A water balance approach to indicate effects of man-made enhanced greenhouse warming on groundwater recharge in the Kalahari

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Abstract In this study the distributed, process-oriented, physically-based water balance model MODBIL is set up for two Kalahari sub-catchments in northeastern Namibia and northwestern Botswana to show possible impacts of climatic change on groundwater recharge. The results of the 22-year-long calibration period are verified with the chloride mass balance and hydro-graphs, and are in the next step compared with results of a prediction simulation. For the prediction water balance model, precipitation time series under conditions of enhanced greenhouse warming have been produced based on statistical downscaling procedures of large-scale circulation models and regional climate. Results reveal that summer rainfall in northeastern Namibia will be temporarily more pronounced with significantly increased precipitation during January and February, but less precipitation in March. With this approach an increase in mean groundwater recharge and interflow is predicted for the two catchments.

Key words greenhouse warming; groundwater recharge; Kalahari; statistical downscaling; water balance model

INTRODUCTION

The most important water resource in drylands such as the Kalahari is groundwater. There the groundwater recharge and its temporal and spatial variations need to be assessed reliably in order to prevent the survival-threatening over-exploitation of aquifers. This becomes even more important with future changes in climate, especially precipitation.

Reviews on groundwater recharge estimation are available in Lerner *et al.* (1990), Simmers (1997) and Scanlon & Cook (2002). Most of the reliable techniques for groundwater recharge estimations are limited to temporal or spatial point results, but grid-based conceptual water balance models with sensible simplifications at the catchment scale are the only appropriate tools for long-term water resource planning. Basic demands on such water balance models are the adequate representation of physical processes. Furthermore, models must be set up for a significantly long time span with a high temporal resolution. Daily climatic data, which acknowledge the important significance of single events, are found to be appropriate for recharge estimation in drylands (Hendrickx & Walker, 1997). One of the most critical factors is still the determination of evapotranspiration. An appropriate and detailed review on estimation of actual evapotranspiration is given by Allen *et al.* (1998). The simulation of groundwater recharge must be based on physical processes in the soil moisture storage, again in small time steps, at least daily. A common simplification here is the concept of field capacity, where a soil drains freely once the relevant water content is reached (e.g. Rushton *et al.*, 2006).

The study area gets rainfall mainly in summer (from November to April) linked to tropical disturbances of high convective activity. Arid conditions across widespread areas of Namibia and Botswana are due to strong subtropical high pressure influence in combination with the cold Benguela current moving northward along the coast of South Africa and Namibia. Tropical and extratropical circulation influences rainfall in this region, including interactions between these dynamical systems (Tyson, 1986). Basic aspects concerning circulation dynamics and summer rainfall are discussed in Jury & Engert (1999) or in context with dynamical teleconnections in Philipp & Jacobeit (1999). Rainfall changes on a regional scale are to be expected due to manmade enhanced greenhouse gases absorbing outgoing longwave radiation from the Earth's surface. This enhanced greenhouse warming is assessed with different scenarios concerning emission rates, reduction efforts and reactions of the climate system to amount between 1.4 K and 5.8 K until the end of the 21st century (IPCC, 2001). The "best estimate" considering simultaneous cooling from sulphate aerosols shows a warming rate of approximately 0.2 K per decade resulting in a further temperature increase of about 2 K until 2100. For different regions of the African continent, temperature is expected to increase until the year 2050 between 1 and 3 K (Houghton, 1997).

Assessments of regional precipitation changes in the context of global warming are much less reliable. Since rainfall is highly dependent on small-scale dynamical and geographical factors, general circulation models (GCMs) characterized by relatively coarse spatial resolution of some hundreds of kilometres are not able to reproduce rainfall variability sufficiently close to reality. Investigating rainfall changes in arid regions due to enhanced greenhouse warming requires on the one hand assessments in a spatially high resolution, and on the other hand temporally high resolved estimates at least on a monthly base. Estimates of future rainfall changes are therefore obtained by the method of statistical downscaling.

