

Area differentiated analysis of impacts of climate change scenarios on groundwater resources in Northwestern Germany

Frank Wendland¹, Ralf Kunkel¹, Imke Lingemann¹, Björn Tetzlaff¹, Richard Knoche²
Harald Kunstmann²

1: Research Centre Jülich, Institute for Chemistry and Dynamics of the Geosphere (ICG-4), D-52425 Jülich, Germany

2: Institute for Meteorology and Climate Research, IMK-IFU Forschungszentrum Karlsruhe Kreuzackbahnstrasse 19, D-82467 Garmisch-Partenkirchen, Germany

Regional climate change scenarios were studied with the water balance model GROWA (Kunkel and Wendland, 2002) to predict the temporal development of mean long – term total runoff, direct runoff and groundwater runoff, including regionally differentiated analyses for river basins, regions and administrative units. Special emphasizes was given to the regionally differentiated prediction of the mean long-term impacts on groundwater recharge, which determines both, the river discharge and ecological status of rivers during dry periods, as well as the upper limit for the sustainable abstraction of groundwater (e.g. prognosis of groundwater hydrograph trends in regions, where water supply is fed from groundwater). As a reference, the GROWA model was calibrated and validated for the hydrological period 1971 – 2000 in an area of ca. 90.000 km² in the North – Western part of Germany, i.e. for the entire Federal States of North Rhine - Westphalia, Lower Saxony, Hamburg and Bremen.

1. Introduction

Groundwater plays an important role for the drinking water supply in Germany. According to Genesis – online (2005), in 2001 ca. 85% of the drinking water demand in the Federal States of North – Rhine Westphalia and Lower Saxony were fed from groundwater resources (including sources and bank filtrate). For this reason, the regional groundwater availability belongs to the key issues of the federal water resources management policy. Groundwater availability depends decisively on percolation water infiltrating the aquifer (groundwater recharge).

The regional groundwater recharge rate represents the framework for granting concessions of groundwater withdrawal rights to public water suppliers and for the required status reviews of the groundwater bodies according to the EU Water Framework Directive (EU, 2000). It is also essential for the discharge of rivers and the maintenance of wetlands at low flow conditions in dry periods.

Groundwater recharge can be determined by a number of methods. Their type and applicability depend on the availability of model input data, the purpose of the investigation and the catchment size. Locally groundwater recharge rates can be meas-

ured by means of lysimeters (e.g. Schröder, 1983). Especially for detailed runoff analyses in individual small catchment areas precipitation – runoff models like NA-SIM (Mittelstädt, 2005), WASIM – ETH (Schulla & Jasper, 1999), ArcEGMO (Becker et al, 2002), WASMOD (Reiche, 1994) have been developed. As integrative values for sub-basins groundwater recharge can be determined by evaluating runoff records observed at gauging stations, e.g. according to the methodologies of Wundt (1958) and Kille (1970).

For assessing long-term groundwater recharge rates in large catchment areas or regions empirical models turned out to be sufficient (e.g. Dörhöfer & Josopait, 1981; Renger & Wessolek, 1996; Meinardi, 1994; Kunkel & Wendland, 1998; DeWit et al., 1999). These models allow a determination of the long-term water balance as a function of the interaction between the actual land cover and climatically, pedagogical, topographical and hydro geological conditions with reasonable accuracy. The GROWA model (Kunkel & Wendland, 2002) belongs to this type of models. In the last years GROWA has been applied for area-covering calculations of natural long-term groundwater availability in the Federal States of Bremen, Hamburg, North-Rhine-Westphalia and Lower-Saxony (Kunkel et al., 2006; Bogena et al., 2003; Tetzlaff et al., 2004; Wendland et al., 2003). In the Environmental Agencies and Geological Surveys of these Federal States, GROWA model results were used for practical water resources management related issues, e.g. the grants of water withdrawal rights to public water suppliers and for the required status reviews of the groundwater bodies according to the EU Water Framework Directive.

In this contribution the impacts of regional climate change (derived by dynamical downscaling of the global climate scenario B2 of ECHAM4 with MM5) on the regional water balance in the Federal States of North Rhine – Westphalia, Lower Saxony, Hamburg and Bremen will be analysed. Special emphasizes will be given to the prediction of the mean long-term impacts on groundwater recharge, which determines both the river discharge and ecological status of rivers during dry periods and the upper limit for the sustainable abstraction of groundwater (e.g. prognosis of groundwater hydrograph trends in regions, where water supply is fed from groundwater).

The calibrated and validated model results for the hydrological period 1961 – 1989 will be the reference for the assessment of the impacts of climate change. Results of the MM5 regional climate model (e.g. Grell et al., 1994) for the time period 2071 – 2099 will be used in the GROWA model in order to predict the long-term trend of groundwater recharge in the four Federal States, including regionally differentiated analyses for river basins, regions and administrative units.

2. Climate model

For receiving regional information out of Global Climate Models (GCMs), it is necessary to improve the spatial resolution. Therefore, the meteorological mesoscale Model MM5 is nested in the GCM ECHAM4 (Roeckner et al., 1996). MM5 is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation (e.g. Grell et al., 1994). The development of MM5 started in the 1960's at Penn State University (USA) and has been improved by the National Center for Atmospheric Research (NCAR). In this application, MM5 is applied in a horizontal resolution of 19.2 km. The vertical dimension is divided in 27 layers. The time step is ~70 seconds (Keuler et al., DEKLIM, 2006).

