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Determination of spatially differentiated water balance components including groundwater recharge on the Federal State level – A case study using the mGROWA model in North Rhine-Westphalia (Germany)

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A B S T R A C T

Study region: The Federal State of North Rhine-Westphalia (NRW), Germany.

Study focus: On behalf of the Federal State Agency for Nature, Environment and Consumer Protection of North Rhine-Westphalia, Germany (LANUV) the mGROWA model is applied, in order to simulate the water balance components actual evapotranspiration, total runoff, direct runoff and groundwater recharge at Federal State level. mGROWA-simulations were performed in daily time steps for the hydrological reference period 1971–2000 and in a spatial resolution of 100 by 100 m. mGROWA results for groundwater recharge and State-wide recorded groundwater withdrawal rates have been used to assess the extent of groundwater exploitation in NRW.

New hydrological insights: Simulated groundwater recharge levels are presented as long-term annual averages and as long-term monthly values in order to indicate the seasonal fluctuation of groundwater recharge rates. Quantitative statistics indicate that mGROWA enables the simulation of total runoff and groundwater recharge without significant tendency of over- or underestimation. Against this background mGROWA simulation results are used by LANUV to support regional water resources management, e.g. for determining the status of groundwater exploitation in NRW. The majority of groundwater bodies in NRW are at present not at risk of unsustainable groundwater usage. A small number of groundwater bodies along the river Rhine, however, have been assessed as being close to unsustainable groundwater exploitation.

1. Introduction

The development and macro-scale application of distributed water balance models, such as the GROWA model (Kunkel and Wendland, 2002; Wendland et al., 2003), the model "Hydrological Atlas of Germany" (Jankiewicz et al., 2005) or the methodology by Dörhöfer and Josopait (1980), have a long history in Germany. Although the grid-based distributed models are based on empirical equations and do not focus on the simulation of runoff concentration and river discharge like classical hydrological (rainfall-runoff) models do, e.g. TOPMODEL (Beven and Freer, 2001; Beven and Kirkby, 1979), SWAT (Arnold

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et al., 1998), WASIM-ETH (Schulla, 1997), SHE (Abbott et al., 1986) or HBV-96 (Lindström et al., 1997), their relevance to support decision-making in local and regional water management in Germany is undisputable.

The explicit designation of spatial patterns of groundwater recharge enables the determination of the sustainably available groundwater volumes in managed aquifers. The GROWA model for instance provides annual or long-term mean annual groundwater recharge distributions which have been used for the quantity status assessment of groundwater bodies according to EU-WFD (2000) in several German Federal States, e.g. for North-Rhine Westphalia (Kunkel et al., 2006). Moreover, the water balance quantities calculated by the GROWA model are suitable boundary conditions for the analysis of diffuse pollution at the river basin scale (e.g. Andelov et al., 2014; de Wit et al., 2000; Kunkel et al., 2010; Tetzlaff et al., 2009a) or for modelling of groundwater dynamics on the regional scale (e.g. Herrmann et al., 2009).

During the last years the consideration of inner-annual variability of groundwater recharge has become more important, especially with regard to the assessment of the impact of climate variability and climate change on the available groundwater resources. The yearly sums of groundwater recharge, as modelled by the large-scale empirical models in Germany, are not sufficient for these kinds of applications. Instead, regional groundwater recharge models should perform simulations on a monthly or daily basis in order to obtain reliable inner-annual groundwater recharge distributions (Dripps and Bradbury, 2007).

In order to meet the present requirements the GROWA model has been extended to the mGROWA model (Herrmann et al., 2013) by the multiple-layer soil water balance model BOWAB (Engel et al., 2012), which is able to simulate soil moisture dynamics, actual evapotranspiration and percolation water dynamics on a daily basis. This paper describes the mGROWA model and an analysis of model results of its first application in the Federal State of North Rhine-Westphalia (NRW), Germany. Additionally, the benefit of mGROWA-simulated groundwater recharge levels for assessing sustainability of groundwater use and the corresponding quantitative status assessment of groundwater bodies is demonstrated.

2. mGROWA model description

2.1. Basic modelling approach

According to the categorisation schema of Becker and Serban (1990), mGROWA can be classified as a deterministic grid-based distributed hydrological water balance model. This implies a description of hydrological processes reflecting the fundamental laws of physics (in particular hydro- and thermodynamics) in a simplified, approximate manner. In addition this concept involves (in general) a certain degree of empiricism (Becker and Serban, 1990). Aside from that, the modelling concept was rigorously aligned to both, the spatial resolution of the data commonly available for hydrological modelling and the necessity to obtain spatially highly resolved groundwater recharge patterns (e.g. on a 100 m grid) for the local and regional groundwater management.

Regarding the temporal resolution, the following discretisation was chosen for mGROWA: (1) Soil moisture dynamics, capillary rise from groundwater into the root zone, actual evapotranspiration and total runoff generation are calculated in daily steps. (2) Groundwater recharge and the direct runoff components respectively are summarised and presented in monthly resolution as groundwater management requires this temporal aggregation level.

Fig. 1 shows the general modelling scheme realised in mGROWA that resulted from the considerations mentioned above. The in- and outfluxes (i.e. actual evapotranspiration and total runoff) of each individual grid cell of the study area are calculated separately without considering lateral water or energy fluxes. For this purpose a simplified physically based approach using climate data and data bases characterising the land surface, the vadose and the saturated zone (digital elevation models, land use models, soil maps, hydrogeological maps, etc.) is used.

In water balance models, the consideration of soil moisture dynamics is important due to the dependency of (1) evapotranspiration rate on plant available water stored in the root zone and (2) percolation rate of soil water and capillary rise rate from shallow groundwater on soil moisture tension. The first issue is commonly accounted for by using reduction-functions as recommended e.g. by Minhas et al. (1974) or Disse (1995). This type of approach is also implemented in mGROWA. In water balance model applications on the Federal State level, the vertical movement of soil water in the root zone would has to be considered over long time spans (more than 30 years) and for several million grid cells. In mGROWA, the simplified multiple-layer soil water balance model BOWAB (Engel et al., 2012) which respects the continuity equation but ignores the dependency of percolation on unsaturated hydraulic conductivity was chosen in order to account for that water fluxes. The algorithms of the mGROWA model automatically create 1-dimensional multiple-layer sub-models, each representing the soil column in a grid cell based on soil profile descriptions and hydraulic parameters (e.g. field capacity) in the underlying soil map.

The total runoff calculated in the first simulation step is subsequently separated into direct runoff and groundwater recharge (Fig. 1). A practical way which has been proved to be suitable in this context is to use the empirical approach of Base Flow Indices (BFI). This concept was first introduced by (Lvovich, 1972) and further developed by the Institute of Hydrology (1980). The Base Flow Index was originally defined as the proportion of base flow in the river discharge, for indexing the effect of geology and other site conditions on low flows. Base flow is referring in this article to the discharge of groundwater into the streams. Following Meyboom (1961), the basic hydrologic equation of groundwater in a catchment can be given as groundwater recharge = base flow ± change in groundwater storage. In case of long-term hydrologic considerations changes in the groundwater storage of aquifers become negligible. Accordingly, base flow can be considered equal to groundwater

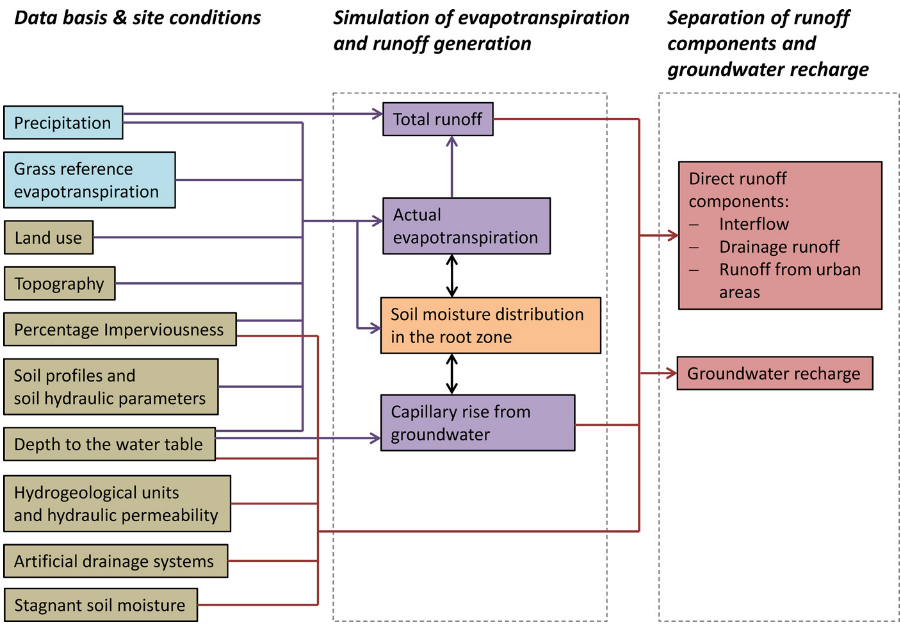

Fig. 1. Data basis and general modelling scheme of the mGROWA model.

recharge. The BFI value of a catchment is then defined as the ratio of groundwater recharge to total runoff in catchments without considerable groundwater withdrawal.

BFIs can be derived for both whole catchments and single model elements (i.e. grid cells) of a groundwater recharge model. Geological information can be correlated with BFIs in both cases (compare Bloomfield et al., 2009). The concept has been successfully used in several studies in central Europe, e.g. in applications of the GROWA model (Kunkel and Wendland, 2002; Wendland et al., 2003) or the hydrological model ARC/EGMO (Haberlandt et al., 2001). It has been turned out that this concept led to more reliable groundwater recharge values in central Europe's catchments than obtained by modelling concepts which do not use BFI-values, e.g. in Huang et al. (2010) using SWIM (Krysanova et al., 1998) for the German low mountain range catchments.

2.2. Simulation of evapotranspiration and runoff generation

The water content and the daily vertical water fluxes are calculated based on the water balance equation as it is common practice in water balance modelling:

$$\Delta s = p + q_i - et_a - q_t \quad (1)$$

where p is the precipitation (mm/d); q_i is an additional influx into the storage of a cell (mm/d) which can be capillary rise in case of shallow groundwater, irrigation, etc.; et_a is the land-use-specific actual evapotranspiration (mm/d); q_t is the total runoff (mm/d); and Δs is the change of the storage level (mm/d). s is equivalent to the soil moisture content θ in the root zone (mm) of surfaces covered with vegetation or the water stored on impervious surfaces in case of urban areas.

