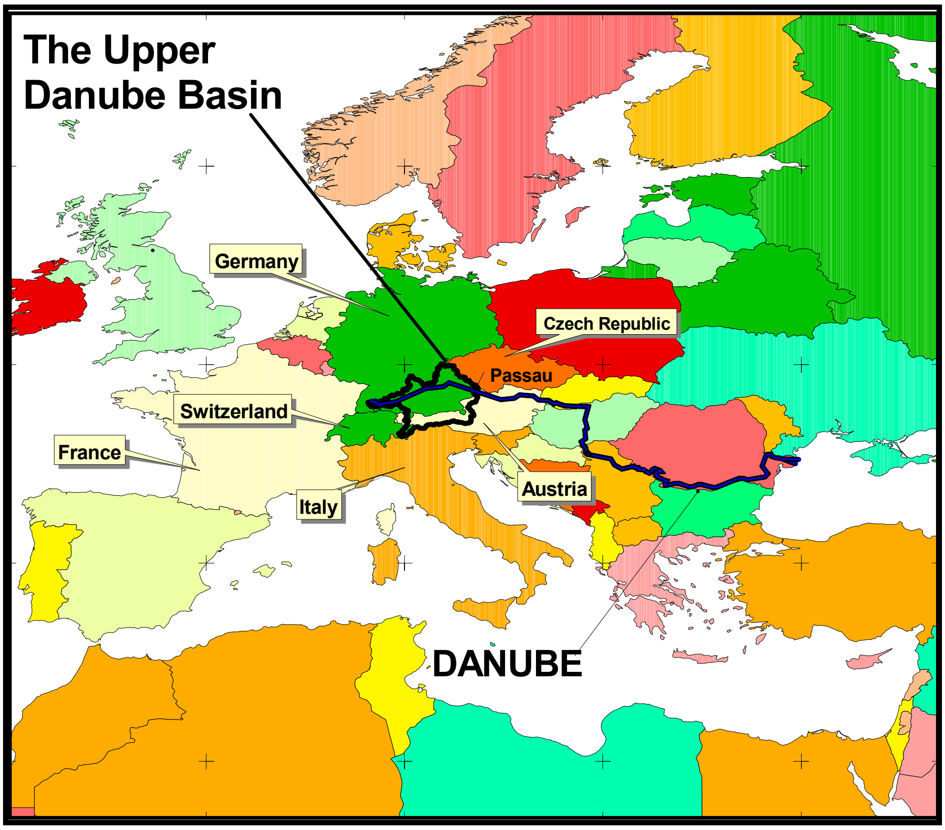

Figure 1: Location of the Upper Danube Basin

In this article section 2 describes the methodology used in DANUBIA to deal with the hydrological processes in some more detail. Section 3 introduces briefly the approach to generate the climate scenarios which were used to create the results that are presented in section 4. Section 5 summarizes the main conclusions of the study. This article is meant to be a short overview which of course cannot address all aspects and issues of a large-scale multi-disciplinary research project.

2. Investigation approach to assess the impacts of Climate change on the groundwater resources

The overall scope of GLOWA-Danube is rather broad, covering many socio-economic and natural science aspects. This article however, focuses on the application of DANUBIA to evaluate the impacts of Climate Change on the *groundwater system*. The socio-economic influences which are also included in DANUBIA (see Janisch et al.[1], Barthel et al.[2]) are not considered here. Therefore the description of the DANUBIA approach is limited here to the 'hydrological complex' within DANUBIA which comprises a hydrological, a hydraulic and a groundwater flow model (see Table 1, Figure 2).

The general approach to simulate the impact of climate change on the groundwater resources is shown schematically (i.e. without showing the full range of exchange parameters and temporal dependencies – for that purpose refer to Mauser and Strasser, 2005) in Figure 2. The 'atmosphere' component is responsible for the generation of the climate scenarios. Two options exist in DANUBIA: 1) the model-based downscaling of Global Climate Model (GCM) output using MM5 (see Früh et al., 2006) and a stochastic approach to generate climate scenarios based on measured data. In this paper only the results from the second approach are used and described (see section 0).