The aim of the present study is to show the strength of a complete water balance model for two sub-catchments of the Kalahari. A calibration period of 22 years (1982–2004) is verified with the results of the chloride mass balance method (CMB) and by comparison with groundwater hydrographs. It is then compared with the results of a prediction period that considers the effects of man-made enhanced greenhouse warming on precipitation.

METHODS AND DATA

Statistical downscaling

Statistical downscaling, further described in detail by Hewitson & Crane (1996), has been increasingly used within climate research since 1990. This technique links large-scale variables (e.g. hemispheric pressure data or geopotential heights) and small-scale

variables (e.g. rainfall data with a high spatial resolution) by means of statistical transfer functions (e.g. multiple regression or canonical correlation analyses). According to physical relationship the large-scale parameters represent the statistical predictors which determine the dependent predictands (small-scale variables). Details on the method and applications with precipitation as predictand and varying predictors for southern and eastern Africa, respectively, are described e.g. by Mason (1998), Mutai *et al.* (1998), Joubert *et al.* (1999), Landmann & Tennant (2000), and Beyer (2001).

In this investigation the technique was used to generate rainfall assessments from geopotential heights by using multiple regression models as transfer functions. Calculated $0.5^{\circ} \times 0.5^{\circ}$ gridded data from a global data set for all terrestrial areas are used as small-scale "observational" data (1951–1997). This precipitation data set from the Climate Research Unit (CRU) Norwich, UK, is part of a mean monthly climatology of high quality (New et al., 1999). Regression models are calculated for every $0.5^{\circ} \times 0.5^{\circ}$ grid (monthly rainfall amount) for every month of the rainy season (November to March) in a calibration period, and validated in a verification period with independent data. As predictors in the regression models geopotential heights for three atmospheric levels (300, 500, 1000 hPa; 1951–1997) from the National Center Environmental Prediction/National Center for Atmospheric Research for (NCEP/NCAR) (details published by Kalnay et al., 1996) global reanalysis data set $(2.5^{\circ} \times 2.5^{\circ} \text{ resolution})$, field data between 20°N–50°S and 80°W–100°E are extracted, under the assumption that most of the important rain generating atmospheric processes and potential teleconnections are captured in this area. Details on the calculation processes and validation are published by Beyer (2001). The rainfall assessment itself is done by replacement of the reanalysis data by GCM output and recalculating all models. Therefore model data from the ECHAM4-T42 OPYC general circulation model from MPI Hamburg (Oberhuber, 1993; Roeckner et al., 1996) in same spatial structures and domain as reanalysis data for a transient doubled CO₂-concentration scenario ("business-as-usual-scenario") and a control run $(1 \times CO_2)$ are used. Results for northeastern Namibia and boundary regions reveals that the spatial pattern of distribution does not change, but global warming might induce an intra-seasonal redistribution (Table 1) towards more accentuated conditions with increased precipitation in January and February and less rainfall at the beginning and end of the rainy season, especially during March (Bever, 2001; Bever & Jacobeit, 2002).

Table	1 Summary	of mean mo	nthly precip	itation and	l standard	deviation	for the study	area for '	Tsumkwe
station	1971-2000	, CRU data	1971-2000	and the p	orediction	period for	November,	January,	February
and Ma	arch (Octobe	er and Decer	nber: no rel	iable predi	ction mod	els; April-	September:	dry seaso	n).

	Monthly sum of precipitation (mm)										
	Tsumkwe 1971-2000		CRU 1971-2000		Prediction (transient doubled CO ₂ -conc. scenario)						
	MEAN	SD	MEAN	SD	MEAN	SD					
November	44.1	44.7	37.7	42.2	85.7	46					
January	118.3	91.8	42.5	56.9	250.7	84.7					
February	102.4	79.2	84	88.7	202.7	86.6					
March	61.1	53.7	109.3	57.8	36.9	30					

Water balance model

The distributed, GIS-based, process-oriented, physically based water balance model MODBIL (Udluft & Dünkeloh, 2005) used in this study considers the major water balance components: precipitation, groundwater recharge, surface runoff/interflow, and evapotranspiration. MODBIL calculates a spatially differentiated water balance by simulating water fluxes and storage at temporal and spatial resolutions based on met-eorological, topographic, soil physical, land cover, and geological input parameters.

