# Determination of recharge patterns by combining remote sensing and the chloride method

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**Abstract** Water supply in semiarid Botswana is, to a large extent, based on groundwater. In the planning of a groundwater abstraction scheme, criteria for the sustainability of the abstraction with respect to both quantity and quality have to be satisfied; groundwater models can aid this task. The most important model parameter in the context of quantitative sustainability is the long-term average groundwater recharge together with its spatial distribution. A method is developed to calculate a recharge map that can be used in a groundwater model. The distribution of recharge is obtained from remotely sensed data and the absolute values of recharge are derived from the chloride method.

**Key words** chloride method; groundwater recharge; numerical groundwater modelling; remote sensing

## INTRODUCTION

The project area is situated in the Chobe Region, in the northern part of the Republic of Botswana, including the Chobe Enclave close to the Namibian border and the Chobe National Park. The Chobe Enclave lies next of the Kachikau Fault, running from Ngoma Bridge through Mabele, Kavimba and Kachikau. In Kavimba, Mabele and Kachikau the fault separates the Chobe flood plain from the Chobe Forest Reserve on the plateau. The Forest Reserve lies up to 70 m higher (at Ngoma Bridge) than the flood plain.

Several approaches are available to compute groundwater recharge. A common method consists of calculating recharge rates as a residual from a surface water balance. As it is possible to obtain the required input data for the surface water balance using satellite imagery data, it can be calculated with high spatial resolution. However, the accuracy of the absolute values is low.

A more accurate indicator for recharge is the chloride concentration in the unsaturated soil profile. Recharge rates calculated with the chloride mass balance are point values. If a correlation between recharge rates calculated by the surface water balance and recharge calculated by the chloride mass balance can be found, the recharge map obtained by remote sensing can be used to regionalize the local recharge rates obtained from the chloride concentration in the soil profile or—in a further approximation—in shallow boreholes.

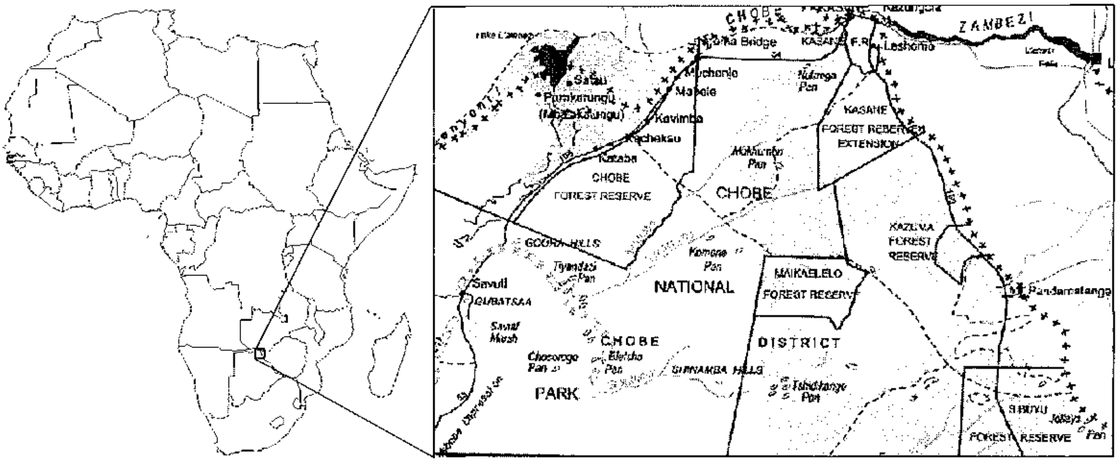


**Fig. 1** Location of the study area.

## SURFACE WATER BALANCE

The water balance equation for a soil cube of unit cross-sectional area and height $d$ extending from the surface down to the zero upward flux plane is given by:

$$d\frac{\partial \theta}{\partial t} = P - ET - Q - R$$

where: $d$ is the height of the soil cube (mm), $\partial\theta/\partial t$ is in the change in the soil water content ($\text{year}^{-1}$), $P$ is precipitation ($\text{mm year}^{-1}$), $ET$ is evapotranspiration ($\text{mm year}^{-1}$), $Q$ is surface runoff ($\text{mm year}^{-1}$), and $R$ is recharge ($\text{mm year}^{-1}$).