The downscaled (1 x1 km grids) output of the *Atmosphere* component are then used by the *LandSurface* component which is responsible for the simulation of all processes at or near the land surface. The most important outputs in the context of the present paper are groundwater recharge, direct runoff and interflow. Groundwater recharge is provided to the groundwater flow model, the

[1] submitted to Environmental Modelling and Software, November 2006, currently under revision
[2] submitted to Water Resources Management, August 2006, currently under review

runoff to the hydraulic surface water model. The hydrological cycle is conceptually closed by the exchange of baseflow (In- and Exfiltration) groundwater level and river level between the groundwater, the hydraulic, and the hydrological model (Figure 2).

Table 1: DANUBIA-Models to describe the hydrological complex

Compartment	DANUBIA Component*	DANUBIA Model	Type	Based on
Unsaturated zone [1,2]	*LandSurface*	*Soil*	physically-based, spatially distributed hydrological SVAT scheme (soil vegetation atmosphere transfer model); Richards Equation	PROMET (Mauser, 1989)
Surface Waters [3]	*RiverNetwork*	*RiverNetwork*	physically-based; Saint-Venant-Equations	DAFLOW (Jobson, 1989)
Groundwater	*Groundwater*	*GroundwaterFlow*	physically-based numerical, FD Boussinesq-Equation:	MODFLOW (McDonald and Harbaugh (1988)

* 16 DANUBIA models are grouped in the 5 main components: *Atmosphere-LandSurface-Groundwater-RiverNework-Actors*

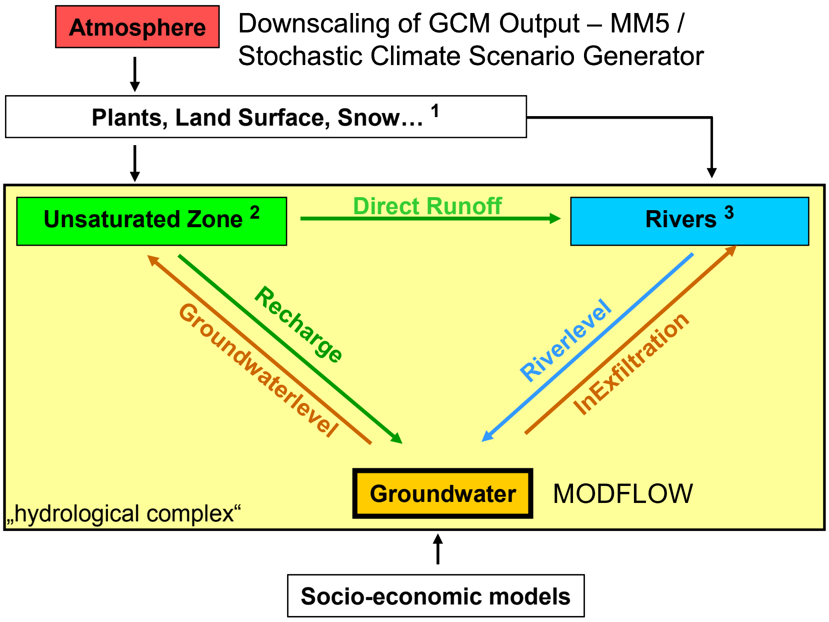

Figure 2: Generalized coupling scheme of DANUBIA, hydrological models. For an explanation of the superscripts used see Table 1.

3. Stochastic generation of climate scenarios

Climate scenarios in DANUBIA are based on a stochastic procedure to derive long time series of synthetic future climate data from measured historical records. The stochastic procedure is used to create more likely realisations of future climate scenarios than regional climate models can provide for mountainous regions at reasonable computational costs. To compile a future meteorological data set spanning over the next 100 years, the procedure considers measured relations between temperature and rainfall, applies a random variation of temperature, overlays the trend, and selects the appropriate time slice from the given basic population of measurements (30 years of DWD (German Weather Service) recordings). In our case study, a scenario following the general trends of an IPCC B2-type scenario predicts a temperature increase of 2.7 K for the Upper Danube watershed until 2100. It has to be noted that the methodology introduced in Figure 3 has some disadvantages: reduced representation of auto-correlation, changes in extreme values are not considered and an increase of the relative error of determination when approaching the edges of distributions. But for the present purpose, the advantages clearly dominate: Immediate applicability; physical consistency of meteorological input data; meteorological model inputs within a validated range; methodological consistency for ensemble simulations; validation versus baseline scenarios possible; consistent spatial resolution of input data.