The scenario used in this study follows the SRES emission-scenario of the B2-family. The B2 scenarios are characterized by continuously increasing population, but at a slower rate than in A2, emphasis on local rather than global solutions to economic, social and environmental stability, intermediate levels of economic development, less rapid and more fragmented technological change than in B1 and A1. (SRES,2007)

3. Water balance model GROWA

The GROWA model represents an empirical procedure with a minimal temporal resolution of one year. In a first step mean long – term evapotranspiration rates are determined according to Renger & Wessolek (1996), who used extensive lysimeter data to derive linear relationships between evapotranspiration rates and different land use types and climatic as well as soil physical site conditions for plain, rural areas at some distance from the groundwater table. For a general, i.e. area-wide, application several extensions were developed and implemented to calculate the real evapotranspiration in hilly (Golf, 1981) or urban areas (Wessolek & Facklam, 1997) as well as for regions close to the groundwater table (ATV, 2004). In a second step total runoff levels are calculated as the difference between precipitation and real evapotranspiration:

$$Q_{ges}(\ell) = P_{So} + P_{Wi} - h_{relief} \left[a_{\ell} \cdot P_{Wi} + b_{\ell} \cdot P_{So} + c_{\ell} \cdot \log(W_{pfl}) + d_{\ell} \cdot ET_{pot} + e_{\ell} \cdot D_p + f_{\ell} \right] \quad \text{Gl. 1}$$

mit:	$Q_{ges}(\ell)$	mean annual total runoff for soil covet type ℓ	(mm/a)
	h_{relief}	correction factor for consideration of relief areas	
	P_{So}	precipitation level in hydrologic summer period	(mm/a)
	P_{Wi}	precipitation level in hydrologic winter period	(mm/a)
	W_{pfl}	plant available soil water (mm)	
	ET_{pot}	mean annual potential evapotranspiration	(mm/a)
	D_p	degree of sealing	
	$a_{\ell}, \dots, f_{\ell}$	coefficients depending on soil cover	

In a subsequent step total runoff is separated into the runoff components “direct runoff” and “base flow”. Whereas *direct runoff* designates the sum of the fast runoff components *surface runoff*, *interflow* and *drainage runoff*, base flow is equal to the runoff components, which reach the surface waters via groundwater runoff. In case longer time periods are considered groundwater runoff can be regarded as more or less constant, so that there is a balance between the water percolating into the aquifer from the soils (groundwater recharge) and the groundwater discharging into the receiving waters. Thus, mean long – term groundwater discharge into rivers corresponds to the observable low flow in rivers (MNQ) and hence the mean long – term groundwater recharge.

A mean base runoff fraction $r_{b,ber}$ was calculated for a total of 205 gauged subcatchment areas located in the Federal States of Lower Saxony and North Rhine – Westphalia. Following Wundt (1958) it was assumed that the base flow conditions and hence the groundwater recharge is represented best by the monthly low water runoff flow (MoLWR) for unconsolidated rock areas. For consolidated rock areas rich in precipitation it was observed by Kille (1970) already that the monthly low flow runoff may contain direct runoff fractions, especially during the winter season, so that

groundwater recharge is over-estimated. Therefore an approach is used, which allows the separation of the direct runoff fractions in the monthly low flow runoff (Bogena et al., 2005).

In this approach the groundwater recharge accounts for the average monthly low flow runoff beneath the linear zone of the distribution curve of all monthly low water runoff values observed. Within a subcatchment, mean long – term groundwater recharge can be expressed site specific (area – differentiated) by a fixed runoff ratio (groundwater runoff / total runoff) and depends on the interplay of groundwater runoff relevant site conditions in the catchment. Therefore characteristic runoff ratios are allocated to geofactors (degree of sealing, artificial drainage, hydraulic conductivity of solid rocks, depth of groundwater, perching water and slope). By summation from the product of the relative area ratio a_i of a certain area property and the respective base runoff fraction $r_{b,i}$ the site specific groundwater recharge can be determined:

$$r_{b,ber} = \sum_{i=1}^n r_{b,i} \cdot a_i$$

The sum covered all 19 different site features, e.g. in the unconsolidated rock areas the categories of groundwater and perching water as well as the hill slope. In the next step, the base runoff fractions were varied so that the sum of the quadratic deviations between the calculated and the base runoff fractions measured in the individual subregions for all 205 subcatchment areas considered took on the smallest value (min):

$$\sum_{j=1}^n (r_{b,gem,j} - r_{b,ber,j})^2 = Min$$

In this way a set of fixed r_b – values has been derived. It can be assumed that these values reflect the observed low flow situation in the subcatchments most suitable (see Kunkel & Wendland, 2002).

4. Data base

Digital data bases for GROWA modelling were provided by the Geological Surveys of Lower Saxony and Northrhine-Westfalia and the Environmental Agency of Hamburg. As all these data bases (see table xx) were available area – covering for the Federal States with a similar spatial resolution and with similar information contents, a consistent calculation of the water balance was possible.

The input data were in parts available in vector format, in parts as grids with varying grid sizes. Previous to the modelling data were transformed to grids of 50m x 50m. The processing and representation of data was carried out by means of the GIS Arc-Gis Desktop.