For long-term averaged steady-state conditions the soil water content is constant and its time derivative equals zero. For issues of quantitative sustainability only long-term averages are relevant. Hence steady-state conditions are presumed. In most of the project area no major surface runoff exists and $Q$ can be set to zero. With these simplifications the recharge rate can be calculated from precipitation and evapotranspiration. Over permanent water bodies such as rivers or swamps, the assumptions of the simplified water balance do not apply as water is imported by river flow.

The absolute value of evapotranspiration depends on various parameters such as vegetation, radiation or soil type, and can only be estimated with a large error. The absolute value of rainfall is also a parameter with uncertainty. Therefore, their difference, i.e. recharge, is an even more unreliable quantity. In semiarid areas, it cannot be computed from the water balance. Still, the resulting difference-map can be used for the identification of distinct zones of recharge if such zones show up in a systematic fashion.

### Precipitation

The estimation of the accumulated precipitation is based on the GOES Precipitation Index (GPI) algorithm (Herman *et al.*, 1997). Using data provided by the geostationary satellite METEOSAT 5 and raingauge reports from meteorological stations, precipitation over southern Africa can be estimated with a spatial resolution of 5 $km^2$. Compared with the measured rainfall in the project region during the same period, the GPI algorithm overestimates the rainfall. As we are interested in the distribution of rainfall and not in its absolute value a further adjustment of rain data estimated with the GPI algorithm is not required.

### Evapotranspiration

In the computation of daily evapotranspiration from multi-spectral satellite images (NOAA-AVHRR, 1-$km^2$ resolution), the method of Roerink *et al.* (2000) was employed. On the basis of several processed daily evapotranspiration maps, average yearly evapotranspiration was calculated as described in Bauer *et al.* (2002). The empirical parameters used to calculate a daily evapotranspiration value were determined during a field campaign in the project region; the required meteorological data were provided by the meteorological stations.

## CHLORIDE METHOD

The chloride content in groundwater depends on the chloride input by wet and dry deposition, input or output by lateral groundwater movement, dissolution of chloride from minerals, and land use. The chloride deposition from the atmosphere corresponds to the chloride flux into the groundwater under the assumption that the chloride ion is conservative and neither taken up in significant quantities by vegetation, nor dissolved from halites in the subsoil. The chloride method is usually applied in the unsaturated soil zone between the surface and the zero upward flux plane. However, in an approximation it can also be applied between surface and shallow groundwater. Recharge calculated with the chloride mass balance represents a long-term average.

Runoff from surrounding areas and dissolution of chloride from minerals in the soil can usually be neglected in the typical environment of the Chobe Forest. For steady-state conditions, the recharge rate calculated with the help of the chloride method is given by Gieske (1992):

$$R = \frac{P * c_p + D}{c_{gw}}$$

where: $R$ is the mean annual recharge rate (m $year^{-1}$), $P$ is mean annual rainfall (m $year^{-1}$), $D$ is the dry deposition of chloride (g $m^{-2}$ $year^{-1}$), $c_p$ is the chloride concentration in the precipitation (g $m^{-3}$), and $c_{gw}$ is the chloride concentration in the shallow groundwater (g $m^{-3}$).

With a total average chloride deposition of 142 mg $year^{-1}$ $m^{-2}$ (Gieske, 1992) and chloride concentrations in the groundwater between 5 and 1850 mg $l^{-1}$, recharge rates range from 28 mm $year^{-1}$ to nearly zero.

Over 60 boreholes are located in the Chobe region, both in the Forest Reserve and in the Chobe flood plain, and for most of them a chemical analysis is available. For some boreholes several chloride concentrations were determined, depending on the depth from which the analysed groundwater was drawn. Unfortunately, this depth was not recorded. The deep layer of the aquifer located in the Chobe Forest Reserve is saline, and only the chloride concentration in the shallow aquifer can be used to estimate the recharge rate. The available chloride data were filtered. If measurements with large differences in chloride concentration from the same borehole were available, only the smallest values were taken into account.

A characteristic feature of the chloride method is that it yields local values. The total recharge of an area, however, is the areal integral of the specific recharge rate. Therefore areal weights for recharge rates are needed before the Chloride Method can be used to quantify the areal integral recharge.