In the mGROWA model special attention has been paid to the calculation of actual evapotranspiration and the associated storage functions (Eq. (2)). The grass reference evapotranspiration et_0 (mm/d) is determined based on the Penman–Monteith-equation (Allen et al., 1998, 1994; Monteith, 1965); k_{LN} is a land use specific evapotranspiration factor (given in ATV-DVWK, 2002) which is similar to crop coefficients given in Allen et al. (1998); $f(\beta, \gamma)$ represents a topography function in order to correct actual evapotranspiration according to hill slope and exposition (taken from Kunkel and Wendland, 2002); and $f(s)$ is a storage function which takes the water available for the evapotranspiration processes into account.

$$et_a = et_0 \cdot k_{LN} \cdot f(\beta, \gamma) \cdot f(s) \quad (2)$$

The storage function is defined differently for different site conditions. The following site conditions are currently implemented in mGROWA: (1) land surfaces covered with vegetation, (2) impervious surfaces in urban areas and (3) free water surfaces.

2.2.1. Land surfaces covered with vegetation

For land surfaces covered with vegetation, soil water dynamics and the evapotranspiration balance are simulated by means of the multiple-layer soil water balance sub-model. Due to the large number of parameters, constraints and adaptations for special soil conditions implemented in mGROWA, only the basic concept and selected key equations are described in the following (for all details see: Engel et al., 2012; Herrmann et al., 2013).

The amount of evapotranspiration from land surfaces covered with vegetation depends on the grass reference evapotranspiration as well as on (1) the plant available soil water, (2) the soil moisture pressure head h (in hPa) and (3) the rooting depth of the vegetation. The latter is accounted for through monthly varying vegetation-specific depths of the root zone. The dependence of evapotranspiration on the soil moisture content and thus on the pressure head is controlled by the Disse-function (Disse, 1995). This function (Eq. (3)) represents the storage function in Eq. (2) in the case of a vegetation-covered surface:

$$R_{Disse} = \frac{1 - e^{-r \cdot ((\theta - \theta_{pwp})/\theta_a)}}{1 + e^{-r \cdot ((\theta - \theta_{pwp})/\theta_a)} - 2 \cdot e^{-r}} \quad (3)$$

Herein e is the Euler number, r a plant-specific factor, θ_a (in Vol.-%) the plant available water capacity of the soil, θ_{pwp} (in Vol.-%) the water content at the permanent wilting point, and θ (in Vol.-%) the actual water content. The function values of the Disse-function are in the range of 0–1. In case the water content in the balanced grid cell has decreased to the water content at permanent wilting point, actual evapotranspiration becomes 0. In case the soil water storage has filled up to field capacity, actual evapotranspiration becomes 1, i.e. it has reached the level of potential evapotranspiration.

According to Eq. (1), the second source of soil water is capillary rise from groundwater, which may occur in case the root zone of soils overlap at least temporarily with the capillary fringe above the water table of shallow aquifers. Capillary rise may occur only, if the hydraulic gradient between the root zone and the water table is sufficiently high. The process generally depends on the distance between water table and the soil layer having a water deficit, the soil moisture pressure head in this layer and the soil texture. In the mGROWA model a pragmatic approach has been implemented in order to account for this temporary vertical water flux rising from the groundwater surface into the root zone. It is based on empirical soil texture-specific capillary rise rates and corresponding thresholds of soil moisture pressure heads which indicate incipient capillary rise (e.g. Müller and Waldeck, 2011). An example for capillary rise rates for medium sand is given in Table 1.

In order to identify days with incipient capillary rise, the water content in the soil layers is converted into a pressure head. This conversion is performed by the van-Genuchten-equation (van Genuchten, 1980):

$$\left|h\right| = \frac{[((\theta_s - \theta_r)/(\theta - \theta_r))^{(n/(n-1))} - 1]^{(1/n)}}{\alpha} \quad (4)$$

The parameters θ_s, θ_r, n and α are soil texture specific and were collected from literature (e.g. Renger et al., 2009; Schwärzel et al., 2006; Vereecken et al., 2010). Finally, Eq. (5) shows the function used for the determination of the daily amount of capillary rise where the subscript *tab* indicates the empirical values described above and z_a (in dm) the distance between the water table and the soil layer displaying a sufficiently high water deficit.

$$q_{cr} = \begin{cases} q_{\text{cr,tab}}(z_a), & \left|h\right| > \left|h_{\text{tab}}\right| \text{ and } \theta_{fc} - \theta \geq q_{\text{cr,tab}}(z_a) \\ \theta_{fc} - \theta, & \left|h\right| > \left|h_{\text{tab}}\right| \text{ and } \theta_{fc} - \theta < q_{\text{cr,tab}}(z_a) \\ 0, & q_{\text{cr,tab}}(z_a) < 0.1 \end{cases} \quad (5)$$

Percolation water flux between the different soil layers is calculated within mGROWA using a simple overflow-concept. Vertical downward flow from one soil layer to the layer beneath is assumed to occur in case the water content of the upper layer exceeds field capacity. Percolation water generated from the deepest layer is equated with total runoff. It is consequently used for the separation of direct runoff components and groundwater recharge based on the BFI-concept described in Section 2.3.

Table 1
Example of empirical capillary rise rates for medium sand (taken from Müller and Waldeck, 2011).

Soil texture	Distance between water table and soil layer having a water deficit z_a in dm and corresponding capillary rise rates $q_{\text{cr,tab}}(z_a)$ in mm/d													$\left|h\right|$ in hPa
	1	2	3	4	5	6	7	8	9	10	11	12	13	
Medium sand	5	5	5	5	3	1.2	0.5	0.2	0.1	0	0	0	0	120

2.2.2. Impervious surfaces in urban areas

Urban areas are characterised by both, impervious surfaces (such as paved areas and roofs) and surfaces with vegetation cover (green areas, gardens). The portion of impervious surface in a grid cell can be expressed as the percentage imperviousness pi which can range from 0 to 1. Thus, for grid cells representing urban areas total runoff (and also actual evapotranspiration) is averaged over the impervious and the vegetation-covered parts:

$$q_{t,\text{urban}} = q_{t,\text{vegetation}} \cdot (1 - pi) + q_{t,\text{impervious}} \cdot pi \quad (6)$$

Total runoff (and also actual evapotranspiration) from the vegetation-covered parts of a grid cell in an urban area is calculated according to above described method. Following Wessolek and Facklam (1997) it is assumed that an impervious urban surface displays a water storage capacity of 1 mm. This is also the maximum amount of water that can evaporate per day at such sites. The storage function of impervious surfaces is defined in Eq. (7). In case daily precipitation exceeds the assumed storage capacity of 1 mm, the precipitation surplus corresponds to the generated (direct) runoff. Accordingly, the portion of runoff from urban areas increases with the portion of imperviousness.

$$f(s) = \begin{cases} 1, & s \geq et_0 \cdot k_{LN} \cdot f(\beta, \gamma) \\ 0, & s = 0 \\ \dfrac{s}{et_0 \cdot k_{LN} \cdot f(\beta, \gamma)}, & 0 < s < et_0 \cdot k_{LN} \cdot f(\beta, \gamma) \end{cases} \tag{7}$$

2.2.3. Free water surfaces

The storage function is defined as $f(s) = 1$ in case of free water surfaces because sufficient water is available for the process of evaporation. In order to avoid balance errors in river catchments, the evaporated surface water has been already balanced in another part of a catchment as total runoff, the amount of water that evaporates is considered as an influx according to Eq. (8):

$$q_i = \begin{cases} et_a, & p = 0 \\ et_a - p, & p < et_a \\ 0, & p > et_a \end{cases} \tag{8}$$

2.3. Separation of runoff components and groundwater recharge

Apart from total runoff, mGROWA simulations include the determination of direct runoff q_d and groundwater recharge q_r. Groundwater recharge is the share of total runoff which infiltrates into aquifers and corresponds quantitatively to groundwater runoff (base flow) in case long-term periods are considered. The remaining parts of total runoff, i.e. surface runoff, natural interflow, and runoff from artificial drainage systems, are subsumed as direct runoff. Here, natural interflow is referring to subsurface runoff in shallow depth reaching surface waters slightly delayed compared to surface runoff.

In order to separate total runoff into groundwater recharge and direct runoff components a hierarchical approach is used as proposed by Kunkel and Wendland (2002), where characteristic site conditions are evaluated in order to allocate a site-specific BFI-value (Base Flow Index) to each single grid cell. These BFI-values describe the different runoff components as relative shares of total runoff. The basic equation is as follows:

$$q_t = BFI \cdot q_t + (1 - BFI) \cdot q_t = q_r + q_d. \tag{9}$$

Fig. 2 shows the schema employed to determine the site characteristics which control runoff separation. The decisive factor for runoff-separation in urban areas is the percentage of imperviousness. Groundwater recharge is generated in the portions of the urban grid cell displaying a vegetation cover only. In contrast, no groundwater recharge occurs beneath impervious surfaces, where the total generated runoff fully contributes to direct runoff.

For sites displaying vegetation covers (pervious surface), the most important factor to be considered for runoff separation is the depth to the water table. In case of shallow aquifers, where capillary water reaches the root zone, net groundwater recharge q_{rn} is calculated (following Dingman, 2002), which may become negative in months where capillary rise is dominant. An additional recharge-controlling factor on groundwater-influenced sites is the existence of artificial drainage systems. At those sites, drainage runoff q_{drain} is the dominant runoff component which leads to a reduction of groundwater recharge especially in winter months. As a consequence an appropriate data base showing the geographical position of the artificially drained areas in a study region is important in order to determine reliable groundwater recharge values.

For sites where shallow groundwater does not affect the root zone, the most important factor controlling groundwater recharge is the rock type. It is well-known that BFIs in solid rock regions predominantly depend on hydraulic conductivity (e.g. Haberlandt et al., 2001) which can be attributed to an individual rock type (Kunkel and Wendland, 2002) or the aquifer typology (Wendland et al., 2008). As a rule, aquifer typologies showing poor hydraulic conductivities (e.g. crystalline rock and schist) display low BFIs accordingly. There, the portion of direct runoff components is significantly higher relative to aquifer typologies like Karst or Sandstone which display higher hydraulic conductivity values and correspondingly higher BFIs.

Finally, in case of sites in unconsolidated regions displaying a moderate to high permeable vadose zone, the generated total runoff fully contributes to groundwater recharge.