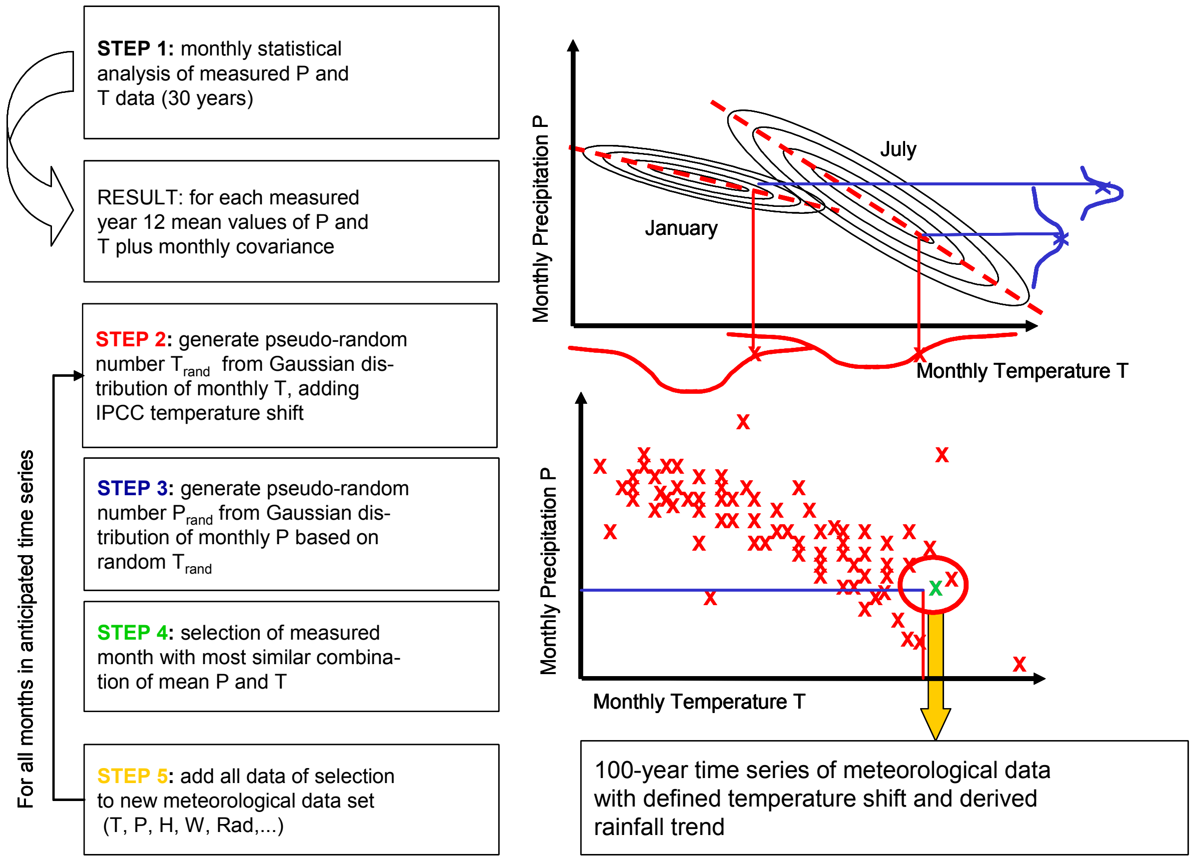

Figure 3: Flowchart and principle description of the stochastic climate generator used to generate the driving scenario for the results presented in this section.

4. Results

Results from DANUBIA scenario simulations are many and multifaceted. A full scale discussion of DANUBIA results, which would also require a more detailed description of the natural and socio-economic characteristics of the Upper Danube catchment, is not possible here. In this article the following results are presented:

a) The results of climate scenario generation using the stochastic climate generator,
b) the impacts of the generated climate scenario on river discharges,
c) the impacts of the generated climate scenario on groundwater recharge and groundwater levels.