## COMBINING CHLORIDE METHOD WITH SURFACE WATER BALANCE

Principle component analysis of over 97 recharge maps showed that the recharge pattern in the project region remains stable in time. In contrast to the water balance which only represents a recharge rate over a time period equal to the time interval of input data, the Chloride Method yields a long-term average. Thus the constant recharge pattern is the precondition that allows comparison of recharge rates calculated with both methods.

The boreholes are not distributed homogeneously over the project area; numerous boreholes are found near villages while in the unpopulated areas of the Chobe National Park boreholes are sparse. As some boreholes are close together, sometimes even located on the same pixel, they were summarized into clusters. Clusters were formed in areas where the boreholes are close to each other and the recharge map yields homogeneous conditions.

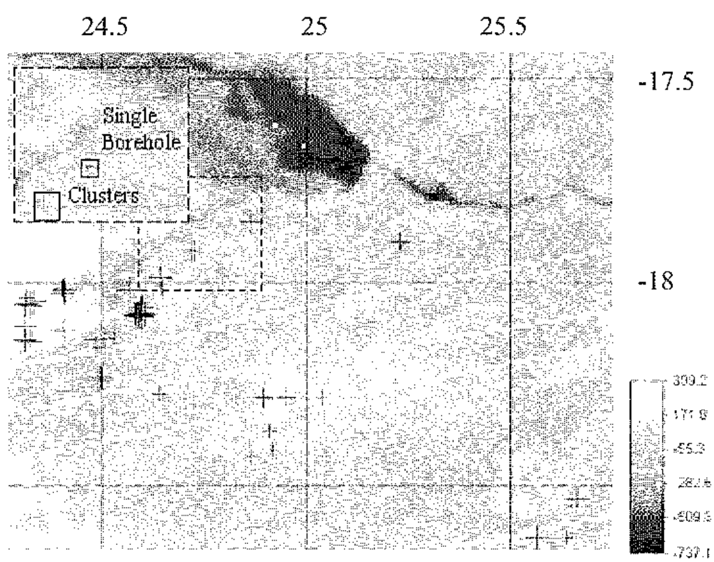


**Fig. 2** Resulting map of precipitation minus evapotranspiration (mm year$^{-1}$); the crosses are boreholes. The boreholes south of 18° longitude and west of 24.4° latitude are located in the Chobe flood plain and have not been taken into account. The white lines are due to scanning errors in some of the 97 images used.

For each single borehole, the recharge rate calculated with the chloride method was plotted against the average recharge of the pixels surrounding the borehole pixel.

This averaging reduces the effects of uncertainties of the applied georeference (having an accuracy of 1 km), as well as inaccuracies in the positions of the boreholes. No boreholes in the Chobe flood plain were taken into account. The structure of the flood plain is extremely heterogeneous; very large differences of chloride concentration are observed in boreholes adjacent to each other, making it impossible to compare them with an average value over 1 km$^2$ as obtained from the water balance. Further, the Chobe flood plain is sporadically flooded and due to the water imports the chloride concentration in the aquifer cannot be used to calculate a long-term recharge rate. The Chobe flood plain can be seen clearly in Fig. 2, northeast of the Kachikau Fault.

The chloride concentrations of the clusters were averaged before conversion into recharge in order to reduce their influence on the recharge value. The variation between measurements in the cluster was used to compute a standard deviation which leads to the error bars in Fig. 3. After clustering and eliminating the boreholes in the flood plain, eight clusters and four single boreholes were used for further examination. The pixels where the used boreholes are located in Fig. 2 cover nearly the entire range of the precipitation minus *ET* of the area which was scaled.

## RESULTS AND DISCUSSION

The recharge rates calculated with the chloride method were plotted against the average of the recharge rate obtained from the water balance of the pixels within the cluster (Fig. 3). A regression line ($y = ax + b$) is also shown in Fig. 3. The gain of the linear regression ($a$) is 0.085, the offset ($b$) equals −1.7. The correlation coefficient ($r^2$) is 0.7.