3. Case study area and data basis

The Federal State of North Rhine-Westphalia covers an area of about 34,000 km^2. As NRW stretches across various landscape types and features, different pedological, hydrological and hydrogeological site conditions occur. NRW is one of the most industrialised areas in Germany. The industrial centre zone is situated in the Rhine-Ruhr metropolitan region alongside

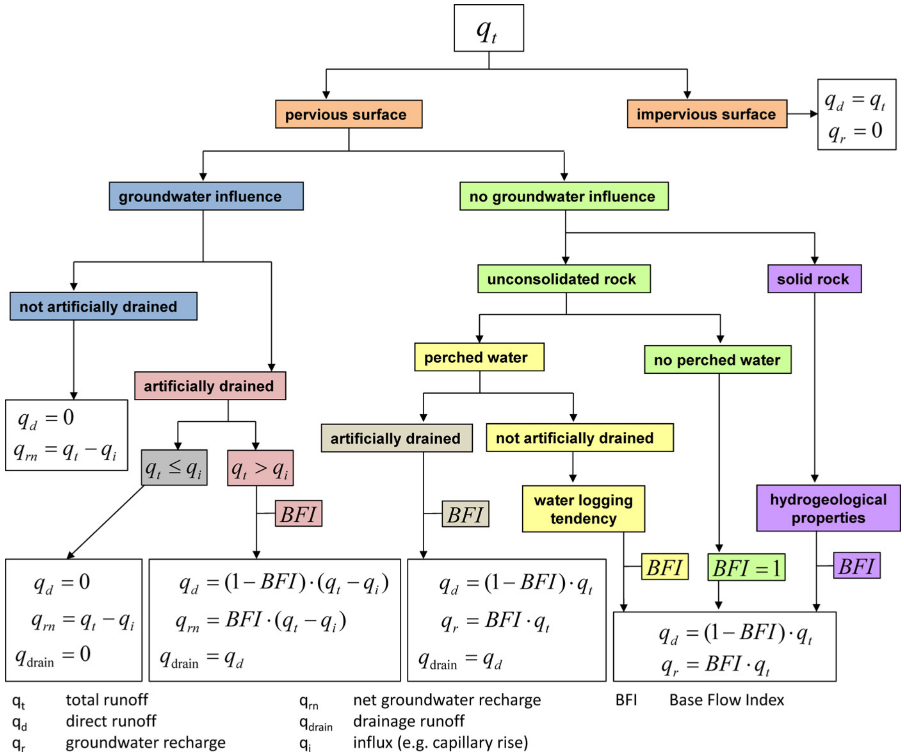

Fig. 2. Hierarchical BFI-approach for runoff-separation.

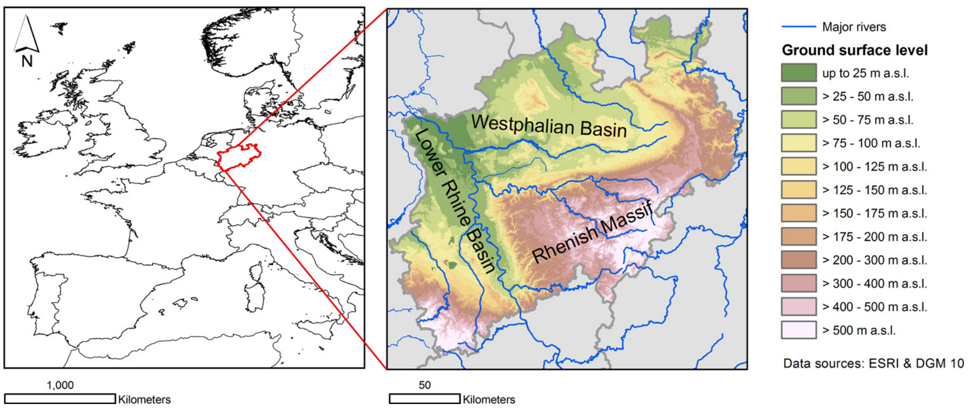

Fig. 3. Location of North Rhine-Westphalia in Europe and relief.

the main watercourses in the Lower Rhine and the Westphalian Basin (Fig. 3). Due to the high population (approx. 18 million inhabitants), the needs of intensive agriculture, and industry and mining activities, NRW's total water demand is very high.

Table 2 summarises all data bases used for the mGROWA simulation for NRW. The input data, i.e. data on climate, topography, soil cover, soil parameters, hydrogeological parameters, etc. have been made available from the Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of the Federal State of North Rhine-Westphalia and the German Meteorological Service. Many of these parameters were derived from digital maps, whose scale ranged from 1:50,000 to 1:200,000. For the climate data, the time period of 1971–2000 has been used as a temporal reference period. For the evaluation of the model results discharge data of 30 gauged sub-basins in NRW have been used. Individual data bases are described in detail in the following sections.

3.1. Land use

The dimension of urban areas in NRW is reflected by its high share (approx. 18%) within the surface types of North Rhine-Westphalia (Table 3). However, the major part of NRW is covered by vegetation, i.e. arable land dominating in the Lower

Table 2
Data bases and data sources.

Data base and parameter	Data source
Land cover map	ATKIS DLM 25 (Bezirksregierung Köln, Abteilung 7)
– Land use categories	
– Percentage imperviousness	
Digital terrain model	DGM 10 (Bezirksregierung Köln, Abteilung 7)
– Ground surface slope	
– Ground surface exposition	
Soil map and soil profile description	Soil map 1:50,000 (Geologischer Dienst Nordrhein-Westfalen)
– Thickness of soil horizons	
– Soil texture	
– Bulk density	
– Field capacity	
– Plant available water capacity	
– Substance volume of organic soils	
– Depth to water table	
– Waterlogging tendency	
Map of artificially drained areas	Derived based on the method of Tetzlaff et al. (2009a) and Tetzlaff et al. (2009b)
Hydrogeological rock units	Hydrogeological map 1:100,000 (Geologischer Dienst Nordrhein-Westfalen)
– Hydraulic conductivity classes	
Observed climate data (daily station values)	Deutscher Wetterdienst (DWD, German Weather Service)
– Precipitation	
– Air temperature	
– Sunshine duration/solar radiation	
– Wind speed	
– Air humidity	
Stream flow records	
– Time series of discharge on a daily basis	– Discharge records of 27 sub-catchments (period 1971–2000) provided by Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen
– Time series of base flow on a daily basis	– Base flow time series of 3 subsurface catchments (period 1971–2000) provided by Erftverband
Surface and subsurface catchment boundaries	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen

Rhine basin and the Westphalian Basins and forest and pasture prevailing in the low mountain range of the Rhenish Massif (Fig. 3).

The detailed land cover information which is elementary for the modelling of the regional water balance was gathered from the digital landscape model (DLM). Land use specific evapotranspiration factors, percentage of imperviousness and rooting depth of the vegetation were assigned for the respective land use types of the DLM based on literature data (ATV-DVWK, 2002).

3.2. Topography

As can be seen from Fig. 3, NRW consists of plain to slightly hilly basins and the low mountain ranges of the Rhenish Massif. For the mGROWA modelling the ground surface elevation from a digital terrain model (DTM) of 10 m cell-size has been aggregated to a resolution of 100 m cell-size. Surface parameters from the DTM, i.e. slope and exposition values, were derived using techniques described in Burrough and McDonell (1998) and then used for the correction of incoming solar energy available for the evapotranspiration process (Eq. (2)).

3.3. Soils

For the mGROWA model, distributed area-covering soil data is needed in order to parameterise 1-dimensional multiple-layer soil models for each of the 100 m grid cells used for the spatial discretisation of NRW. The distribution of soil units and their corresponding soil profiles originated from a soil map 1:50,000. A total of 7768 soil profiles including descriptions have been parameterised using pedotransfer functions from the NIBIS-system (Müller and Waldeck, 2011). The derived

Table 3
Surface types in North Rhine-Westphalia (100 m grid).

Surface type	Number of grid cells	Area in km^2	Share in %
Vegetation	2,756,492	27,565	80.8
Urban area	601,015	6010	17.6
Free water surface	39,126	391	1.1
Bare soil or rock without vegetation	15,947	159	0.5
Σ	3,412,580	34,125	

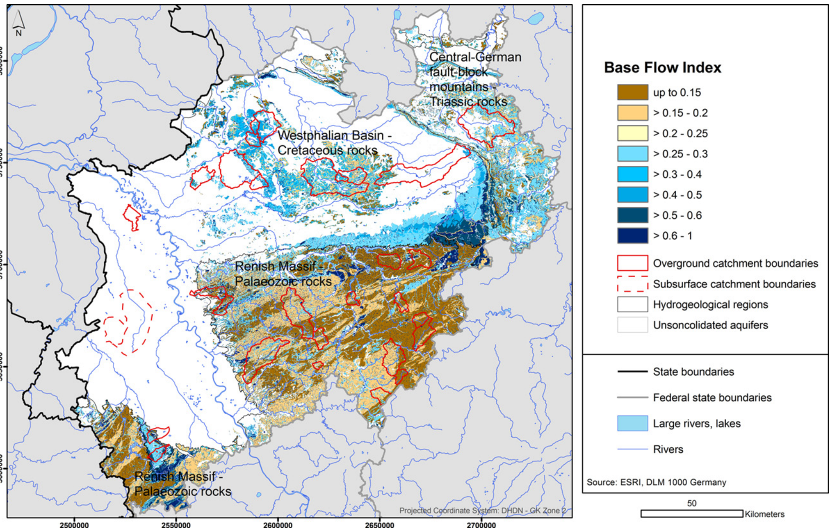

Fig. 4. BFI distribution in the solid rock aquifers of North Rhine-Westphalia.

parameters (e.g. field capacity, plant available water capacity etc.) are soil texture-specific and characterise mainly the capability of soils to store and to (vertically) release water.

Soils occurring in NRW display a wide range of soil textures. In the Westphalian Basin and along the alluvial terrace of the river Rhine sandy and loamy soils dominate. In the low mountain ranges on the contrary, soil textures with high shares of silt and clay occur frequently. In addition, the soil map contains information on the average depth to the water table and on the waterlogging tendency of cohesive soils which are used for the determination of the BFI values according to Fig. 2.

3.4. Artificial drainage systems

Intensive agriculture in the lowland river catchments of NRW especially within the Westphalian Basin is unthinkable without artificial drainage (Tetzlaff et al., 2009a). The artificial drainage installations play a major role as runoff pathways in the regions concerned. However, still little information exists concerning their location within larger river basins. Therefore, Tetzlaff et al. (2009a) developed a GIS-based approach for delineation of artificially drained areas by combining various site conditions like soil properties and land use type. This approach was validated by interpreting aerial photographs and applied to large parts of north-western Germany (98,000 km^2) including NRW (Tetzlaff et al., 2009b). For the mGROWA modelling the resulting map was re-interpreted with regard to the derivation of suitable BFIs for drained areas.

3.5. Hydrogeology of solid rock regions

In order to obtain a reliable spatial distribution of groundwater recharge in solid rock regions using mGROWA, the hydrogeological characteristics have to be considered carefully. The solid rock units occurring in NRW and their hydraulic aquifer properties are described in the Hydrogeological Map of NRW (1:100,000). This map was used in previous studies in order to calibrate characteristic BFI values for the solid rock units of NRW (Bogena et al., 2005), which have been confirmed using observed runoff records from more than 100 catchments in north-western Germany (Kunkel et al., 2006).

Fig. 4 shows the distribution of BFIs used for the separation of simulated total runoff into groundwater recharge and direct runoff in the solid rock units of NRW. The major part of the solid rock units display BFIs in the range from 0.1 up to 0.6 depending on the hydraulic conductivity of the rocks. BFI values >0.6 are only to be found in isolated Karst aquifers located in the Rhenish Massif, the Westphalian Basin and the Central-German fault block mountains.