Tab. 1: *input data for water balance model GROWA.*

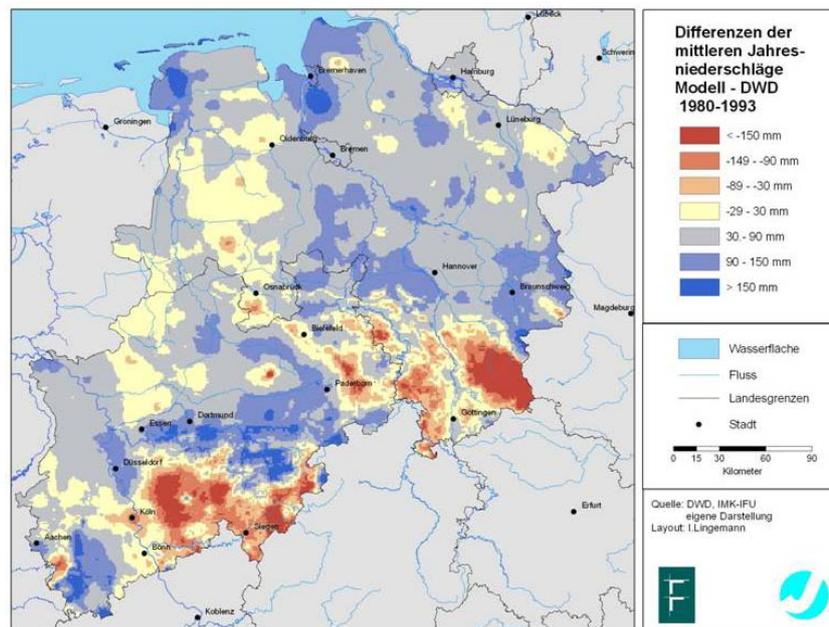
Themengebiet	Datengrundlage	Datentyp	Quelle
Grunddaten	Verwaltungsgrenzen Fließgewässer, Seen	Vektor	ATKIS-DLM 25 (LGN) DLM 1000 (BKG) Hydrographische Karte (NLÖ) Stadtkarte HH
Klima	Sommerniederschlag Winterniederschlag Potenzielle Verdunstung nach Wendling	Raster	Deutscher Wetterdienst
Boden	effektive Durchwurzelungs- tiefe nutzbare Feldkapazität kapillare Aufstiegshöhe Flurabstand Staunässegrad	Vektor	BK50 (GD NRW) BÜK 50 (NLFb) Bodenökologische Konzeptkarte (HH)
Landnutzung	Bodenbedeckungskategorien	Vektor	CORINE Land Cover (Stat. Bundesamt) Biotopkartierung (BUG HH)
Hydrogeologie	Durchlässigkeitsklassen	Vektor	HK100 (GD NRW) HK 200 (NLFb) GK Hamburg (GLA HH)
Topografie	Hangneigung Hangexposition	Raster	DGM25 (Landesvermessungsamt NRW) ATKIS DGM 50 (LGN) Höhenlinienkarte 1:20.000 (Baubehör- de HH)
Validierung	Einzugsgebietsgrenzen	Vektor	Landesumweltamt NRW Hydrographische Karte 1:50.000 (NLÖ)
	Tagesmittel der Abflüsse	Punkt	Landesämter, Wasserverbände Abflussdaten des NLÖ, DGJ 1990 Weser- u. Emsgebiet (NLÖ)

5. Processing and comparing of precipitation data

Climate data (precipitation values, potential evapotranspiration values) was available from different sources. For the time period 1961 – 1990 climate data was available for the monitoring stations of the German Meteorological Survey (DWD) as daily values for the individual monitoring stations. These values were already used by Kunkel et al. (2006) to calibrate the GROWA model and to calculate the actual mean long – term groundwater recharge level (1961 – 1990). In addition, MM5 regional climate modelling results from dynamically downscaled ERA15 global reanalysis fields were available in daily time steps for the period 1980 – 1993 in a spatial resolution of 19,2 km x 19,2 km.

In order to check the differences between the DWD data set and the MM5 data set, a comparison of precipitation data for the period 1980 – 1993 was carried out, i.e. for a period, for which data from both data sources was available. With the example of the mean precipitation values 1980 – 1993, figure 1 shows considerable differences amongst the two data sets.

Fig. 1: Comparison of the mean precipitation values 1980 – 1993 for the DWD data set and the MM 5 data set



Especially in the high altitude areas of the low mountain ranges in the southern part of the study area, the mean precipitation values 1980 – 1993 measured by the DWD data set are up to more than 150 mm/a higher than the values given by MM5 for the same period. In the lee of the low mountain ranges and the regions near the coastline however the difference is the other way round: the precipitation values of the DWD data set are up to more than 150 mm/a below the values given by the MM5 derived data set.

The different spatial resolutions between the DWD – data set (250 m) and the MM5 data set (19,2 km) and along with these the different representations of topographic effects have been identified as the main reasons for these systematic differences.

It can be expected that the conclusions with regard to the long-term development of groundwater recharge rates from 1961 – 1989 to 2071 – 2099 will differ significantly. In case of the MM5 climate data, 2071 - 2099 is compared to the groundwater recharge rate modelled based on the DWD data set and the MM5 data set (control run) as a reference.

The following example illustrates this problem. In the DWD data set the precipitation level in the Harz mountains is on average about 1000 mm/a for the period 1980 - 1993. In the MM5 data set the precipitation level for the time period 1980 – 1993 amounts to ca. 800 mm/a only.

- First case: groundwater recharge rates modelled based on the MM 5 precipitation values 1980 – 1993 (ca. 800 mm/a) in the Harz mountains are used as a reference data set. Its comparison to the groundwater recharge rates modelled with the MM5 precipitation values 2071 – 2099 (ca. 850 mm/a) would suggest a slight increase of groundwater recharge in the Harz mountains.
- Second case: groundwater recharge rates modelled based on the DWD precipitation values 1980 – 1993 (ca. 1000 mm/a) in the Harz mountains are used as a reference data set. Its comparison to the groundwater recharge rates

modelled based on the MM5 precipitation values 2071 – 2099 (ca. 850 mm/a) would suggest a decline of groundwater recharge in the Harz mountains.

Consequently, the systematic differences in regional precipitation patterns will influence the modelled groundwater recharge rates presented in section xx and hence the conclusions with regard to the probable consequences for a sustainable groundwater resources management.