A statistical test was performed of the data plotted in Fig. 3, based on the hypothesis that the recharge estimates of the water balance are not related to those from the chloride concentration (Stahel, 1995). The hypothesis was rejected; a correlation

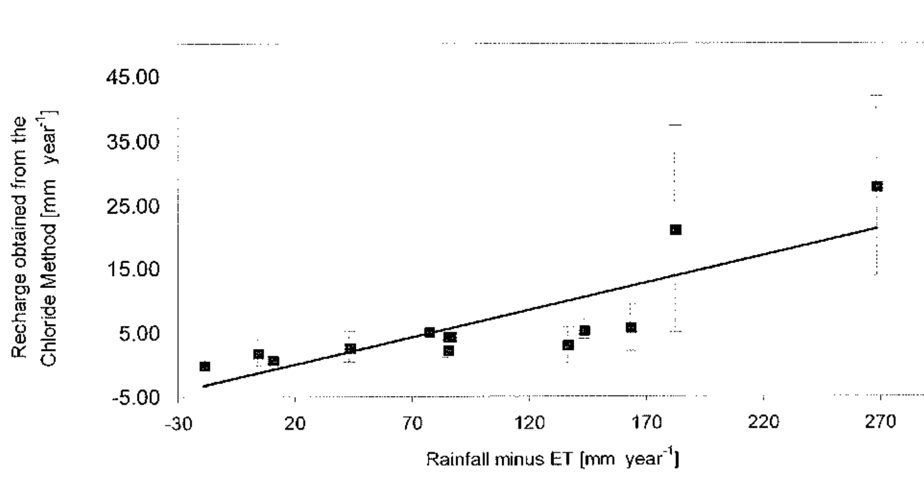


**Fig. 3** Plot of recharge calculated with the chloride method *vs* recharge calculated with the surface water balance; the standard deviations within the clustered pixels are also plotted.

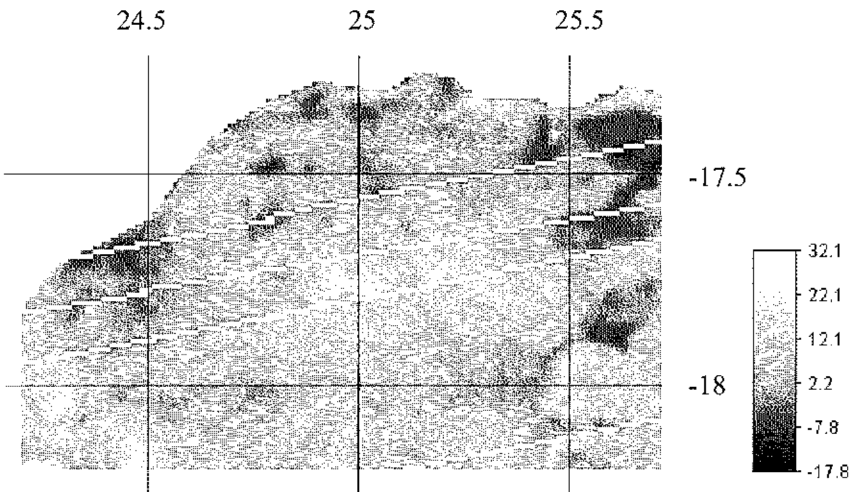


**Fig. 4** Scaled water balance map, where one unit in the legend is mm year$^{-1}$.

between the differently calculated recharge rates can be assumed. The estimated standard error of the gain is $1.69 \times 10^{-2}$, and of the offset, 2.1.

Some clustered boreholes show a high variance of the recharge calculated with the chloride mass balance. Of course the variance of recharge calculated from the surface water balance within a cluster is small, but the chloride concentration of boreholes close to each other varies up to a factor 3.5. As can be seen in Fig. 3, large variances are mainly observed in boreholes with small chloride concentrations. Measurement uncertainties of small chloride concentration have a larger influence on recharge than those of measurements in boreholes with high chloride concentrations, as the relationship between chloride concentration and recharge is nonlinear. A set of reliable chloride measurements drawn from a defined depth would most probably reduce the variance within a cluster.

As a correlation between the recharge estimates has been found, the recharge map obtained from the water balance method can be scaled according to the regression line. The map was only calculated for those regions where the assumptions for the water balance and the Chloride Method are fulfilled. A recharge map based on this procedure was used as input for a regional groundwater model (Brunner *et al.*, 2002).

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