There are three solid rock areas of regional importance in NRW having their own genesis and aquifer properties, respectively (see Fig. 4). The Palaeozoic rocks of the Rhenish Massif comprise the largest part of the solid rock areas in the southern part of NRW to the west and east of the river Rhine. The dominant aquifer typology in this region is “schist and shales” (Wendland et al., 2008), which includes folded and partly metamorphosed clastic deposits, e.g. shales, quartzites, greywackes. Groundwater flow in this type of aquifer is bound to fractures and fissures. Groundwater storage volumes are generally small, so that the corresponding BFIs are very low in general (<0.2). Hence, a significant portion of subsurface water is transported as direct runoff (i.e. natural interflow) in the weathered top-layers of the groundwater covering layers to the surface waters. Due to the very low hydraulic conductivity, this region is used for groundwater exploitation only to a limited degree. It is however of great interest for water management with regard to the storage of direct runoff in dams.

The Triassic rocks of the central-German fault-block mountains occupy the north-eastern part of NRW. The dominant aquifer rock type in this region is “Triassic sandstone” (Wendland et al., 2008), which includes alternating sequences of

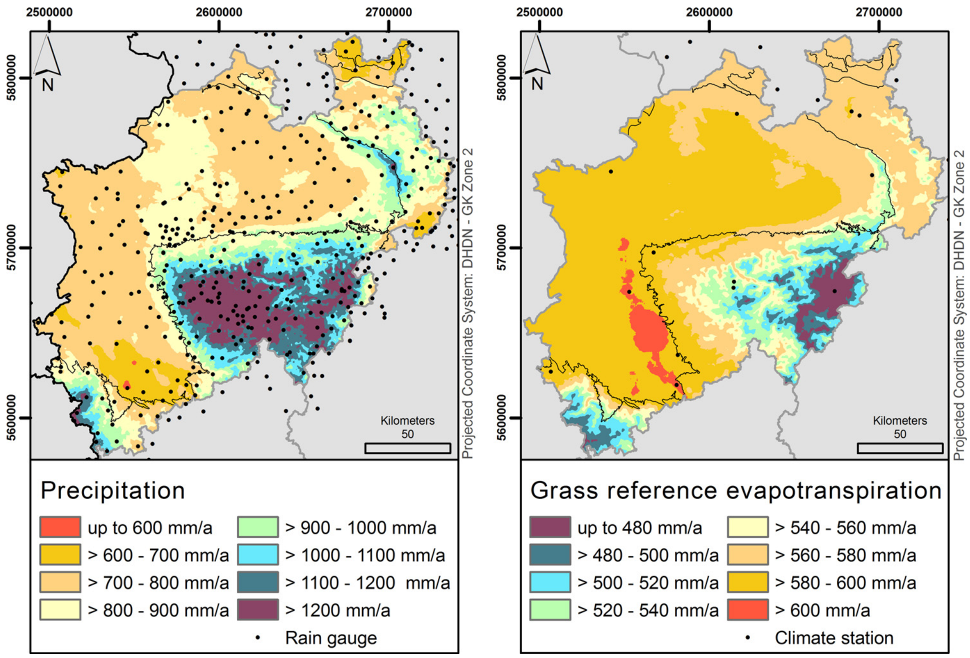

Fig. 5. Long-term mean precipitation and grass reference evapotranspiration (1971–2000) in NRW. Data basis: DWD. (mm/a = mm per year).

clastic sedimentary rocks (sandstone, marlstone, mudstone, etc.) in mostly horizontal bedding. The units exhibit a broader range of hydraulic conductivity from very low to high depending mainly on the joint-system (tectonic stress), so that BFI values range between 0.25 and 0.5. The aquifers in this region are only partially important for the regional water supply.

West of the “Triassic sandstones” a Cretaceous sedimentary basin has developed, which consists of alternating sequences of marine sediments, which show the same BFI values between 0.25 and 0.5. According to Wendland et al. (2008) these sediments belong to the aquifer typology “Limestone”.

3.6. Climate

Driving forces of the terrestrial water balance are precipitation as well as the atmospheric parameters temperature, humidity, wind speed and solar radiation, which influence the (potential) grass reference evapotranspiration level at a site. The German Weather Service (DWD) provided 360 area-covering maps (1 km raster) with monthly sums of precipitation and 360 maps containing grass reference evapotranspiration, respectively. The regionalisation of observed station-based climate data into the raster format was performed by DWD using the method of Müller-Westermeier (1995). In addition to the 1 km raster data provided by DWD, daily time series (1971–2000) of precipitation from 481 rain gauges and grass reference evapotranspiration from 23 climate stations in and around NRW was available. The daily time series from the stations were used in the mGROWA simulation in order to derive daily spatial distributions of the two climate factors based on the monthly sums given in the DWD-maps, respectively.

Due to its orography and the predominating weather conditions, comparably high mean long-term annual precipitation levels up to 1200 mm/a (mm per year) occur in the Rhenish Massif, whereas the basins obtain annual precipitation levels of 600 up to 800 mm/a only (Fig. 5, left). The level of grass reference evapotranspiration is shown in the right part of Fig. 5. Comparatively high levels up to 600 mm/a are observed in the Lower Rhine Basin, whereas decreasing levels are observed with ascending terrain and decreasing temperature in the low mountain ranges.

4. Simulation results

Water balance simulation using mGROWA has been performed for the entire Federal State of North Rhine-Westphalia based on observed climate in a spatial resolution of 100 m (approx. 3.36 million grid cells) for the time period from 1971 to 2000. In order to illustrate the time behaviour of the mGROWA model in case of land surfaces covered with vegetation, Fig. 6 shows the simulated water balance components in daily time steps for an individual grid cell for the hydrologic year 1973. The climatic input data precipitation and grass reference evapotranspiration are shown in the upper two rows. In particular the grass reference evapotranspiration shows the inner-annual (seasonal) ups and downs which are typical for temperate latitudes. Actual evapotranspiration (3rd row) follows this cycling with the exception of periods at which the soil water content is near to the permanent wilting point (6th row). This divergence was strongly pronounced end of June to beginning

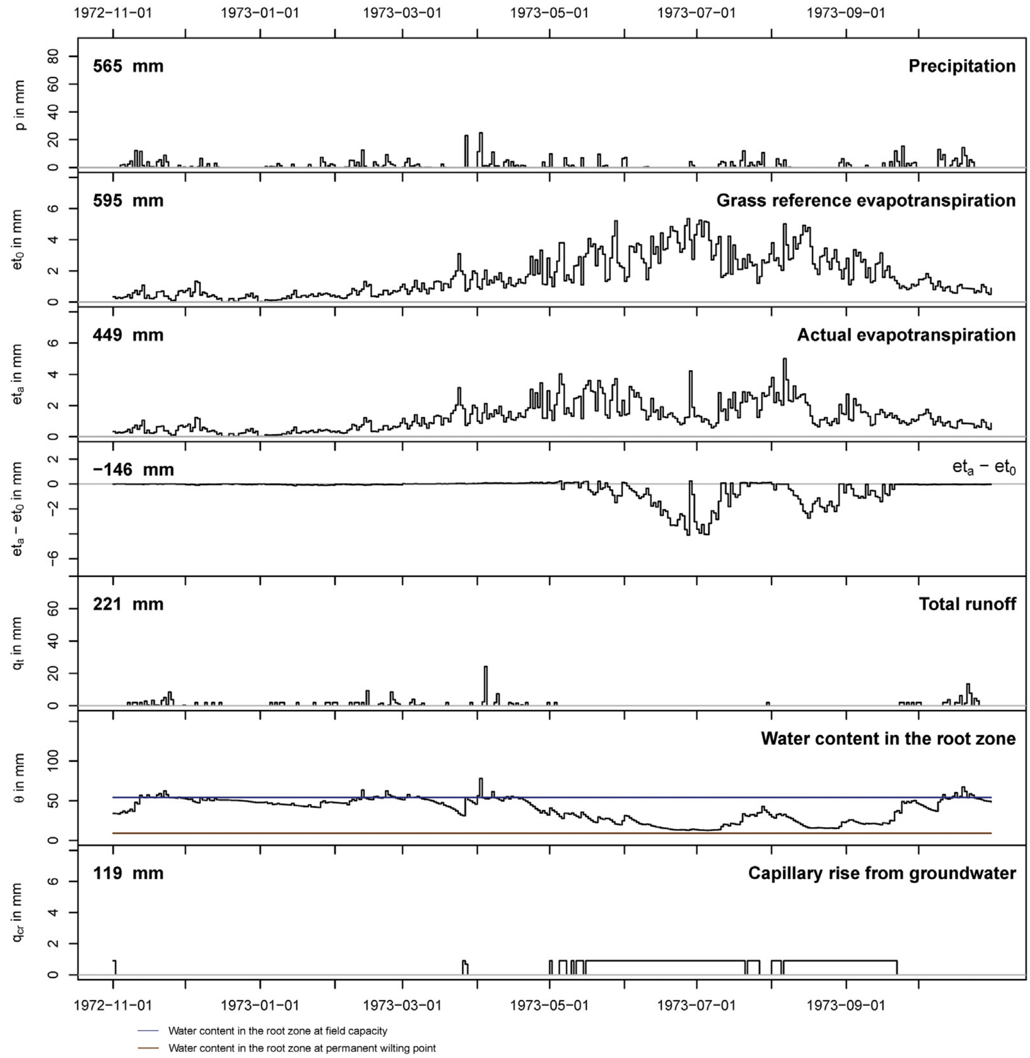

Fig. 6. Example of temporal development of simulated water balance (hydrologic year 1973) for an individual grid cell in the Federal State of North Rhine-Westphalia displaying the following site conditions: pasture as land cover, a depth to water table of 8 dm, a sandy soil on a fluvial terrace of the Ems river, a rooting depth of 3 dm. The numbers in the upper left parts of each row indicate the annual sum of the water balance quantity.

July and end of August 1973 (4th row) due to a drought even though the soil water deficit of the selected grid cell was partly compensated by capillary rise (7th row). Total runoff (5th row) is predominantly generated during winter half year, i.e. at times when the water content of the soil layers has reached field capacity. As can be seen, runoff generation may also occur in rainy phases of the summer half year, however to a considerable lesser extent.

For an overview of the general spatial distribution of the simulated water balance quantities, corresponding simulation results in daily time steps have been summarised to long-term averages shown in Fig. 7. The spatial distribution of the actual evapotranspiration and the generated total runoff is mainly influenced by the climate, soil and land cover. Due to the high percentage of imperviousness, urban areas exhibit actual evapotranspiration levels below 350 mm/a, but high total runoff levels and thus, high direct runoff levels. In the low mountain ranges of the Rhenish Massif, actual evapotranspiration decreases with ascending terrain. There however, total runoff exceeds 600 mm/a in high altitudes due to the high precipitation levels. Depending mainly on the type of vegetation cover and water availability, actual evapotranspiration varies between 450 and 550 mm/a in lowland regions with deep groundwater tables, e.g. in the Lower Rhine basin. There, total runoff ranges from 200 up to 400 mm/a. In lowland regions with shallow groundwater tables, where capillary rise from the aquifer into the root zone occurs, actual evapotranspiration may exceed 650 mm/a. Combined with a mean long-term precipitation level below 700 mm/a these sites tend to have a negative water balance which means that groundwater discharge by evapotranspiration during summer exceeds the generated runoff (and net groundwater recharge).