It should be noted that only average values for the whole basin which to a certain degree disguise the local extremes are shown here.

4.1 Regional Climate Scenarios

The stochastic climate generator was applied to the Upper Danube catchment. Figure 4 shows the resulting temperature and the correlated snow precipitation, which is a very important variable for the water balance in the mountainous Upper Danube catchment area. Figure 4 shows the trends of summer and winter precipitation. Together with the general trend of rising temperature, the tendency towards dryer summers and warmer winters is the main characteristic of this scenario. The scenario, even if compiled using a relatively simple and limited methodology, is in accordance with regional climate scenarios that were established using much more sophisticated approaches to downscale output from GCM.

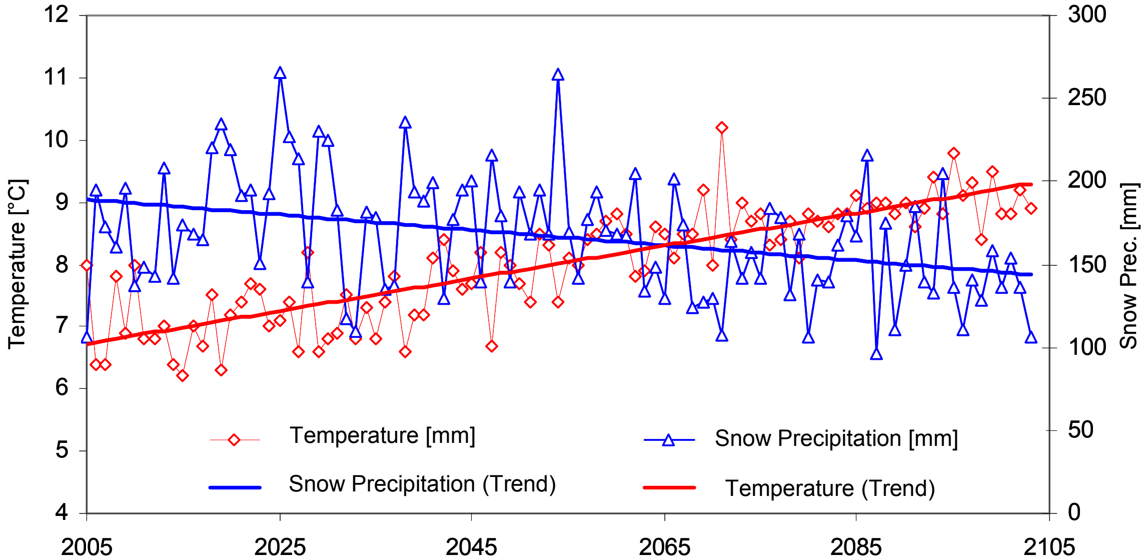

Figure 4: Change in Temperature and Snow Precipitation 2005 – 2104 in the Upper Danube catchment according to the generated scenario