The model handles the temporal and spatial variations of the water balance components in two major process steps. In the first step, meteorological data are interpolated for each active raster cell depending on topographic parameters. Effective precipitation is then calculated with respect to the canopy storage capacity. The second model step simulates storage, evapotranspiration, surface runoff, interflow and groundwater recharge based on soil, subsoil and land cover parameters. A one layer model calculates the soil moisture conditions and the relevant fluxes into and out of the soil system for each time step. Surface runoff and infiltration are calculated depending on effective precipitation, soil hydraulic conductivity and surface hydraulic conductivity. The infiltrating part is added to the soil water storage. Surface runoff and/or interflow occur if (a) the infiltration amount exceeds the maximum infiltration capacity, which is limited by permeability, or (b) the soil moisture storage has reached the maximum value (field capacity).

In addition, soil water is lost in every time step due to actual evapotranspiration. This is calculated using potential evaporation, soil water content and vegetation type in a modified method after Renger *et al.* (1974) and Sponagel (1980). The potential evaporation is calculated using the Penman-Monteith equation (Monteith, 1965; Allen *et al.*, 1998). Deep percolation/groundwater recharge starts if soil water content exceeds effective field capacity. The amount of groundwater recharge is driven by the percolation amount in the soil, and by the hydraulic conductivity of both the soil and the subsoil. Interflow occurs if the percolation exceeds the maximum permeability of the subsoil.

Precipitation, effective precipitation, potential evapotranspiration, actual evapotranspiration, soil water content, groundwater recharge and interflow are the output parameters of the model at a daily resolution. In the model and the output, interflow comprises surface runoff, and interflow generated in both process steps.

Spatial data

The study covers the area of the upper catchments of the Nhoma and Khaudum ephemeral rivers in the Khaudum National Park and adjacent land in northeastern Namibia and northwestern Botswana (412000E to 529000E and 7854000S to 7977000S). The entire area is divided into cells each 500×500 m, forming a grid of 57564 boxes arranged as 246 rows \times 234 columns. The catchments are represented by a total of 39890 grid boxes, which constitute the active cells. Each grid point is identified by its georeferenced position in UTM 34S coordinates. This forms the basic georeferenced platform of the study area.

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Topographic elevation, slopes and aspects, effective hydraulic conductivity at field capacity of the soil, plant available water content, interception storage, and saturated hydraulic conductivity of the subsoil are the spatial input data required for the water balance model. Spatial variations on these data have been revealed by the use of published data on vegetation, soils (Klock, 2002; Mendelsohn *et al.*, 2002; Wanke, 2006) and elevation (SRTM) in combination with detailed field work.

Climatic data

Daily precipitation, minimum and maximum daily temperature and relative humidity at 14:00 hours are the temporal input data used in MODBIL. Grootfontein station has been used for the three latter data time series for the calibration period 1982–2004. Tsumkwe, Rundu and Mashare are the three relevant precipitation stations for this study. These stations are able to reproduce the general precipitation gradient over the study area. However, a major problem of precipitation regionalization in drylands is the spottiness of single events. If three stations, each recording local rain events, are used in a general interpolation procedure, the local events are smoothed-out over the entire area leading to a precipitation regime that has more events, but in which each single event is of a lower precipitation amount. Thus, the precipitation regime revealed from such a standard interpolation does not mirror the actual conditions. In contrast, using only a single station reflects the typical temporal variations (frequencies and intensities) of precipitation well, but not precipitation gradients. Therefore, virtual time series were produced for the two stations Mashare and Rundu, and used together with the real time series from Tsumkwe. To produce the virtual precipitation series, the total annual rainfall at Tsumkwe has been compared with Mashare and Rundu respectively. Daily rain data from Tsumkwe have been multiplied by the appropriate factor to produce virtual Mashare and virtual Rundu rain time series. The daily precipitation grids obtained do not, therefore, represent single stations and single days, but they mirror the long-term precipitation regime significantly better than standard interpolation procedures.