The distribution of net groundwater recharge and direct runoff depends on the underground conditions. Due to the low hydraulic conductivity and water storage capacity of the aquifer typologies situated in the Rhenish Massif, direct runoff

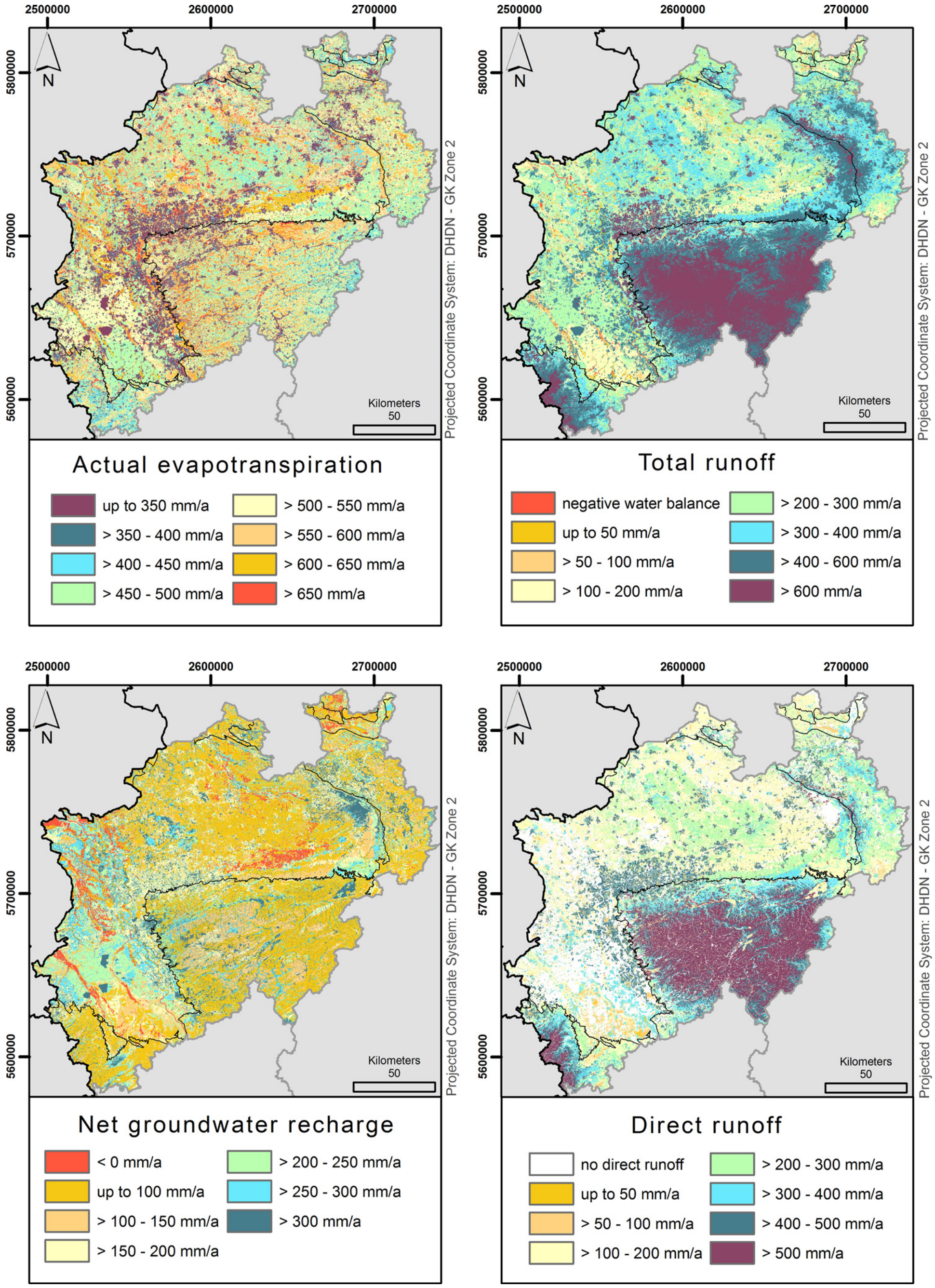

Fig. 7. Long-term mean water balance quantities in North Rhine-Westphalia (1971–2000). (mm/a = mm per year).

(surface runoff and natural interflow) is the dominant component (Fig. 7). Highest net groundwater recharge rates (150 up to 300 mm/a) occur in the lowland regions and coincide with the occurrence of unconsolidated sand and gravel aquifers and deep water tables. A moderate net groundwater recharge of around 100 mm/a takes place in lowland areas showing stagnant soil moisture or medium percentages of imperviousness. In lowland regions net groundwater recharge may become negative in cases artificial drainage systems have been installed on agriculturally used land with shallow groundwater tables. It becomes evident that drainage systems generate an "artificial" direct runoff in those regions.

Fig. 8 shows a time series of the NRW-wide averaged annual groundwater recharge rates for the period 1971–2000. The long-term mean groundwater recharge rate is approx. 170 mm/a. The differences between the individual years however is high and range from 50 up to 280 mm/a. A succession of years with low, medium and relatively high groundwater recharge is visible. The low-pass-filtered curve (red) has been calculated in order to point up the succession of a decade with groundwater

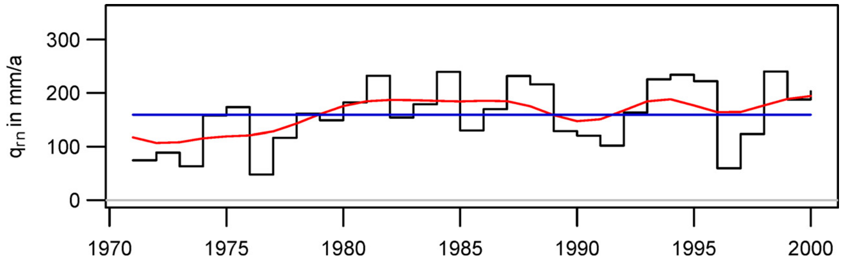

Fig. 8. Simulated annual groundwater recharge in North Rhine-Westphalia. Red curve: low-pass-filtered (10-year-period); blue line: long-term average 1971–2000. (mm/a = mm per year). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

recharge below the long term average (the seventies) and the ensuing decade with groundwater recharge above the long term average (the eighties). This periodicity seems to change in the nineties, but there seems to be no trend indicating increasing or declining groundwater recharge rates.

Fig. 9 shows the average monthly groundwater recharge (1971–2000). The main groundwater recharge period begins in October end ends in March. Maximum rates are reached in December and January. Then, with the start of the vegetation period in April, groundwater recharge ceases. At this time of the year capillary rise on sites with shallow groundwater is initiated due to the increasing soil moisture deficit in upper soil layers (Fig. 9; red-coloured areas showing negative net groundwater recharge).

5. Model evaluation

5.1. Methodology of evaluation

The goodness of the simulated water balance components can be assessed on the Federal State level by comparing simulated total runoff and groundwater recharge levels with recorded hydrographs in suitable sub-catchments. A total of 30 hydrographs of relatively small headwater catchments with a preferably long observation period (1971–2000 if possible) which cover an area of approx. 3300 km^2 (approx. 10% of NRW) were chosen for the evaluation (Fig. 4). They are relatively evenly distributed within the model area.

For the assessment of simulated total runoff, the observed long-term mean river discharge has been used. These values can be calculated easily from the hydrograph by averaging the daily mean discharge values. In contrast, long-term mean base flow levels which are commonly used to compare with simulated groundwater recharge are not directly measurable and must therefore be derived from hydrographs by suitable runoff separation techniques (Tallaksen, 1995). The runoff separation techniques most commonly used in Germany comprise the method of Wundt (1958) for watersheds where unconsolidated aquifers are dominant and Demuth (1993) for watersheds where hard rock aquifers prevail (Bogena et al., 2005). In anthropogenic influenced catchments such as in the Lower Rhine lignite mining area where discharge is lowered due to extensive groundwater withdrawal, base flow can be estimated by the Multichannel-Wiener-Filter approach (Bucher, 1999). Using this approach it is possible to derive a base flow time series from the time-behaviour and fluctuation range of a groundwater hydrograph. Three of those filtered time series were available for gauges in the mining-influenced region of the Lower Rhine Embayment and have been used in order to evaluate the subsurface catchment results shown in Fig. 4.

Simulated water balance components can be regarded as representative if simulated long-term total runoff levels match their observed counterparts and the simulated long-term groundwater recharge levels the observed base flow levels sufficiently well. In order to objectively evaluate both quantities, the quantitative statistics NSE (Nash-Sutcliffe efficiency) and PBIAS (percent bias) have been used as recommend by Moriasi et al. (2007) for stream flow.

The Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) is a normalised statistics that indicates how precise simulated and observed data fit to the 1:1-line. NSE may reach values between $-\infty$ and 1.0, however only values between 0 and 1.0 indicate an acceptable efficiency. According to Moriasi et al. (2007), a "very good" or "good" model efficiency in individual catchments is achieved with NSE quality levels higher than 0.75 and 0.65, respectively.

NSE is usually applied for the comparison of two discharge time series and basically compares the variance of observed discharge values against the residual variance of the simulation results. In such an application the NSE is used for individual gauging stations in order to check if the simulated runoff values show the same time behaviour as the observed runoff values. In this study, the NSE concept is applied differently. It is applied simultaneously to all selected gauging stations in NRW, however, only mean runoff values of a defined time period (years, hydrological periods) are considered. In order to avoid a disproportional influence of small catchments on this NSE application, the individual catchment area sizes are included as weights in the calculation:

$$\mathrm{NSE_C} = 1 - \frac{\sum_{j=1}^{m}(A_{C,j} \cdot (q_{\mathrm{obs},j} - q_{\mathrm{sim},j})^2)}{\sum_{j=1}^{m}(A_{C,j} \cdot (q_{\mathrm{obs},j} - q_{\mathrm{obs},A_{CV}})^2)}. \quad (10)$$