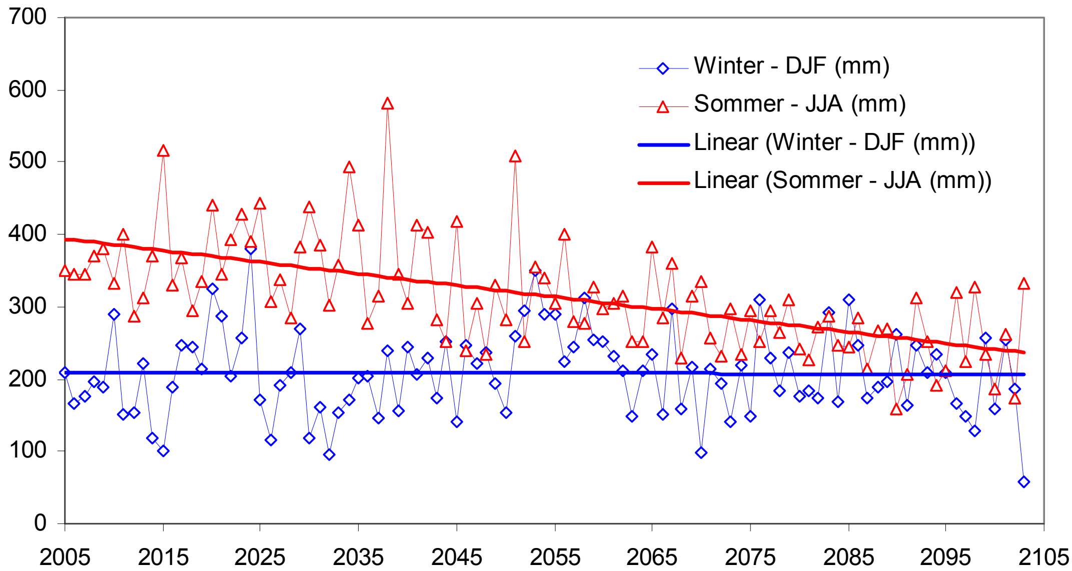

Figure 5: Change in Summer- (JJA – June, July, August) and Winter Precipitation (DJF- December, January, February) 2005 – 2104 in the Upper Danube catchment according to the generated scenario

4.2 Climate Impacts on River Discharges

Based on the output of the stochastic climate generator, DANUBIA was used to calculate discharges with a temporal resolution of 1 d and a spatial resolution of 1 km. Results show that the increase of temperature and decrease of precipitation is accompanied by an increase of radiation and evapotranspiration and a corresponding decrease of groundwater recharge and stream flow. With respect to groundwater resources, low flows in rivers are most significant, as in dry periods a large portion of the river discharge comes from groundwater discharge (baseflow). The lowest average discharge within a 7 day interval (NM7Q) was statistically analyzed for its change in return period during the 100 years for selected tributaries. The analysis shows that serious decreases in discharge lead to a vast change in return period for given minimum discharges (Figure 6).