Thus, in order to predict the influence of climate change on groundwater recharge, the systematic differences between the DWD data set and the MM5 data set have to be balanced. The disaggregation of the MM5 data to the 250 m grids by means of a statistical downscaling (e.g. Bürger & Chen, 2005; Matulla et al., 2002) is the most recommended way to do this. However, due to the complexity of this task and the limited time frame of this study this has not been carried out here.

Instead, the systematic difference between the DWD and MM5 data sets have been overcome is has been done in two pragmatic steps. In a first step the differences between the MM5 periods 1961 – 1989 and 2071 – 2099 have been determined, assuming that these differences reflect the climate change. In a second step, the net difference between the MM5 data sets has been added up to the values given by the DWD data set 1961 – 1989. In this way the probable impact of climate change - expressed by the difference in the precipitation values of the MM5 periods- on groundwater recharge is related to groundwater recharge levels, which have been assessed using observed precipitation values given by the DWD data set as input:

$$P_{CC} = P_{DWD_{1961-1989}} + (P_{MM5_{2071-2099}} - P_{MM5_{1961-1989}})$$

Leaving all other model input parameters (table 1) unchanged, the net difference within the data sets from the MM5 is used to predict the impacts of climate change scenarios on groundwater resources in North-western Germany.

6. Results

6.1 Groundwater recharge rates for the hydrologic reference period 1961 – 1990

Figure xx shows the mean long-term groundwater recharge rates modelled for the hydrologic reference period 1961 -1990 following Kunkel et al. (2006).

As can be seen the calculated groundwater recharge rates range in both cases from less than 25 mm/a to more than 300 mm/a. This reflects the diversity of climatic, pedological and geological conditions. In plain unconsolidated rock areas of at some distance from the water table in the North German Plain and the Lower Rhine Embayment , the groundwater recharge generally amounts to more than 150 mm/a.

In unconsolidated rock areas influenced by the groundwater and water logging (e.g. in flood lands) the groundwater recharge is less than 50 mm/a. The major runoff fraction (more than 80 %) is discharged in the form of direct runoff and reaches the receiving waters via the soil surface or as drainage runoff. The same is true of areas on Palaeozoic and crystalline rocks where, although the base flow can amount to 150 mm/a and more, the groundwater recharge contributes less than 30 % to the total runoff.

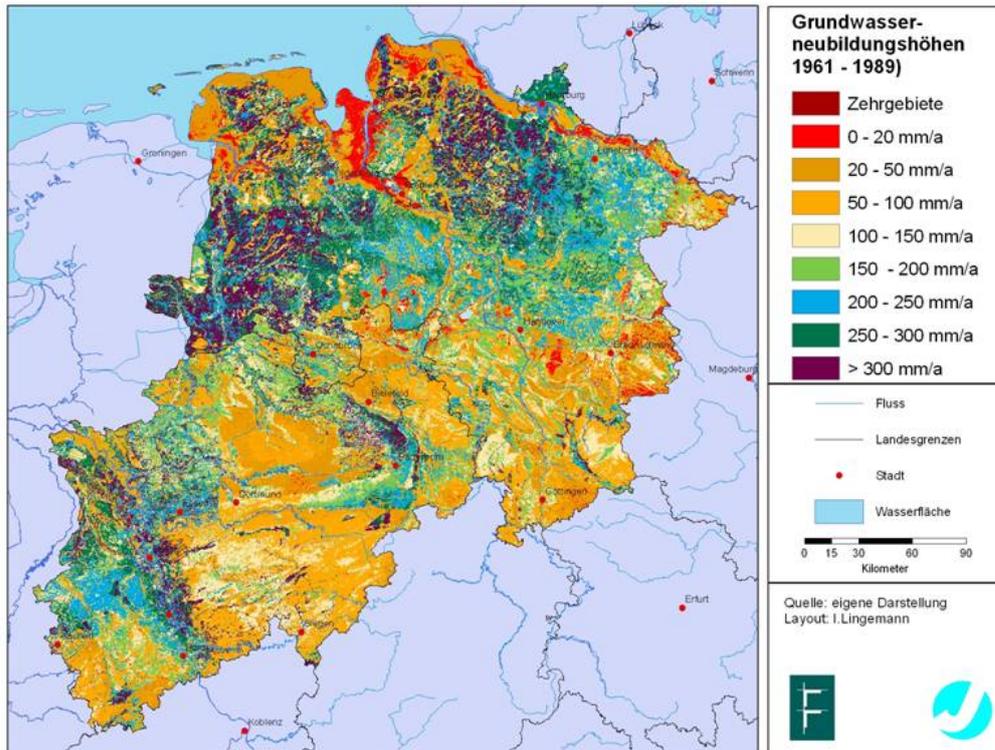


Figure 2: Groundwater recharge rates calculated for the time period 1961 – 1989.

The reliability and representativeness of the calculated area-differentiated groundwater recharge values were verified on the basis of long-term monthly runoff data from representative gauging stations. In selecting the gauging stations, attention was primarily paid to achieving the greatest possible variability with respect to catchment area size as well as land use and climate. For reasons of continuity, only those gauging stations were selected for which long-term time series were available from the period between 1961 and 1990. The calculated groundwater recharge values were integrated for each gauge-related catchment area and compared with the measured MoMnQ – values. MoMnQ – values from xx subbasins were available (see figure 3, left part). Figure 3 (right part) shows a comparison of the calculated groundwater recharge rates to the measured groundwater runoff rates.

As can be seen from Figure 3, the deviation of the calculated groundwater recharge levels differ from the measured values for most gauging stations between 0 and ± 15 %. Errors in this order of magnitude lie within the usual variation range of an empirical model. Furthermore, small but unavoidable measuring and interpolation errors are also undoubtedly involved. It also has to be taken into account that the deviations can be explained by the fact that in separating the groundwater recharge levels deviations from two submodels are superimposed (total runoff modelling, separation of runoff components).