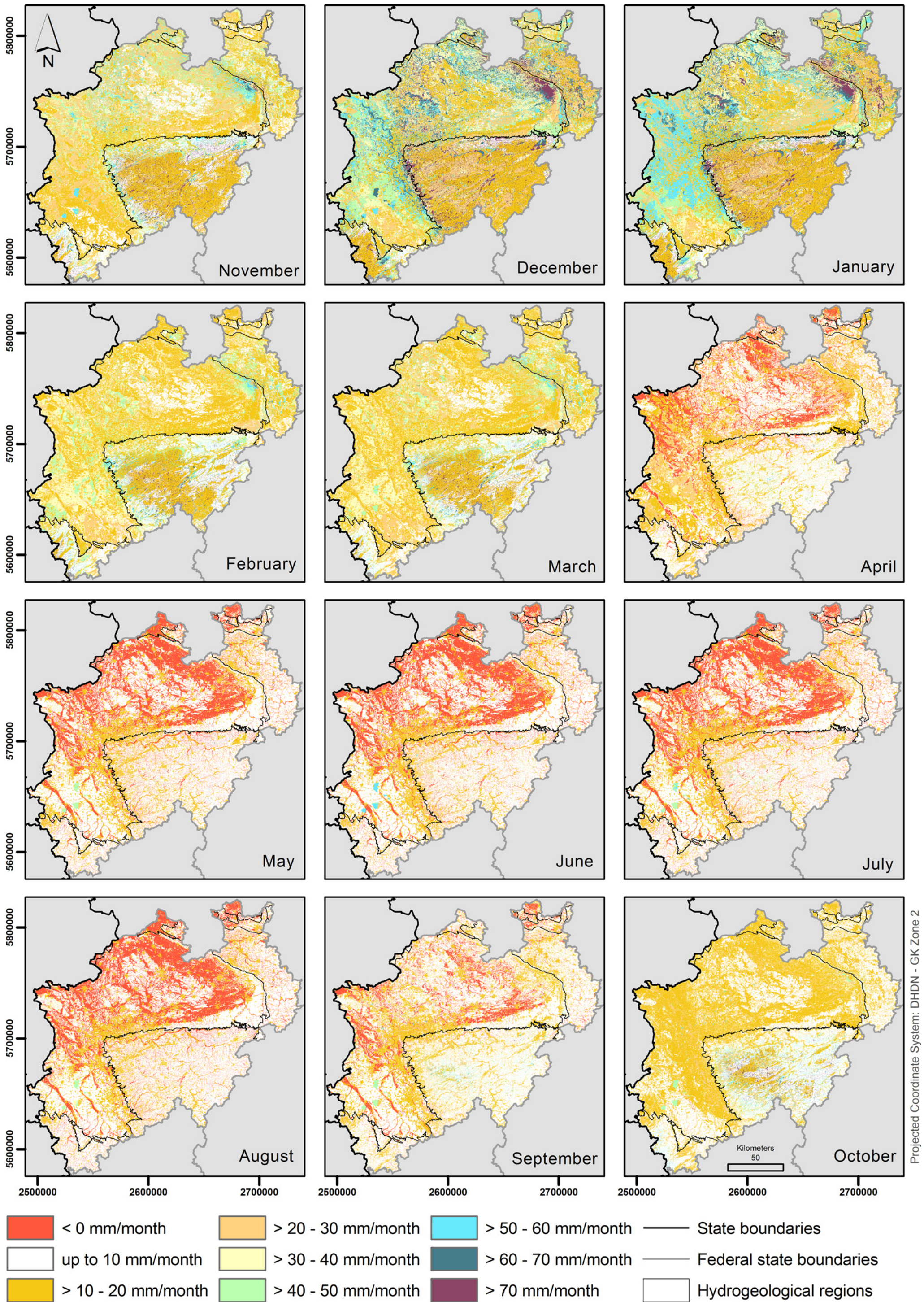

Fig. 9. Average simulated monthly net groundwater recharge (1971–2000). Negative net groundwater recharge rates occur at sites where capillary rise from shallow aquifers exceeds groundwater recharge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

In Eq. (10) q_{obs} denotes the observed discharge per unit area, q_{sim} the corresponding simulated values, $q_{obs,A_{CV}}$ the observed overall discharge per unit area of all the catchments under consideration, A_C the individual areas of the catchments and j the catchment index. In that way, NSE_C can be used as a measure of efficiency for the evaluation of the simulated spatial distribution of mean total runoff and mean groundwater recharge for an arbitrary time period and a variety of catchments.

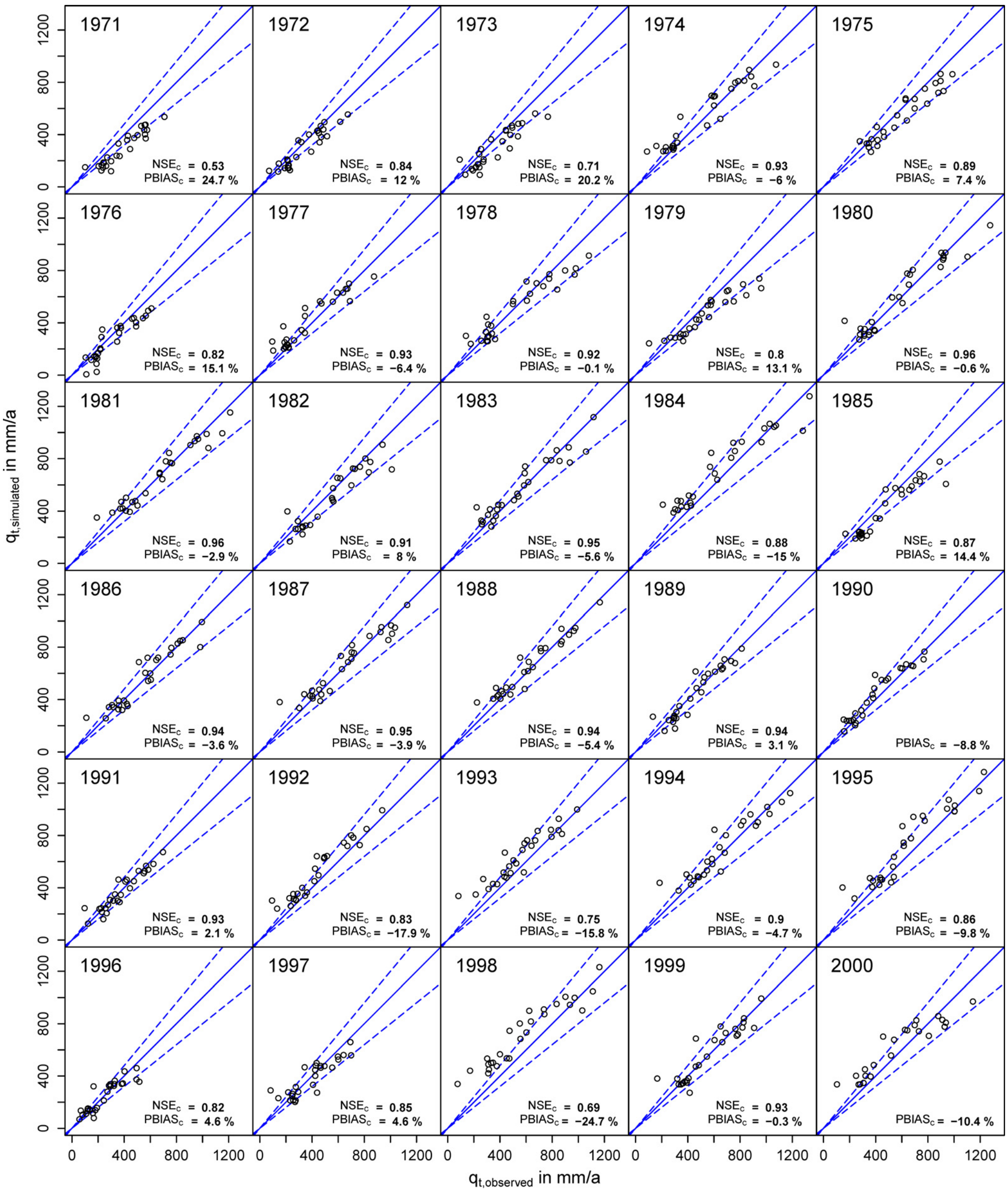

Fig. 10. Evaluation of simulated yearly total runoff in the overground catchments shown in Fig. 4. Blue continuous line: 1:1-line; Blue dashed lines: 20% deviation. NSEC could not be calculated for each year due to gaps in the observed hydrographs of single catchments. (mm/a = mm per year).

Using the areas of the catchments as weights ensures that a good match of observed and simulated flow regime in a relatively large catchment has a stronger influence on the resulting model performance than the results of a smaller one.

PBIAS characterises the tendency of a simulated discharge time series to over- or underestimate the observed hydrograph (Gupta et al., 1999). The optimal value of PBIAS is 0. PBIAS has a positive value in case the model simulation underestimates the observed values and a negative value in case the observed values are overestimated. According to Moriasi et al. (2007), "very good" or "good" performance ratings in individual catchments are achieved by PBIAS within a range of ±10% and ±15%, respectively. Similar to NSE_C, $PBIAS_C$ is calculated using the catchment areas as weights (Eq. (11)). Accordingly, $PBIAS_C$ has been used to assess the tendency of mGROWA simulations to over- or underestimate the runoff regime on the whole in North Rhine-Westphalia.

$$PBIAS_C = \frac{\sum_{j=1}^{m}(A_{C,j} \cdot (q_{obs,j} - q_{sim,j}) \cdot 100)}{\sum_{j=1}^{m}(A_{C,j} \cdot q_{obs,j})} \quad (11)$$

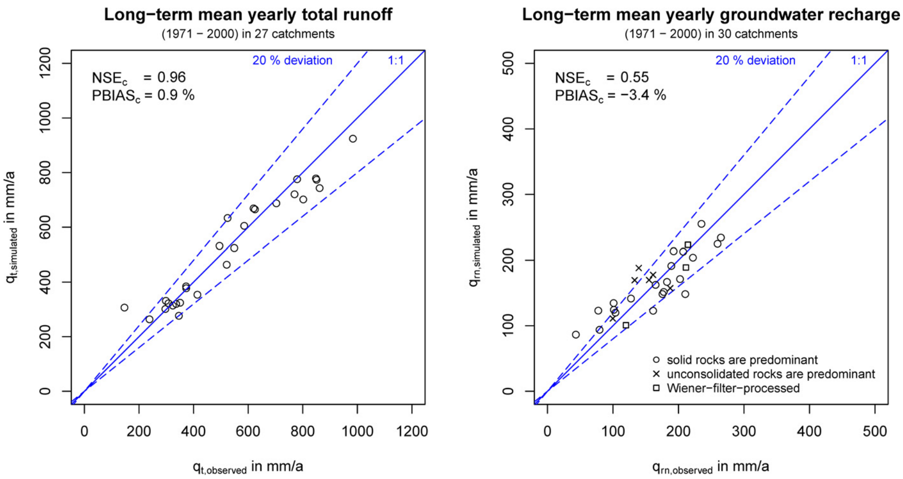

Fig. 11. Evaluation of simulated mean long-term yearly total runoff and groundwater recharge for the hydrologic period 1971–2000. (mm/a = mm per year).

5.2. Evaluation results

Since runoff concentration in the river network and water storages below the root zone (soil) are not considered in mGROWA, a comparison of simulated daily total runoff values with observed daily runoff values on the level of gauged catchments is not recommended. Accordingly, Fig. 10 shows the comparison of observed and simulated total runoff values for the period 1971–2000 on a yearly basis.