Windspeed has been set to a constant of 2 m s^{-1} (mean value for Grootfontein) since time series for this parameter show large gaps.

Only the precipitation time series have been changed for the prediction water balance model. Therefore factors between CRU-precipitation 1971–2000 (assumed to present the calibration period) and prediction precipitation (Table 1) for mean and standard deviation have been calculated and used as factors to modify the Tsumkwe, Mashare and Rundu daily precipitation time series.

RESULTS AND DISCUSSION

With the calibration model, a mean annual groundwater recharge of 11.5 mm a^{-1} is calculated for the upper Khaudum and Nhoma catchments. This parameter ranges spatially from 0 to 17.5 mm a^{-1} . In general an increasing groundwater recharge can be observed from the south to the north, which reflects the precipitation gradient. The

pattern is modified by the influence of vegetation and soil, e.g. highest recharge values occur in the *Burkea africana* savannah and relatively low recharge values are found in the *Acacia* shrubland. Interflow for the entire study area is 1.1 mm a⁻¹ and occurs almost exclusively in the ephemeral rivers and a few pans. Simulated interflow in the ephemeral Khaudum River is slightly higher than in the Nhoma River.

Groundwater recharge has a high inter- and intra-annual variability. It only occurs during the second half of the rainy season in years with extraordinarily high precipitation amounts (Fig. 1). However, the total annual precipitation is not the only parameter that influences groundwater recharge, e.g. in the rainy season 1999–2000, which received a cumulative precipitation amount of 878 mm a⁻¹, only a relatively small amount of recharge is simulated (6.9 mm a⁻¹, 0.8% of the precipitation amount). In this case, a large part of the precipitation occurred early in the wet season and was interrupted by several dry periods that allowed much of the soil water to evaporate.



Fig. 1 Daily groundwater recharge and precipitation for the calibration and prediction period.

The most important years for groundwater recharge within the modelling period are 1987–1988 (4.2% of the precipitation amount), 1988–1989 (4.2%), 1993–1994 (18.9%) and 1996–1997 (11%). It is observed for these years that a period of extensive rain occurred prior to the recharge events. For example, in 1993–1994 recharge occurred from 4 to 23 January as a consequence of a cumulative precipitation amount of 390 mm from 1 to 23 January. Within this period 16 rainy days occurred with daily rain amounts between 1.6 and 89 mm d⁻¹, and the last 7 days contributed 237 mm to the total.

In this study the chloride mass balance has been used to verify the groundwater recharge results of the calibration run. Detailed descriptions of the method can be found in Edmunds *et al.* (1988) or Edmunds & Gaye (1994). In general it is used in the unsaturated zone, but can also be applied to relatively shallow groundwater samples. In this case the results represent an average recharge between the point where the water entered the saturated zone and the sampling point. We have used 29 water samples to estimate the area's groundwater recharge rate. A mean value of 11.9 mm a⁻¹ is obtained which corresponds closely to the results from the water balance model (11.5 mm a⁻¹). In addition, groundwater recharge rates for wells with very shallow groundwater (less than 10 m for the Kalahari) are compared to point data from the simulation. A very close match was found for five out of these seven samples which confirms the spatial pattern of the simulation.

Monthly groundwater hydrographs from Tsumkwe were used for the temporal verification of the simulated recharge events. Hydrographs from Tsumkwe are from three abstraction wells, but production time series show large gaps so that quantitative recharge estimation is not possible on this basis. However, the hydrographs, which show increasing groundwater levels during the relevant months, confirm the simulated recharge events.

A calibration of the model with runoff data is not possible as it is not measured for the catchments. However, no flood events are recorded from either ephemeral river by local people. The higher amount of interflow (including runoff in this model) in the ephemeral Khaudum River than in the Nhoma River is consistent with field observations: depressions in which water was collected are found more often in the Khaudum River. Gradients are very low and runoff is collected locally in numerous pans in the river bed. One ephemeral/seasonal spring is known from the Khaudum River (opened by elephants a few years ago) which is most likely fed by interflow.