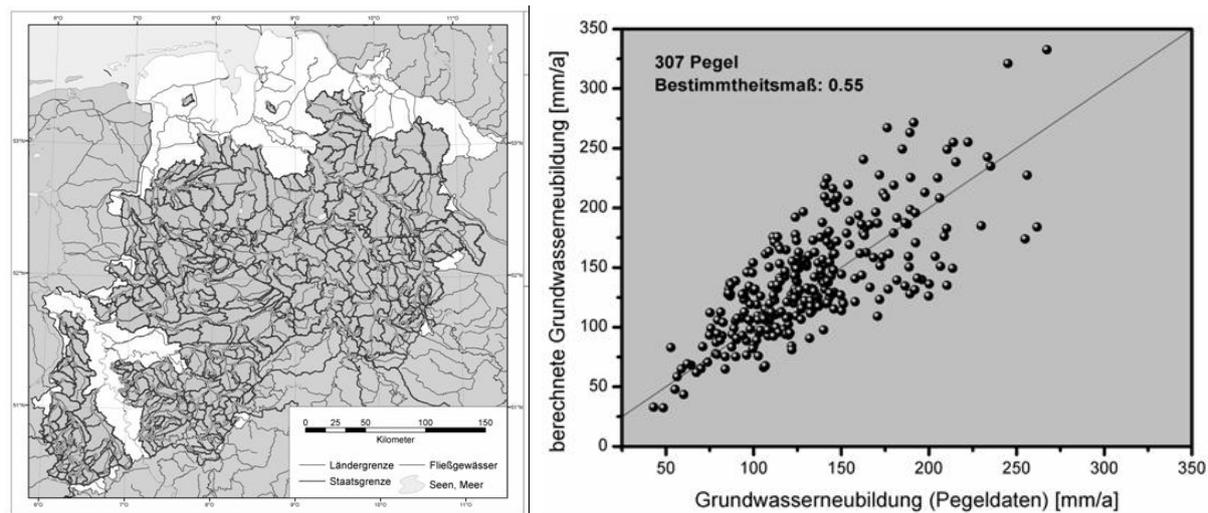


Figure 3: Gauging stations and related subbasins used for validation of the calculated runoff (left part); result of validity check for 307 sub-catchment areas in Lower Saxony and North – Rhine Westphalia.

6.2 Predicted groundwater recharge rates for the period 2071 – 2099

Figure 4 shows the predicted groundwater recharge rates calculated for the time period 2071 – 2099 using the MM5 data set as input.

Compared to the mean long-term groundwater recharge levels calculated for the period 1961 – 1989 (see figure 2) it becomes obvious that the general spatial distribution patterns of groundwater recharge rates remain unchanged. In this way the plain unconsolidated rock areas in the North German Plain and the Lower Rhine Embayment at some distance from the water table displays the highest groundwater recharge rates, whereas in consolidated rock areas groundwater recharge is considerably higher. However, there seems to be the general tendency that groundwater recharge rates will get higher in all unconsolidated rock areas and decline in the consolidated rock areas.

Figure 5 shows the probable regional changes in the groundwater recharge rates in case the actual groundwater recharge rate 1961 – 1989 is compared to predicted groundwater recharge rates for the time period 2071 – 2099 using the MM5 data set as input.

According to figure 5 for large parts of the unconsolidated rock areas occurring in Lower Saxony and North – Rhine Westphalia an increase of the groundwater recharge rate by 15 mm/a to ca. 35 mm/a to 2100 is predicted. There the groundwater table might rise in the coming years. For large parts of the consolidated rock areas, a decline of up to ca. 15% was calculated. Referring these values to the mean long – term change in the two Federal States this corresponds to an increase of groundwater recharge in Lower Saxony by 17% and by less than 5% in North Rhine – Westphalia. It has to be taken into account that these values are strongly influenced by the compensation of areas indicating a net increase with areas indicating a net decline. The fact that in North – Rhine Westphalia the portion of areas indicating a decline or an increase of groundwater recharge values are almost equal shared indicates a relative low change “on average”.