The NSE_C values for the individual years are in general >0.65 indicating a “good” model efficiency. The $PBIAS_C$ values calculated on a yearly basis fluctuate in an acceptable range too. However for 11 individual years (compare Fig. 10, e.g. years 1973 and 1998) $PBIAS_C$ values are above 10% or below −10%, which indicates that mGROWA seems to over- or underestimate the observed total runoff periodically. The reason for this behaviour is the inter-annual filling-up and discharging of the catchment storages and the corresponding time lag until generated total runoff becomes apparent at the gauges. In wet years, e.g. 1998, the simulated total runoff may exceed the observed runoff. In this case, a part of the generated total runoff is used to replenish the subsurface water storages. Consequently, runoff at the gauges is delayed. In dry years however, e.g. 1973, the simulated runoff values may be significantly lower than the observed values. Due to the continuous discharging of subsurface water storages, water released to the surface waters contains a significant portion of base flow which has been generated in former years.

A significant over- or underestimation of the observed hydrologic regime does not exist anymore when long-term mean values of total runoff are compared as shown in Fig. 11(left). Both statistics indicate a “very good” model performance (NSE_C = 0.96; $PBIAS_C$ = 0.9%) as changes in the water storages become negligible in case longer time periods are considered.

For groundwater recharge a “good” model efficiency (NSE_C = 0.55) has been reached (Fig. 11, right). The slight overestimation indicated by $PBIAS_C$ (approx. 3.4%) for the simulated mean long-term groundwater recharge compared to the observed base flow seems likewise insignificant. In judging this evaluation result, the complex geological setting in several catchments as well as the elusive factors influencing the observed low flows in hydrographs should be taken into account.

The good accordance of simulated and observed long-term runoff should not hide the fact that short-term runoff generation was not validated, as a component for the simulation of streamflow in daily time steps has not been included in mGROWA so far. An appropriate extension of mGROWA will be done once this quantity shall be determined in an application of the model. Engel et al. (2012) validated short-term fluctuation of soil moisture simulations based on the multiple-layer soil water balance sub-model of mGROWA using measured soil moisture time series. The good accordance of simulated and observed fluctuations of soil moisture documented by Engel et al. (2012) indicates that short-term runoff generation is represented adequately in mGROWA.

6. Quantitative assessment of present groundwater withdrawals

The area-covering mGROWA model results for groundwater recharge have been used to determine the spatially averaged groundwater recharge in NRWs groundwater bodies. These values are needed for the quantitative status assessment according to EU-WFD (2000) as they are an important input quantity for determining sustainable groundwater availability. The second quantity needed to determine the groundwater body specific sustainable available amount of groundwater is the actual yearly groundwater withdrawal. We suggest to use the ratio of groundwater withdrawal and groundwater recharge as an indicator to assess the extent of groundwater exploitation in the different groundwater bodies and a first approximation whether the exploitation is in some respects sustainable or not.

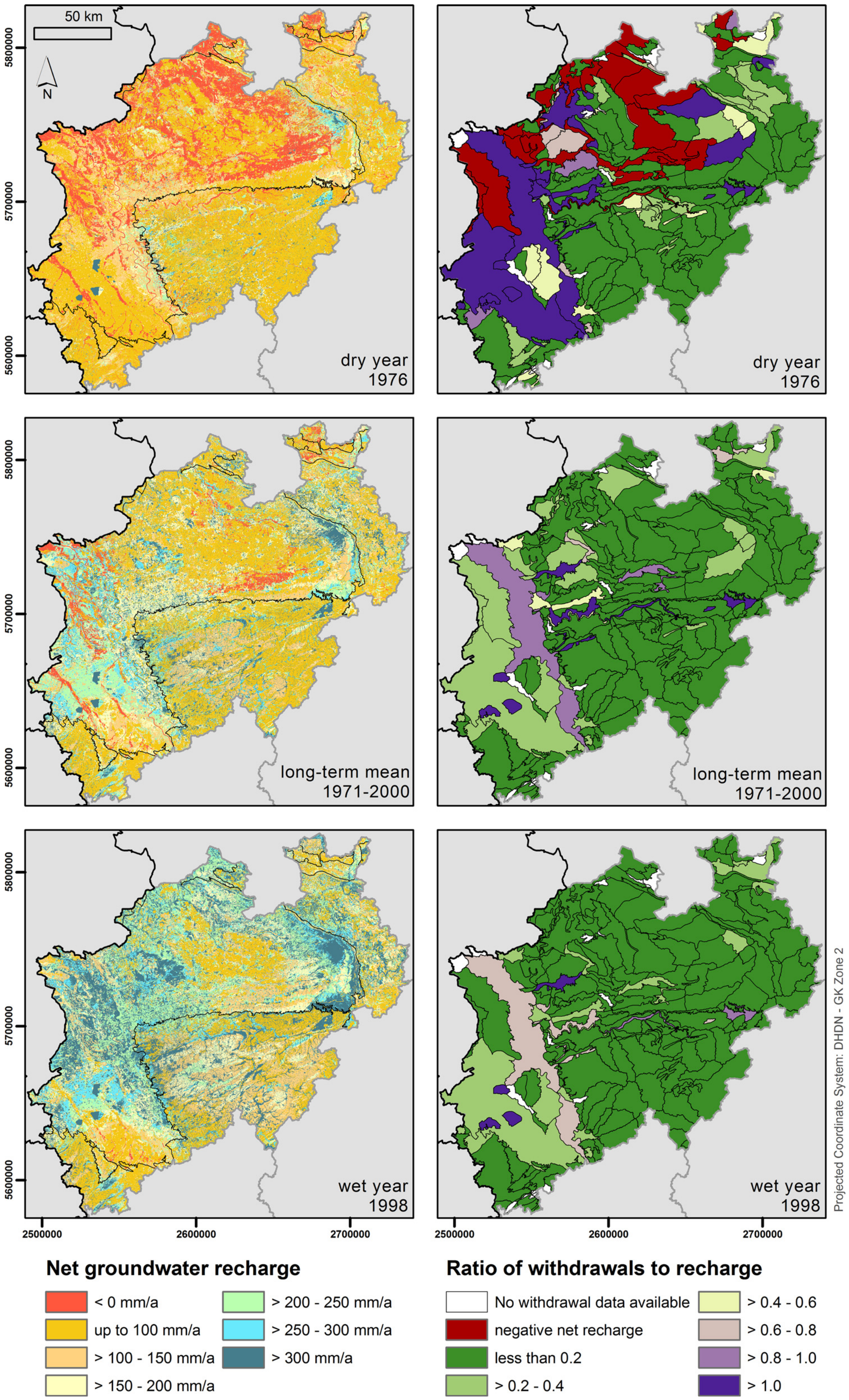

Fig. 12. Net groundwater recharge (left) and groundwater-body-specific ratio of groundwater withdrawals to groundwater recharge (right) in the hydrological years 1976 (left), 1998 (right) and the long-term average 1971–2000 (centre). (mm/a = mm per year).

All in all, recorded withdrawal data of 5135 withdrawal points were available for the years 2003 to 2005 only. They have been used in order to calculate mean values of groundwater body specific withdrawals per year. In order to illustrate the general situation in dry, medium and wet years, the withdrawal values were set in relation to the groundwater body specific recharge simulated for the year 1976, the long-term mean of the period 1971–2000 and the year 1998, respectively (Fig. 12). In these periods, the mean precipitation levels in NRW were approx. 610, 870 and 1120 mm/a. The corresponding groundwater recharge distributions are also shown in Fig. 12 in order to enable a spatial interpretation, e.g. with regard to the extent varying precipitation levels influence groundwater recharge levels.

The ratios of withdrawals to groundwater recharge show for most groundwater bodies in the consolidated rock areas of NRW values below 0.2 which indicates that sustainable use of groundwater resources is guaranteed. The groundwater bodies of the lowland parts of NRW show for wet and medium years partly ratios less than 0.4 which indicate that these areas are at present also not at risk of unsustainable exploitation. However, the ratio can increase with decreasing groundwater recharge considerably and finally reach negative values, if negative net groundwater recharge of the groundwater body is less than zero in single dry years. Assumed that as a consequence of climate change the frequency of such dry years would increase, these groundwater bodies could be at risk of unsustainable exploitation.

However, there are three groundwater bodies in the southern part of the Lower Rhine Basin which show extreme high ratios. This is caused by the open pit draining of the lignite mines located there and should not be regarded as worrying in the context discussed above, as the dewatering mainly affects deep reservoirs. Additionally, several groundwater bodies in the industrial belt along the stretch of the river Rhine show ratios near to 1, indicating that these groundwater bodies are near to unsustainable groundwater exploitation. It has to be taken into account however, that these groundwater bodies are additionally recharged by river bank infiltration and inflows from other upstream groundwater bodies in addition to rain-fed groundwater recharge.

Over-exploitation of groundwater resources may occur in dry periods; above all, however, groundwater bodies showing high withdrawal rates and shallow groundwater are concerned. This constraint implies that the sustainability of groundwater use should not only be assessed based on regional groundwater recharge rates exclusively, but also include regional groundwater withdrawal rates.

7. Summary and conclusions

The mGROWA model has been developed in order to simulate distributed water balance on the level of large river systems or entire countries or Federal States. In a first step, mGROWA simulates soil water dynamics, actual evapotranspiration and runoff generation in daily time steps. In a second step, the determined total runoff levels are separated into the runoff components groundwater recharge and direct runoff (including runoff from artificially drained agricultural areas) using BFI values.

In the application to the entire Federal State of North Rhine-Westphalia the simulation was performed in daily time steps for the hydrological reference period 1971–2000 and in a spatial resolution of 100 by 100 m. Model results for mean long-term averages have shown that total runoff levels above 600 mm/a occur in the Rhenish Massif, whereas relatively low total runoff levels (<150 mm/a) have in contrast been determined for the Lower Rhine basin. Monthly averages of groundwater recharge rates have shown that maximum recharge occurs in December and January, whereas recharge between May to August becomes insignificant. mGROWA model results have been evaluated using stream flow records. There was no significant tendency to over- or underestimate total runoff determined. Good model efficiency has been achieved for groundwater recharge which confirms the chosen BFI approach to derive reliable area-differentiated groundwater recharge levels.

mGROWA model results for groundwater recharge have subsequently been used to assess the degree of groundwater exploitation in the groundwater bodies of NRW. For this purpose the ratio of groundwater withdrawals and groundwater recharge has been calculated. The majority of groundwater bodies display ratios in the range of 0.1–0.4 indicating that there is at present no risk of unsustainable groundwater exploitation. Higher ratios have been assessed for several groundwater bodies in the industrial belt along the river Rhine. These groundwater bodies, however, have been classified as being close to unsustainable groundwater exploitation.

mGROWA simulations cannot only be performed based on observed climate data. In the mGROWA model special attention has been paid to the physically based calculation of actual evapotranspiration and the associated storage functions. This attribute is important in context of water resources management as it is a mandatory precondition for simulations using climate data from regional climate models (RCMs). Doing so will enable the projection of the impact of climate change on runoff generation and groundwater recharge as a prerequisite for the development of regionally adapted groundwater management strategies.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ejrh.2015.06.018. These data include Google maps of the most important areas described in this article.