Results of the calibration model run (groundwater recharge is 2.6% of the mean annual precipitation) are in the same range as results from other studies in southern Africa under similar climatic conditions, e.g. Houston, 1988; Sloots & Wijnen, 1990; Gieske, 1992; Verhagen, 1995; Selaolo, 1998; Klock, 2002. The mean interflow/runoff simulated here as 1.1 mm a^{-1} is a reasonable result for the Kalahari and it is consistent with observation from Külls (2000) in the Omatako catchment west of the study area (range 0.6–1.4 mm a⁻¹) where comparable climatic conditions and soil properties are found.

From the prediction model run it reveals that groundwater recharge and interflow would increase dramatically. The annual area mean values for precipitation, groundwater recharge and interflow are 1337, 622 and 36 mm a⁻¹, respectively. Groundwater recharge occurs under prediction conditions in every year and ranges

from 5 to 2257 mm a⁻¹ as area mean. It turns out that the ratio of groundwater recharge compared to precipitation also increases with increasing precipitation and that thus the total annual precipitation amount becomes more important than the temporal distribution of rain events.

A factor that has not yet been included in this study is indirect recharge, which likely occurs at least locally in the ephemeral rivers or pans. Using results for the Kalahari under comparable conditions from Selaolo (1998) and Külls (2000), indirect recharge calculates as an area mean of only 0.14 mm a⁻¹ and 0.35 mm a⁻¹, respectively. However, the error of the water balance model is assumed to be in the same order of magnitude as the indirect recharge.

For the prediction period it is likely that the amount of indirect groundwater recharge is increased as interflow including surface runoff is increased. But comparing the amounts of interflow/surface runoff to the direct groundwater recharge (1.1 and 11.5 mm a^{-1} for the calibration period (9.5%); 36 and 622 mm a^{-1} for the prediction period (5.8%)) indicates that the ratio of indirect groundwater recharge in the prediction period is probably smaller than in the calibration period.

A major problem of this attempt is the discrepancy between the precipitation data for the Tsumkwe rain station and the CRU-precipitation (Table 1). The monthly ratios of the precipitation (compared with the total annual amount) are more similar for the Tsumkwe station and the prediction scenario than for the Tsumkwe station and the CRU precipitation for the same time period. However, downscaling procedure with the Tsumkwe precipitation data is not feasible due to an insufficiently long observation period.

All assessment results should be understood as general tendencies. It has to be emphasized that these kinds of studies are necessarily scenario-type investigations, depending on particular suppositions concerning the progress of trace-gas emissions and global greenhouse warming (IPCC, 2001). Finally manifold uncertainties concerning general circulation and climate models, used for simulations of possible future climate conditions (e.g. Cubasch *et al.*, 1995) exist. This should be kept in mind even if technical progress seems to multiply modelling facilities.

CONCLUSIONS

MODBIL is shown to be reliable for recent groundwater recharge estimation in the Kalahari and to mirror spatial and temporal variations. As recharge only occurred on a few days it underlines the principle that daily climatic input data are the minimum required for water balance modelling in drylands. If reliable climatic predictions exist, it can also be used for the prediction of possible impacts of climatic changes as in this example shown for precipitation under enhanced greenhouse warming. Consequently the quality of the water balance prediction depends strongly on the quality of the climatic prediction which in turn depends on the quality of the basic climatic data and assumptions.

Acknowledgements The HWP (Hochschulwissenschaftliches Programm der Universität Würzburg) and the DFG (Deutsche Forschungsgemeinschaft, Graduated

School "Geowissenschaftliche Gemeinschaftsforschung in Afrika") are acknowledged for funding parts of the project. Special thanks are due to the Department of Water Affairs in Windhoek, the Weather Bureau of Namibia and the Ministry of Environment and Tourism, Tsumkwe Division.

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