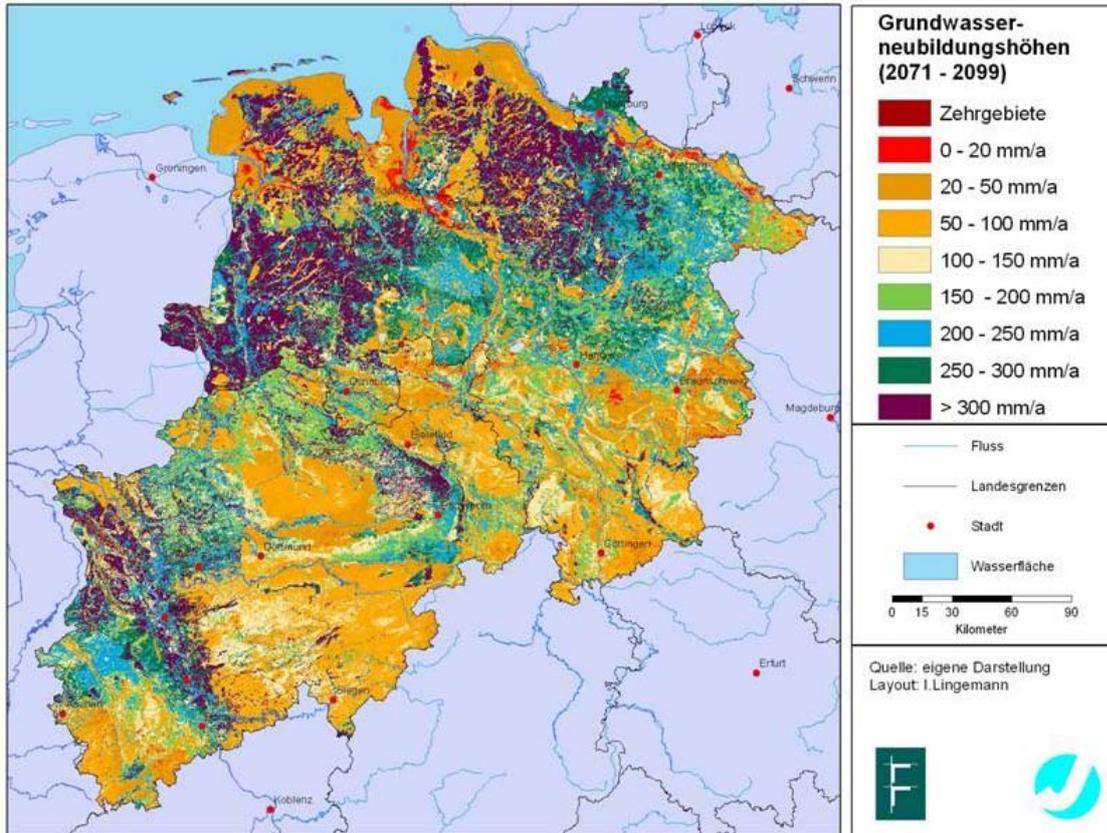


Figure 4: Groundwater recharge rates calculated for the time period 2071 - 2099 based on the MM5 data set as input

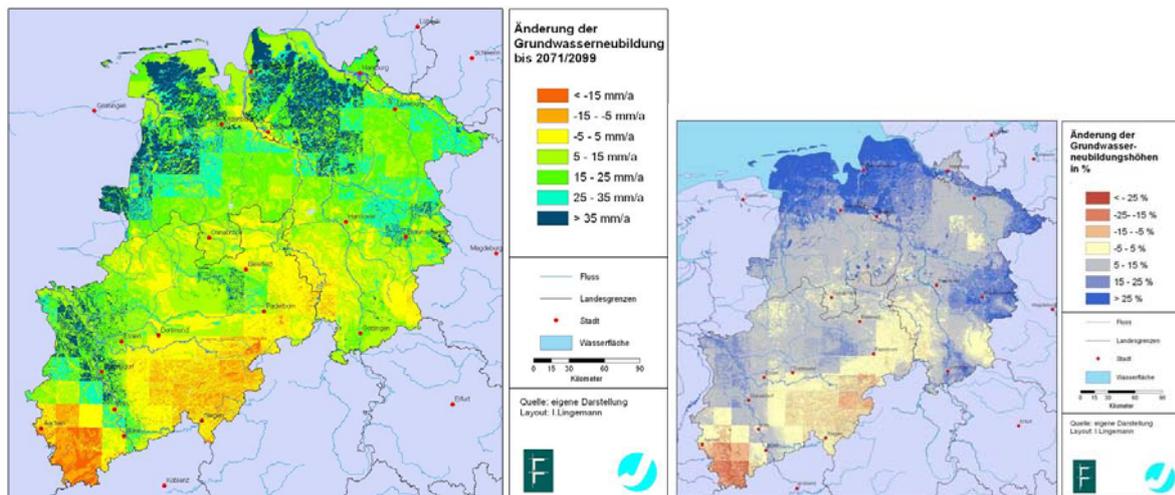


Figure 5: Predicted changes in groundwater recharge in case the actual groundwater recharge rate 1961 – 1990 is compared to groundwater recharge rates for the time period 2071 – 2099 based on the MM5 data set as input. The left part shows the absolute changes, the right part the relative changes.

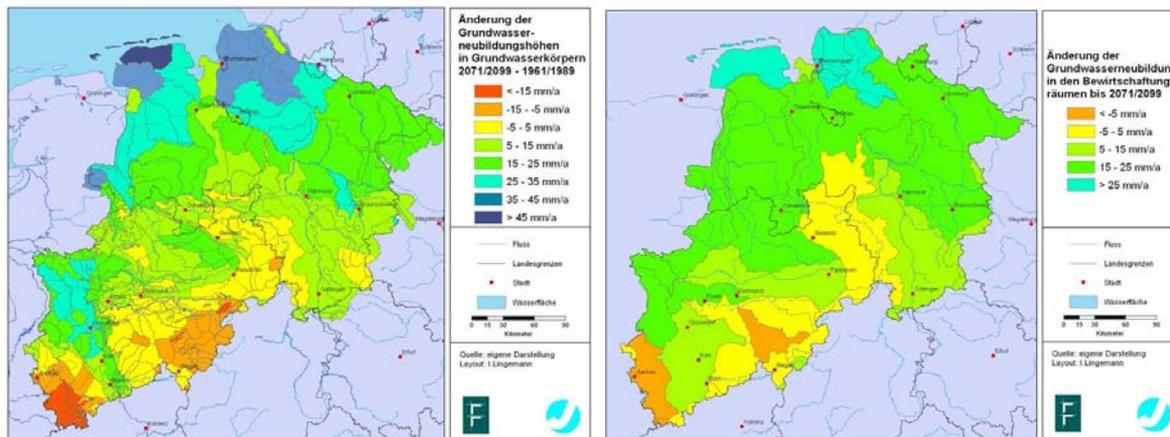
The relative change (see figure 5, right part) conveys an additional effect. Especially along the coast line of the North see, the increase of groundwater recharge corresponds to more than 25% of the groundwater recharge rate calculated for the period

1960 – 1989. This might have some impacts on the regional groundwater management, e.g. the drainage discharge and ecological status of the related wetlands. In case the decrease by 25% calculated for the South – Western part of North Rhine – Westphalia would come true, an impact on the drinking water dams of the Eifel region would be the consequence.