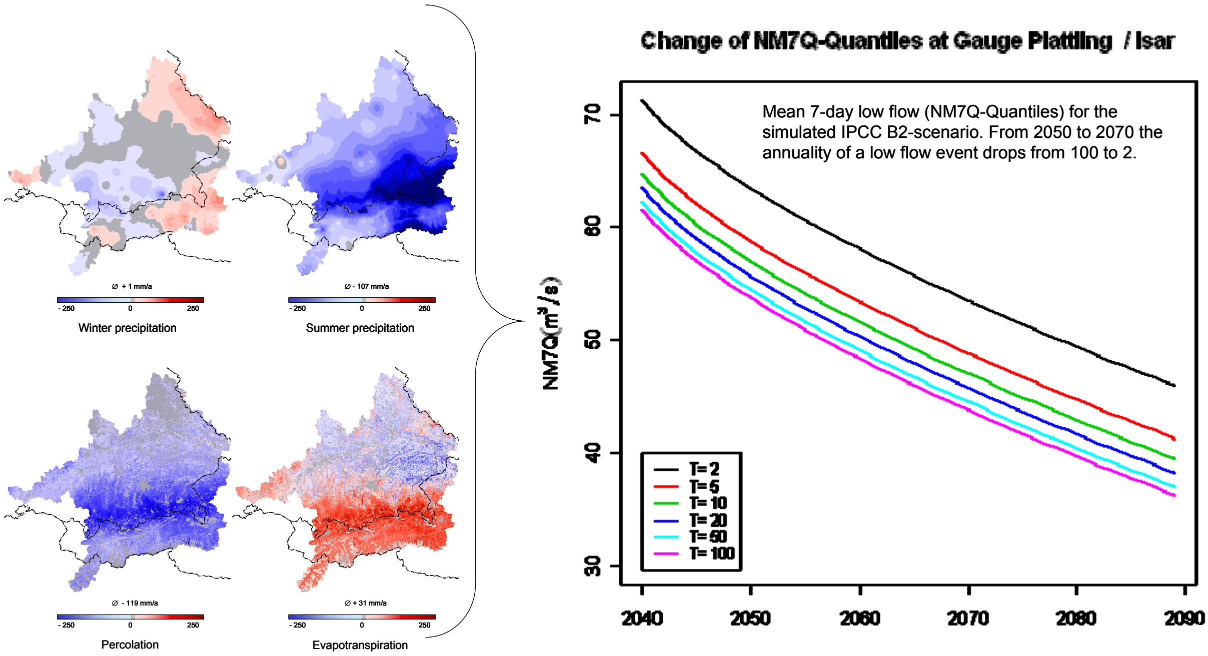

Figure 6: NM7Q-Quantiles at Plattling for different recurrence periods

4.3 Climate Impacts on Groundwater Resources

As shown until here, under conditions of a realistic climate scenario an increase of temperature and a shifting of seasonal patterns of precipitation can be expected. This of course has an influence on groundwater recharge, which is largely controlled by evapotranspiration and surface runoff. Averaged over long periods, groundwater recharge determines how much water is available for withdrawal, but also if the persistence of ecologically important environmental systems such as wetlands can be guaranteed. Lastly, it determines how much groundwater is available for discharge during dry periods. As shown before, low flow situations, which can have severe ecological and economical consequences, might become more frequent and more severe in the future. Figure 7 shows for the Isar sub-catchment of the Upper Danube Basin that recharge, under conditions of the climate scenario applied, will decrease significantly over the next 100 years.

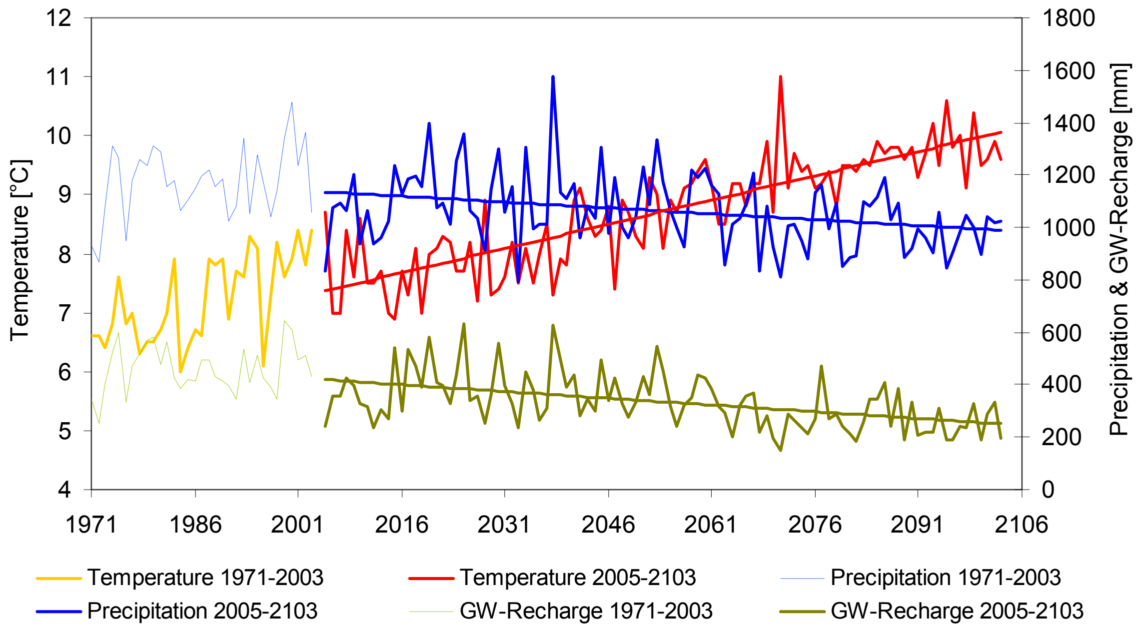

Figure 7: Temperature, Precipitation and Groundwater Recharge during the validation period (1971-2003) and the simulation period (2005-2103) for gauge Plattling (Isar sub catchment: 8435 km^2).

Figure 8 finally shows transient coupled results from the hydrological model (groundwater recharge) and the groundwater flow model (groundwater models). Here three different scenarios are compared. The scenarios are described in more detail in Table 2).

