

## **Estimating recharge values using hydrochemical and geological data: a case study from the semiarid Kalahari catchment of northern Namibia**

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**Abstract** Only a spatially distributed approach can sufficiently describe recharge distribution in a large catchment. In this study the decreasing chloride concentration along groundwater flow paths has been used to represent recharge areas within the groundwater basin. Absolute recharge values, derived by application of the chloride balance method in the saturated zone close to the groundwater divide, have been assigned. A total recharge of  $2.8 \times 10^8 \text{ m}^3 \text{ year}^{-1}$  has been evaluated for the Kalahari basin of semiarid northern Namibia draining towards the Okavango-Makgadikgadi System. The Otavi Foreland (Damara Sequence) is the most important hard rock recharge area for this catchment. Most of the recharge areas which feed the groundwater through partly unconsolidated sediments of the Kalahari Group, are restricted to flood courses.

**Key words** chloride method; GIS; groundwater; Kalahari; Namibia; recharge; regionalization; semiarid

### **INTRODUCTION**

Groundwater recharge rates for the Kalahari of southern Africa have been discussed for decades with estimated annual recharge rates for Namibia and Botswana ranging from 0.01 to 13% of mean annual precipitation (Dachroth & Sonntag, 1983; De Vries & Hoyer, 1988; Gehrels & van der Lee, 1990; Keller & von Hoyer, 1992; Mainardy, 1999; Seeger, 1990; Verhagen, 1995; Wrabel, 1999). Most previous research projects have focused on point data, but as the surface geology varies from Precambrian gneisses to recent soft sediments, point recharge values cannot give sufficient information on the absolute recharge of large basins. A spatial approach is needed both for water resource planning and as input for groundwater flow modelling.

In a first attempt at a spatial approach, groundwater recharge has been regionalized by the use of geological maps assuming that the recharge rates published by Wrabel (1999), Mainardy (1999) and the BGR (e.g. 1998) for northeastern Namibia are equally distributed within each geological unit. Using this method a recharge amount of  $2.07 \times 10^9 \text{ m}^3 \text{ year}^{-1}$  was estimated for the Kalahari catchment of northern Namibia. The use of aggregated recharge amounts as input to a groundwater flow model produced calculated groundwater levels dramatically exceeding the measured ones. Given the range of plausible hydraulic parameters, recharge rates could thus be estimated as 0.1 to  $10 \text{ mm year}^{-1}$ , corresponding to a homogenous distribution of recharge over the entire catchment. As recharge is probably not equally distributed

within each geological unit there will be a discrepancy between a regionalization based on geology and estimates that allow better definition of recharge distribution within single units. This additional information was derived by using variations in chloride concentration along groundwater flow paths.

## Study area

The study area is located in northeastern Namibia (Fig. 1). It is the Namibian part of the entire northern Kalahari basin that drains towards the Okavango-Makgadikgadi System. While the central part of the catchment is covered by partly unconsolidated sediments of the Kalahari Group (Tertiary to recent), most of the groundwater divide (GWD) comprises hard rocks ranging from Precambrian gneisses to Jurassic sandstones and basalts.

The climate is semiarid with summer rainfall. Mean annual precipitation ranges from 300 mm in the central and southern parts, to 650 mm in the north. Potential evaporation amounts to 2700 mm year<sup>-1</sup> in the north and reaches 3200 mm year<sup>-1</sup> in the south. Possible recharge mechanisms are direct recharge from rainfall, and indirect recharge from flood waters in ephemeral rivers and from ponded waters in pans.