6.3 Predicted groundwater recharge rates for the period 2071 – 2099 in groundwater resources management related reference areas

According to annex V of EU WFD the „good quantitative status“ of groundwater is achieved in case the mean long-term groundwater extraction doesn't exceed the mean long-term groundwater recharge (sustainable use of groundwater). Whereas river basin districts provide the basis for the overall regional water resources management, groundwater bodies are the geographic units for regional groundwater resources management within the river basin districts according to EU WFD article 4, paragraph 1 b i and ii. For the Federal States of North Rhine – Westphalia and Lower Saxony 268 respectively 129 groundwater bodies have been delineated in the framework of the of river basin characterisation (2005) according to the groundwater flow conditions. As the EU WFD requires an integrated consideration of surface waters and surface near groundwater occurrences this delineation took the hydrological water sheds into account too.

Figure 6 (left part) shows the expected change in the mean long-term groundwater recharge for the period 1961 – 1990 compared to the groundwater recharge for the period 2071 – 2100 related to the 397 groundwater bodies delineated for the two Federal States. In figure 6 (right part) the expected change in the mean long-term groundwater recharge for the period 1961 – 1990 to the period 2071 – 2099 is shown related to the river basin districts.



As can be seen from figure 6, the conclusions about the expected changes in the mean long-term groundwater recharge for the period 1961 – 1989 compared to the groundwater recharge for the period 2071 – 2099 differ significantly in case groundwater bodies or river basin districts are used as the underlying geographical reference. The groundwater recharge rates in the groundwater bodies of the South - western part of North Rhine – Westphalia for example are predicted to decline by > 15 mm/a. However, in case the expected changes are forecasted on the scale of the river basin district Rur, to which these groundwater bodies belong to, the expected changes for the whole Rur catchment are smoothed to values < 5 mm/a. In the North - Western part, groundwater recharge rates are predicted to increase by > 45

mm/a for individual groundwater bodies. In case these values are generalized on the level of river basin districts, this increase is flattened to ca. 25 mm/a.

7. Summary and conclusion

An area differentiated modelling of mean long – term groundwater recharge rates for the hydrological period 1961-1989 was carried out based on the GROWA model for the Federal States of North Rhine - Westphalia, Lower Saxony, Hamburg and Bremen. The GROWA model conceptually combines distributed meteorological data (winter and summer precipitation and potential evapotranspiration) with distributed site parameters (land use, soil properties, slope gradient, slope exposure, mean depth to groundwater) to facilitate the calculation of long-term annual averages of total runoff. In the GROWA model groundwater recharge is expressed as a constant proportion (baseflow indices) of the total runoff. This portion depends on certain characteristics of the investigated area, e.g. the slope gradient, soil and hydrogeological properties as well as the degree of surface sealing. The accuracy of the calculated groundwater recharge values for the period 1961–1989 was verified on the basis of measured MoMNO – values from more than 300 gauged sub-basins. In general, the differences between modelled and measured runoff values were less than 15 %, indicating the reliability of the chosen procedure. For this reason the GROWA model is suitable for practical groundwater resources management issues like the prediction of the long term changes of groundwater recharge due to climate change. For this purpose the GROWA model was run with the output of the MM5 regional climate model (precipitation levels, potential evapotranspiration levels) for the time slices 1961-89 and 2070 - 2099.

Due to different spatial resolution between the climate data sets -250 m grids for the actual DWD – data set and 19.2 km grids for the MM5 climate scenario data sets-systematic differences in consequence of different representations of topographic effects occur. Hence, the identified differences might not have their origin in the climate change, so that the increase in precipitation rates from 1961 – 1989 to 2071 – 2099 by > 25% in the coastal region has to be handled with care, just like the predicted decrease by > 25% for the South - Western region. Consequently, these regionally differences in the input data sets are reflected in the modelled groundwater recharge rates, so that the “hot spot” regions of an expected increase and an expected decrease of groundwater recharge are identical.

The over- and underestimation of values from the climate scenario imposes considerable restrictions on the informative value of the determined changes in groundwater recharge rates until 2100. Hence, their use for the derivation of possible adaption strategies for the regional groundwater resources management can not be recommended yet.

For this purpose we would suggest a statistical downscaling of climate data from 19.2 km grids down to 250 m grids. Additionally the temporal resolution of the GROWA should be increased from an annual to a monthly or even daily representation of groundwater recharge. In this way the seasonal influence of a changing climate on groundwater recharge can be considered. In this framework the implementation of an irrigation module into the GROWA model is recommended, as the portion of irrigated agricultural areas may rise.

Referring the grid-wise modelled groundwater recharge rates to groundwater bodies and river basin districts has proofed the significance of choosing an adequate management unit. In general the modelled changes in groundwater recharge rates are less significant on the level of river basin districts compared to the changes for individual groundwater bodies. In order to predict the impacts of climate change to guarantee a long – term sustainable use of groundwater resources, e.g. for irrigation or drinking water supply, the groundwater recharge rates should be compared to the groundwater withdrawals already realized today. For “hot spot areas”, in which the long – term groundwater availability is endangered, this allows for the development of well directed groundwater resources management strategies adapted to the climate change.

All these points will contribute to the development of a coupled meteorological - hydrologic model system, which enables a scientifically based prognosis of the future’s groundwater availability under climate change conditions. This innovative tool for the quantitative water resources management may help to implement the EU WFD, e.g. for the establishment of programs of measures under consideration of climate change effects.