Table 2: Climate scenarios used to calculate the results presented in Figure 8

Scenario name	Description	Comment
Business as usual	IPCC B2 type scenario generated as described in section 3 and 4.1	Only the first 33 years are shown
Optimistic	Observed data from 1970 to 2003 were used	Used for model validation; optimistic in the sense that all predictions are warmer than the conditions in this period
Pessimistic	An extremely dry "scenario" generated by simply combining the hottest and driest years from the 1970 to 2003 period	Rather unrealistic and not in accordance with IPCC!

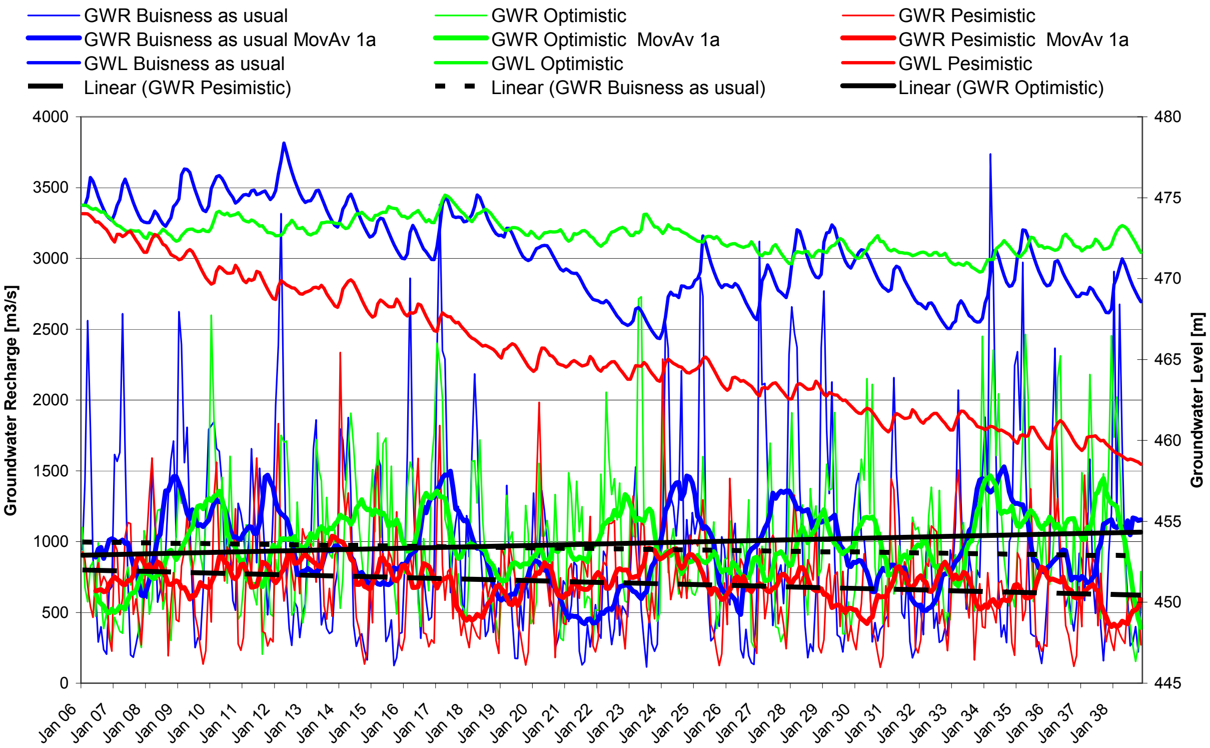

Figure 8: Transient model results – scenario simulations: Mean monthly groundwater recharge (GWR) and groundwater levels (GWL) values averaged over the entire Upper Danube catchment for 3 different climate scenarios (Table 2); linear trends and moving averages (central) are shown for GWR.