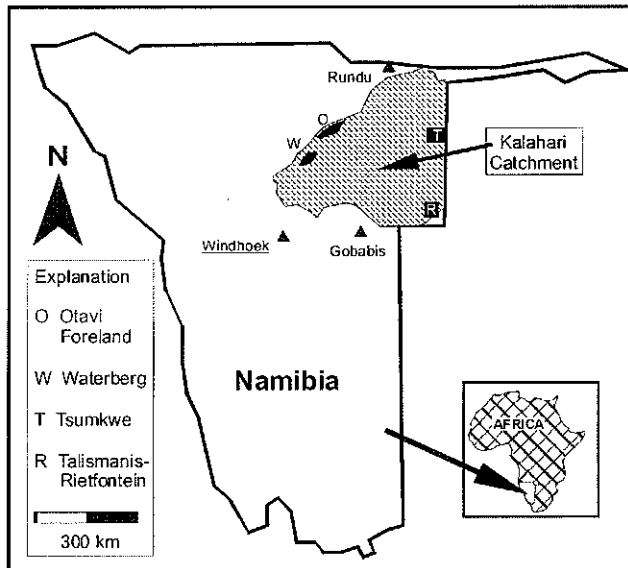


Fig. 1 Location of the Kalahari catchment in northern Namibia.

## METHOD

The method used consists of three steps: (a) obtaining recharge rates for the GWD by the chloride balance method, (b) mapping recharge areas within the catchment inversely from the distribution of chloride concentration, and (c) assessing recharge rates using geological parameters for the defined areas.

## Data collection

Hydrochemical data from groundwater and rainwater samples, mean annual rainfall amounts, maps of geological units and data on groundwater levels are the essential data required in this approach. Hydrochemical data from Huyser (1982) from the Department of Water Affairs in Windhoek (DWA) have been used. Further water samples were obtained during a field trip in 1999 and analysed for major ions. For the entire catchment approximately 2500 analyses were available with a maximum charge balance error of 3%. Rain records for 162 rain stations in northeastern Namibia from the DWA database were used. Chloride concentrations in Namibian rainfall were determined by Mainardy (1999) and Wrabel (1999). The distribution of geological units was adopted from the geological map of Namibia (1:250 000). A groundwater level map was produced from ground elevation and depth to groundwater level data available from the DWA database. The essential data obtained from the piezometric map are the GWD and groundwater flow directions.

## Estimation of recharge rates by use of the chloride balance method

Recharge rates in areas without significant geogenic chloride sources can be estimated using the mass balance for a given groundwater volume (Edmunds *et al.*, 1988):

$$F_N + F_D = F_S + F_M \quad (1)$$

where  $F_N$ ,  $F_D$ ,  $F_S$  and  $F_M$  are mean mass input by wet deposition (precipitation), mean mass input by dry deposition, mean mass output by seepage water, and mean mass output by adsorption and transformation into the mineral phase, respectively. Allison & Hughes (1978) and Gieske *et al.* (1995) showed that chloride can be considered as a conservative tracer, therefore the adsorption and transformation term  $F_M$  is negligible. Equation (2) is obtained by balancing the flux of chloride into a soil column with the outflow at the bottom of the root zone and assuming that surface runoff is not significant:

$$R = (P \times Cl_P) / Cl_{GW} \quad (2)$$

Where  $R$ ,  $P$ ,  $Cl_P$ ,  $Cl_{GW}$  are groundwater recharge, mean annual precipitation, chloride concentration in precipitation and chloride concentration in the groundwater, respectively. Lateral inflow may also contribute to the chloride balance of the saturated zone. Therefore absolute recharge data can be derived only for the GWD.

Recharge amounts have been calculated using equation (2) with the Geographic Information System IDRISI (Clark University, 1997) using maps of chloride concentration in rainfall, mean annual rainfall amount and chloride concentration in groundwater for the water divide only. The map of chloride concentration in groundwater has been produced using the gridding method "inverse distance to a power" in SURFER 7.0 (Golden Software, 1999).

## Definition of recharge areas

The relative change of chloride concentration along flow lines have been used to map recharge areas within the basin. As chloride is highly soluble in the groundwater, a

decrease in chloride concentration cannot be due to precipitation of chloride. A decrease in chloride concentration along a flow path can only result from mixing with water having a lower chloride concentration viz. mixing with other groundwater (confluent flow) or mixing with recharge (parallel or convex flow pattern).

For the definition of recharge areas all confluent groundwater flow areas have been identified and excluded from the analysis. For the remaining areas decreases in chloride concentration have been marked in digitizing mode. Thus a georeferenced recharge area map was obtained.