8. References

- Bogena, H.; Kunkel, R.; Schöbel, T.; Schrey, H.-P.; Wendland, F. (2003): Die Grundwasserneubildung in Nordrhein-Westfalen. Schriften des Forschungszentrums Jülich, Reihe Umwelt, 37, FZ Jülich GmbH, Jülich, Germany, 148 S.
- Bogena, H.; Herbst, M.; Kunkel, R.; Vereecken, H.; Wendland, F. (2004): Skalenabhängige Modellierung des Wasserhaushalts im Flusseinzugsgebiet der Rur. in: Ludwig, R.; Reichert, D.; Mauser, W. (Ed.): 7. Workshop zur großskaligen Modellierung in der Hydrologie - Neue methodische Ansätze zur Modellierung der Wasser- und Stoffumsätze in großen Einzugsgebieten. Kassel University Press, Kassel, Germany, 87-97.
- Bogena, H.; Kunkel, R.; Schöbel, T.; Schrey, H.P.; Wendland, F. (2005): Distributed modelling of distributed groundwater recharge at the macroscale under special consideration of geology. *Ecological modelling* 187 (1), 15 – 26.
- Bürger, C., Chen, Y. (2005): Regression-based downscaling of spatial variability für hydrologic applications. *Journal of Hydrology*, 331: 299-317.
- Climate Change 2007: The Physical Science Basis - Summary for Policymakers. Intergovernmental Panel on Climate Change (2007). Retrieved on 2007-02-02.
- Dörhöfer, G., Kunkel, R., Tetzlaff, B. u. Wendland, F. (2001): Der natürliche Grundwasserhaushalt von Niedersachsen. - Arbeitshefte Wasser, Bd. 1/2001, Hannover.
- Ebel, M., Ludwig, K., Richter, K.G. (2000): Mesoskalige Modellierung des Wasserhaushalts im Rheineinzugsgebiet mit LARSIM. *HW 44*, 2000, H.6, 308 – 312.
- EU (2000): Richtlinie 2000/60/EG des Europäischen Parlaments und des Rates vom 23. Oktober 2000 zur Schaffung eines Ordnungsrahmens für Maßnahmen der Gemeinschaft im Bereich der Wasserpolitik.
- Genesis – online (2005): Staatliches Informationssystem des Bundes und der Länder, <https://regionalstatistik.de>

- Grell, G. A., J. Dudhia, D.R. Stauffer, 1994: A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Technical Note 398+STR.
- Hölting, B., Haertlé, T., Hohberger, K.-H., Nachtigall, K.-H., Villinger, E., Weinzierl, W., Wrobel, J.P. (1995): Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung. Geologisches Jahrbuch Series C, No. 63. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.
- Keuler, K., Heimann, D., Dittmann, F., Berger, C., Bernhofer, D., Knoche, H.-R., Jacob, U., Böhm, M., Kücken und Hauffe, D. (2006): DEKLIM - Abschlussbericht - Quantifizierung von Ungenauigkeiten regionaler Klima- und Klimaänderungssimulationen (QUIRCS). Cottbus, August 2006.
- Kille, K. (1970): Das Verfahren MoMNQ, ein Beitrag zur Berechnung der mittleren langjährigen Grundwasserneubildung mit Hilfe der monatlichen Niedrigwasserabflüsse.- Z. dt. geol. Ges., Sonderh. Hydrogeol. Hydrogeochem: 89-95.
- Kunkel, R. u. Wendland, F. (2002): The GROWA98 model for water balance analysis in large river basins-the river Elbe case study.- Journal of Hydrology 259, 152-162.
- Kunkel, R. & Wendland, F. (1998): Der Landschaftswasserhaushalt im Flußeinzugsgebiet der Elbe - Verfahren, Datengrundlagen und Bilanzgrößen.- Schr. d. FZJ, Reihe Umwelt, Bd. 12; Jülich.
- Matulla, C., E.K. Penlap, H. von Storch: Empirisches Downscaling – Überblick und zwei Beispiele. Klimastatusbericht 2002, 20-31, 2002.
- Mittelstädt, Robert (2005): Detaillierte hydraulische Nachweise nach BWK M3 für Gewässer der Niederungs- und Sandergebiete.- HW 49. 2005, H.6, 309 – 312.
- Renger, G., und Wessolek, G. (1996): Berechnung der Verdunstungsjahressummen einzelner Jahre. In: DVWK-Merkblätter zur Wasserwirtschaft, 238: 47; Bonn.
- Roeckner E., Arpe K., Bengtsson L., Christoph M., Gausson M., Dürnenil L., Esch M., Giorgetta M., Schtese U., Schulzweida U. (1996): The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate, Report Max-Planck-Institut für Meteorologie Nr. 218, Hamburg
- Schröder, M. (1983): Neue Werte zur Grundwasserneubildung unter Wald für das Münsterland.- Dtsch. gewässerkdl. Mitt., 27 (4): 121 – 124.
- Schulla, J., Jasper, C. (1999): Modellbeschreibung WaSiM-ETH ETH-Zürich, 180 p.
- Tetzlaff, B.; Kunkel, R.; Taug, R.; Dörhöfer, G.; Wendland, F. (2004): Grundlagen für eine nachhaltige Bewirtschaftung von Grundwasserressourcen in der Metropolregion Hamburg. Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment, Band 46, Forschungszentrum Jülich GmbH, Jülich, Germany, 87 S.
- Wendland, F.; Kunkel, R.; Tetzlaff, B.; Dörhöfer, G. (2003): GIS-based determination of the mean long-term groundwater recharge in Lower Saxony. Environmental Geology 45 (2), 273-278.
- Wundt, W. (1958): Die Kleinstwasserführung der Flüsse als Maß für die verfügbaren Grundwassermengen.- In: Grahmann, R.: Die Grundwässer in der Bundesrepublik Deutschland und ihre Nutzung.- Forsch. Dtsch. Landeskunde, 104), 47-54, Remagen.