References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., Rasmussen, J., 1986. An introduction to the European Hydrological System – Systeme Hydrologique Europeen. "SHE", 2: Structure of a physically-based, distributed modelling system. J. Hydrol. 87 (1–2), 61–77, http://dx.doi.org/10.1016/0022-1694(86)90115-0.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO – Food and Agriculture Organization of the United Nations.

Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994. An update for the definition of reference evapotranspiration. ICID Bull. 43 (2), 1–34.

Andelov, M., Kunkel, R., Uhan, J., Wendland, F., 2014. Determination of nitrogen reduction levels necessary to reach groundwater quality targets in Slovenia. J. Environ. Sci. (China) 26 (9), 1806–1817, http://dx.doi.org/10.1016/j.jes.2014.06.027.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part 1: model development. J. Am. Water Resour. Assoc. 34 (1), 73–89, http://dx.doi.org/10.1111/j.1752-1688.1998.tb05961.x.

ATV-DVWK, 2002. Verdunstung in Bezug zu Landnutzung, Bewuchs und Boden. Merkblatt ATV-DVWK-M, 504. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.

Becker, A., Serban, P., 1990. Hydrological Models for Water-Resources System Design and Operation. World Meteorological Organisation.

Beven, K., Freer, J., 2001. A dynamic TOPMODEL. Hydrol. Process. 15 (10), 1993–2011, http://dx.doi.org/10.1002/hyp.252.

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. Hydrol. Sci. Bull. 24 (1), 43–69.

Bloomfield, J.P., Allen, D.J., Griffiths, K.J., 2009. Examining geological controls on baseflow index (BFI) using regression analysis: an illustration from the Thames Basin, UK. J. Hydrol. 373 (1–2), 164–176, http://dx.doi.org/10.1016/j.jhydrol.2009.04.025.

Bogena, H., Kunkel, R., Schöbel, T., Schrey, H.P., Wendland, F., 2005. Distributed modeling of groundwater recharge at the macroscale. Ecol. Model. 187, 15–26, http://dx.doi.org/10.1016/j.ecolmodel.2005.01.023.

Bucher, B., 1999. Die Analyse von Grundwasserganglinien mit dem Wiener-Mehrkanal-Filter. Grundwasser 3, 113–118.

Burrough, P.A., McDonell, R.A., 1998. Principles of Geographical Information Systems. Oxford University Press, New York.

de Wit, M., Meinardi, C., Wendland, F., Kunkel, R., 2000. Modelling water fluxes for the analysis of diffuse pollution at the river basin scale. Hydrol. Process. 14 (10), 1707–1723, http://dx.doi.org/10.1002/1099-1085(200007)14:10<1707::AID-HYP64>3.0.CO;2-E.

Demuth, S., 1993. Untersuchungen zum Niedrigwasser in West-Europa. Freiburger Schriften zur Hydrologie. 1. Institut für Hydrologie, Universität Freiburg.

Dingman, S.L., 2002. Physical Hydrology. Prentice-Hall, Inc., Upper Saddle River, NJ.

Disse, M., 1995. Modellierung der Verdunstung und der Grundwasserneubildung in ebenen Einzugsgebieten, Fakultät für Bauingenieur- und Vermessungswesen der Universität Fridericiana zu Karlsruhe (TH).

Dörhöfer, G., Josopait, V., 1980. Eine Methode zur flächendifferenzierten Ermittlung der Grundwasserneubildungsrate, vol. C(27). Geologisches Jahrbuch Reihe, pp. 45–65.

Dripps, W.R., Bradbury, K.R., 2007. A simple daily soil water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas. Hydrogeol. J. 15 (3), 433–444, http://dx.doi.org/10.1007/s10040-007-0160-6.

Engel, N., Müller, U., Schäfer, W., 2012. BOWAB – Ein Mehrschicht-Bodenwasserhaushaltsmodell. GeoBerichte – Landesamt für Bergbau. Energie Geol. 20, 85–98.

Gupta, H.V., Sorooshian, S., Yapo, O.P., 1999. Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J. Hydraul. Eng. 4 (2), 135–143.

Haberlandt, U., Klöcking, B., Krysanova, V., Becker, A., 2001. Regionalisation of the base flow index from dynamically simulated flow components – a case study in the Elbe River Basin. J. Hydrol. 248 (1–4), 35–53, http://dx.doi.org/10.1016/S0022-1694(01)00391-2.

Herrmann, F., et al., 2013. Zeitlich und räumlich hochaufgelöste flächendifferenzierte Simulation des Landschaftswasserhaushalts in Niedersachsen mit dem Model mGROWA. Hydrol. Wasserbewirtsch. 57 (5), 206–224, http://dx.doi.org/10.5675/HyWa_2013,5_2.

Herrmann, F., et al., 2009. Groundwater recharge rates for regional groundwater modelling: a case study using GROWA in the Lower Rhine lignite mining area, Germany. Hydrogeol. J. 17 (8), 2049–2060, http://dx.doi.org/10.1007/s10040-009-0493-4.

Huang, S., Krysanova, V., Österle, H., Hattermann, F.F., 2010. Simulation of spatiotemporal dynamics of water fluxes in Germany under climate change. Hydrol. Process. 24 (23), 3289–3306, http://dx.doi.org/10.1002/hyp.7753.

Institute of Hydrology, 1980. Low Flow Studies Report. Institute of Hydrology, Wallingford, UK.

Jankiewicz, P., et al., 2005. Abflusshöhe – Sickerwasserrate – Grundwasserneubildung – Drei Theme im Hydrologischen Atlas von Deutschland. Hydrol. Wasserbewirtsch. 49 (1), 2–13.

Krysanova, V., Müller-Wohlfeil, D.-I., Becker, A., 1998. Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds. Ecol. Model. 106 (2–3), 261–289, http://dx.doi.org/10.1016/S0304-3800(97)00204-4.

Kunkel, R., Bogena, H., Tetzlaff, B., Wendland, F., 2006. Digitale Grundwasserneubildungskarte von Niedersachsen, Nordrhein-Westfalen, Hamburg und Bremen: Erstellung und Auswertungsbeispiele. Hydrol. Wasserbewirtsch. 50 (5), 212–219.

Kunkel, R., Kreins, P., Tetzlaff, B., Wendland, F., 2010. Forecasting the effects of EU policy measures on the nitrate pollution of groundwater and surface waters. J. Environ. Sci. 22 (6), 872–877, http://dx.doi.org/10.1016/S1001-0742(09)60191-1.

Kunkel, R., Wendland, F., 2002. The GROWA98 model for water balance analysis in large river basins – the river Elbe case study. J. Hydrol. 259 (1–4), 152–162, http://dx.doi.org/10.1016/S0022-1694(01)00579-0.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 hydrological model. J. Hydrol. 201 (1–4), 272–288, http://dx.doi.org/10.1016/S0022-1694(97)00041-3.

Lvovich, M.I., 1972. Hydrologic budget of continents and estimate of the balance of global fresh water resources. Soviet Hydrol., 4.

Meyboom, P., 1961. Estimating ground-water recharge from stream hydrographs. J. Geophys. Res. 66 (4), 1203–1214, http://dx.doi.org/10.1029/JZ066i004p01203.

Minhas, B.S., Parikh, K.S., Srinivasan, T.N., 1974. Toward the structure of a production function for wheat yields with dated inputs of irrigation water. Water Resour. Res. 10 (3), 383–393, http://dx.doi.org/10.1029/WR010i003p00383.

Monteith, J.L., 1965. Evaporation and environment. In: Fogg, G.E. (Ed.), Symposium of the Society for Experimental Biology. The State and Movement of Water in Living Organisms, pp. 205–234.

Moriasi, D.N., et al., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50 (3), 885–900, http://dx.doi.org/10.13031/2013.23153.

Müller-Westermeier, G., 1995. Numerisches Verfahren zur Erstellung klimatologischer Karten, 193. Wetterdienst Offenbach, Deutscher.

Müller, U., Waldeck, A., 2011. Auswertungsmethoden im Bodenschutz. GeoBerichte, 19. Landesamt für Bergbau, Energie und Geologie Niedersachsen.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I – A discussion of principles. J. Hydrol. 10 (3), 282–290, http://dx.doi.org/10.1016/0022-1694(70)90255-6.

Renger, M., et al., 2009. Bodenphysikalische Kennwerte und Berechnungsverfahren für die Praxis. In: Wessolek, G., Kaupenjohann, M., Renger, M. (Eds.), Bodenökologie und Bodengenese. Technische Universität Berlin – Fachgebiet Bodenkunde/Standortkunde und Bodenschutz – Institut für Okologie.

Schulla, J., 69 1997. Hydrologische Modellierung von Flussgebieten zur Abschätzung der Folgen von Klimaänderungen. Züricher Geographische Schriften. Verlag Geographisches Institut ETH Zürich.

Schwärzel, K., Šimůnek, J., Stoffregen, H., Wessolek, G., van Genuchten, M.T., 2006. Estimation of the unsaturated hydraulic conductivity of peat soils. Vadose Zone J. 5 (2), 628–640.

Tallaksen, L.M., 1995. A review of baseflow recession analysis. J. Hydrol. 165 (1–4), 349–370, http://dx.doi.org/10.1016/0022-1694(94)02540-R.

Tetzlaff, B., Kuhr, P., Vereecken, H., Wendland, F., 2009a. Aerial photograph-based delineation of artificially drained areas as a basis for water balance and phosphorus modelling in large river basins. Phys. Chem. Earth Parts A/B/C 34 (8–9), 552–564, http://dx.doi.org/10.1016/j.pce.2009.02.002.

Tetzlaff, B., Kuhr, P., Wendland, F., 2009b. A new method for creating maps of artificially drained areas in large river basins based on aerial photographs and geodata. Irrig. Drain. 58 (5), 569–585, http://dx.doi.org/10.1002/ird.426.

van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44 (5), 892–898, http://dx.doi.org/10.2136/sssaj1980.03615995004400050002x.

Vereecken, H., et al., 2010. Using pedotransfer functions to estimate the van Genuchten-Mualem soil hydraulic properties: a review. Vadose Zone J. 9 (4), 795–820, http://dx.doi.org/10.2136/vzj2010.0045.

Wendland, F., et al., 2008. European aquifer typology: a practical framework for an overview of major groundwater composition at European scale. Environ. Geol. 55 (1), 77, http://dx.doi.org/10.1007/s00254-007-0966-5.

Wendland, F., Kunkel, R., Tetzlaff, B., Dörhöfer, G., 2003. GIS-based determination of the mean long-term groundwater recharge in Lower Saxony. Environ. Geol. 45 (2), 273–278, http://dx.doi.org/10.1007/s00254-003-0879-x.

Wessolek, G., Facklam, M., 1997. Standorteigenschaften und Wasserhaushalt von versiegelten Flächen. Zeitschrift für Pflanzenernährung und Bodenkunde 160 (1), 41–46.

Wundt, W., 1958. Die Kleinstwasserführung der Flüsse als Maß für die verfügbaren Grundwassermengen. In: Grahmann, R. (Ed.), Das Wasserdargebot in der Bundesrepublik Deutschland. , pp. 47–54.