### Recharge values to recharge areas

The water divide is mainly formed by hard rocks, whereas within the catchment a cover of soft sands is widespread. Hence, instead of assigning mean recharge rates to all recharge areas, recharge rates have to be assigned to the recharge areas in relation to the values obtained at the GWD. This was done in IDRISI.

## RESULTS

Mean annual recharge values produced for the GWD (Fig. 2) range from 0.2 mm to locally more than 100 mm, with an average rate of 15.6 mm and a standard deviation of 25.5 mm. Most of the groundwater divide receives recharge amounts of between 1 and 60 mm. Recharge amounts greater than 50 mm are restricted to the northwestern GWD with the Otavi Foreland (karstified carbonate rocks) and to the Waterberg area (jointed sandstones). The eastern and southeastern parts of the GWD (Tsumkwe district and Talismanis-Rietfontein block) receive groundwater recharge of less than 10 mm, and most parts of the GWD covered by Kalahari sand receive recharge of approximately 1 mm year<sup>-1</sup>.

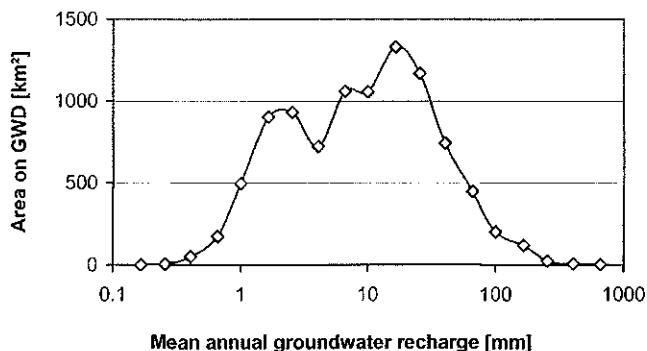


Fig. 2 Frequency distribution of mean annual groundwater recharge (subdivided in logarithmic classes) for the GWD of the Kalahari catchment in northern Namibia, derived from the chloride mass balance of the saturated zone.

The distribution of the recharge areas in the Kalahari catchment of northern Namibia is given in Fig. 3. Recharge areas cover 15 689 km<sup>2</sup> of the 150 604 km<sup>2</sup> large

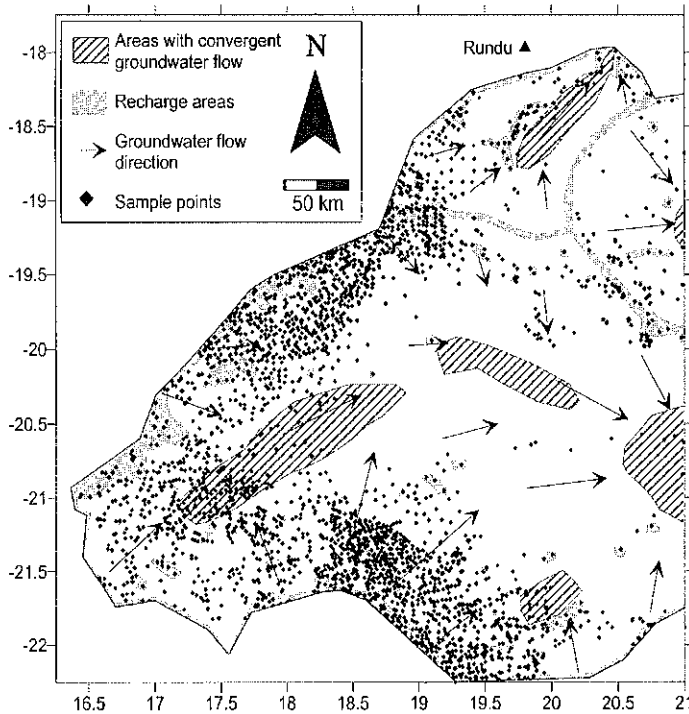


Fig. 3 Distribution of recharge areas within the Kalahari catchment mapped by decreasing chloride concentration along groundwater flow paths.

catchment which is 10.4%. Outside of the narrow strip along the GWD, 85 recharge areas have been mapped. Of those, 38 areas are constrained to ephemeral rivers, 37 occur where hard rocks outcrop or where the hard rocks are only covered by thin sandy sediments. Eight areas in the northern half of the catchment and 14 in the southern half are found neither near ephemeral rivers nor hard rock outcrops. It is possible that recharge results from direct infiltration through a thicker sand cover along preferred flow paths or from infiltration in pans (pan field in the Tsumkwe district). Calcrete layers may be corroded and provide preferential flow paths but mechanically prevent roots from abstracting soil moisture.