4. Conclusions

Based on the output of a stochastic climate generator, DANUBIA was used to calculate the energy- and water balances as well as discharges with a temporal resolution of 1 d and a spatial resolution of 1 x 1 km. Results for a relatively moderate IPCC-B2-type scenario (temperature increase 2.7 K / 100 a) show that the increase of temperature and decrease of precipitation are accompanied by an increase of global radiation and evapotranspiration and a corresponding decrease of groundwater recharge and stream flow. Most important are the massive changes in dynamics and pattern of water balance terms for the Upper Danube. The present article focuses mainly on the simulated changes of the groundwater system with respect to drinking water supply and ecological aspects (low flow – droughts, wetland depletion). Even if the stochastic climate generator has some obvious deficiencies as a tool for creating regional climatic scenario input and the DANUBIA system still needs improvement, results indicate that climate change will probably not be an immediate threat to the groundwater based water supply system of the Upper Danube catchment within the next 25 years– since it is a water rich region – even under relatively extreme conditions. More alarming seems to be the increasing number and severity of low flow situations that was determined in the scenario simulations. According to the hydrological simulation, the changing climatic conditions of the IPCC B2 type scenario may lead to slightly less groundwater recharge and, as a consequence, to declining groundwater levels. However, the changes show a strong spatial pattern and temporal variability, partly because of the regional and seasonal climate change patterns and partly because of the different hydrological and hydrogeological conditions. Such assessment and understanding of the variability and dynamics of groundwater resources is crucial for their sustainable management under future changing conditions.

Acknowledgements: GLOWA-Danube is funded by the BMBF (German Federal Ministry of Education and Research). We would like to thank all governmental organisations, private companies and others who supported our work by providing data, models, advice or additional funding. We would like to thank our colleagues from the partner projects within GLOWA-Danube for the cooperation throughout the last six years.

References

Barthel R, Janisch S, Nickel D, Trifkovic A (submitted for publication) Using the Multiactor-Approach in GLOWA-Danube to Simulate Decisions for the Water Supply Sector under Conditions of Global Climate Change. – Water Resources Management

Barthel R, Mauser W, Braun J 2007. Integrated modelling of global change effects on the water cycle in the upper Danube catchment (Germany) - the groundwater management perspective. IN: J J Carillo & M A Ortega (Editors) Groundwater flow understanding from local to regional scale, International Association of Hydrogeologists, Selected Papers on Hydrogeology, Vol 12, pp47-72.

Barthel R, Rojanschi V, Wolf J, Braun J (2005) Large-scale water resources management within the framework of GLOWA-Danube. Part A: The groundwater model. - Physics and Chemistry of the Earth, 30, 6-7: 372-382

Früh B, Schipper J W, Pfeiffer A, Wirth V, (2006) A pragmatic approach for downscaling precipitation in alpine scale complex terrain. Accepted by Meteorol. Z.

IPCC (2001) Climate Change 2001: Synthesis Report.

Janisch S, Barthel R, Schwarz N, Trifkovic A, Schulz C, Nickel D, Mauser W (submitted for publication) A framework for the simulation of human response to global change. Environmental Modelling and Software

Jobson, H. E. (1989): Users manual for an open-channel stream flow model based on the dif-fusion analogy: U.S. Geological Survey Water-Resources Investigations 89-4133, 73 p.

Ludwig R, Mauser W, Niemeyer S, Colgan A, Stolz R, Escher-Vetter H, Kuhn M, Reichstein M, Tenhunen J, Kraus A, Ludwig M, Barth M, Hennicker R (2003) Web-based modelling of energy, water and matter fluxes to support decision making in mesoscale catchments – the integrative perspective of GLOWA-Danube, Phys. and Chem. of the Earth 28: 621-634

Mauser W, Strasser U (2005) Statusreport GLOWA-Danube Integrative Techniques, Szenarios and Strategies Regarding Global Change of the Water Cycle. - http://www.glowa-danube.de/PDF/reports/statusreport_phase2.pdf

Mauser W, (1989) Die Verwendung hochauflösender Satellitendaten in einem Geographischen Informationssystem zur Modellierung von Flächenverdunstung und Bodenfeuchte, Habiliationsschrift, Albert-Ludwigs-Universität, Freiburg i. Br.

McDonald M G, Harbaugh A W (1988) A modular three-dimensional finite-difference ground-water flow model. Technical report, U.S. Geol. Survey, Reston, VA. USA.