As a result a low annual recharge rate of about 2 mm has been estimated for areas characterized by direct recharge through the thick Kalahari cover, indirect recharge from ephemeral rivers through Kalahari sediments, and infiltration from pans. As the Otavi Foreland obtains the highest recharge amount (see above) a mean annual recharge of 50–100 mm has to be assumed for the recharge area that falls in this geological class. The remaining 30 recharge areas were divided into two recharge groups: (a) good recharge conditions with sandstone, jointed quartzites and flood basalts (10–50 mm), (b) poor recharge conditions with schists, gneisses and granites (4–10 mm).

Assuming the minimum recharge for each of the four classes, (2, 4, 10, 50 mm) the entire region receives an annual recharge amount of  $1.54 \times 10^8 \text{ m}^3$  (without recharge from the GWD), which corresponds to 1 mm mean annual recharge equally distributed over the whole catchment. If the maximum recharge amount resulting from the GWD chloride balance evaluation is assumed for each group (2, 10, 50, 120 mm) a total

annual recharge of  $4.41 \times 10^8 \text{ m}^3$  is obtained (equivalent to 2.9 mm homogeneously distributed over the entire catchment). The most likely recharge amount is between these limits. Assuming recharge amounts of 2, 10, 25, 80 mm within the catchment, and adding recharge on the GWD, a total amount of  $2.8 \times 10^8 \text{ m}^3$  is estimated for the Kalahari catchment of northern Namibia. This equals  $1.9 \text{ mm year}^{-1}$  equally distributed over the entire catchment.

## CONCLUSIONS

A recharge amount of  $2.8 \times 10^8 \text{ m}^3$  for the Kalahari catchment of northern Namibia was estimated by the definition of recharge areas inversely from the distribution of chloride concentration and assessing recharge rates obtained at the GWD of the defined areas. This figure lies within the range delimited by inverse estimation with a groundwater flow model. The total recharge is of the order of one magnitude smaller than previous estimates based on a simple regionalization using geological data. The hydrochemical–geological approach respects the inhomogeneous distribution of recharge areas within geological units. The consideration of this inhomogeneity is consistent with results from Klock & Udluft (2000) who, using Landsat TM imagery, have shown that hard rocks do not outcrop as homogeneously within the geological units as indicated by geological maps of the Kalahari catchment. From the distribution of the recharge areas covered by soft sediments of the Kalahari Group, it is clear that ephemeral rivers play an important role for recharge distribution within the catchment. Nevertheless recharge areas have been defined that are not constrained to flood courses. The recharge from the GWD (and directly associated areas) is about 20% of the total amount although the GWD covers only 6% of the area. The most important recharge area is the Otavi Foreland as proposed by BGR (1998) and Külls *et al.* (2000).

Although this approach gives more reliable results than using geological maps for the regionalization of recharge within a large catchment, two main problems may arise. The first problem is the data availability. Some areas in the southern half of the research area have not been sampled as there are no wells (the areas are not populated), or wells are inaccessible. The second problem is due to the inapplicability of the changing chloride concentration method to define recharge areas in regions with convergent flow. As for both cases no recharge areas are mapped, but may exist, the estimated recharge amount is a minimum value. This will not result in problems for sustainable water resource planning keeping estimates on the safe side. However, under some circumstances it might create problems for groundwater flow modelling. For the case study in northern Namibia, the confluent areas and areas lacking data are expected to contribute only small recharge amounts (thick cover of soft Kalahari sediments).

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