One of the most important techniques for mapping regional geology and structure has proven to be detailed aeromagnetic surveys. Potentially water-bearing fault zones and dolerite dykes overlain by Kalahari beds can be effectively located with this method.

Gravity and magnetics, electrical soundings, and electromagnetic profiling techniques have proven to be the most effective combination of borehole siting methods for exploration of the important fractured-porous type aquifers in the Karoo Basin (Figure 2).

In judging the effectiveness of a particular technique, two different types of success are defined: technical success and utilization success. A borehole is a technical success if the geological and geophysical interpretation is explained. A borehole is judged a utilization success only if it meets the needs originally intended.

ISOTOPE HYDROLOGY OF SEMI-ARID REGIONS: LESSONS FROM THE KALAHARI

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The sand-covered Kalahari thirstland is devoid of surface water, except for the inland Okavango delta in the north-west. Annual rainfall, ranging from 200 mm in the south-east to 600 mm in the north-east is highly variable. Groundwater, mostly phreatic to partly-confined, is held mainly in horizontally-bedded, Carboniferous to Jurassic sedimentary Karoo aquifers. Traditionally, diffuse recharge was regarded as negligible, except in areas where the sandy, unconsolidated Tertiary to Recent Kalahari Beds cover is <6 m or during floods in ephemeral streambeds. Low piezometric gradients towards sedimentary basin centres were taken as evidence of sub-regional flow away from such "recharge areas".

Groundwater levels, at depths of 20 m to over 200 m, tend to follow the Kalahari/pre-Kalahari interface. Regional groundwater gradients are directed towards drainage levels, such as the Makgadigadi salt flats in the north-east. Although this dry lake clearly received groundwater drainage in pluvial times, at present groundwater levels lie below the perched brine level in the lake floor.

Environmental isotope and hydrochemical studies have been conducted over a period of more than 20 years in a number of areas of the Kalahari, usually as part of groundwater development projects. Most of the data was gathered from existing, low-yielding supply boreholes, usually poorly documented. Hence, a semi-statistical approach is usually adopted. Even in specially-drilled project boreholes, integrity of e.g. depth controlled samples was rarely assured.

A selection of these studies is briefly discussed. Various features of this semi-arid environment become apparent from the overall conclusions, leading to some important insights into hydrological processes which may have validity in other semi-arid to arid environments.

1. Gordonia. A relatively fresh groundwater occurence was assumed to be fed from ephemeral river flood infiltration by underflow over a distance of some 40 km. Radiocarbon and hydrochemistry in numerous wells exhibit no trends as evidence of such underflow. Stable isotope values in groundwater near to and further from the river are quite different. This leads to a model of diffuse recharge through thick sand cover occurring only during exceptionally intense rainfalls, whilst evapotranspiration balances infiltration completely due to expanding vegetation activity during prolonged wetter periods, with much lighter isotope signal, when the river flows.

2. Kweneng. A histogram of ^{14}C values in numerous wells shows most frequent values around 55 pMC. Values 10 pMC are all associated with confined conditions. The latter cases are all Na-HCO_3 ,Cl dominant, whilst unconfined groundwater shows various transitions between Ca and Na dominance. There are no clear regional isotopic or hydrochemical trends, which suggest little or no regional flow. Regional permeabilities are thus much smaller than measured in pump tests. An overall model proposes isotopic (80 -0 pMC) and chemical (Ca-Na) depth stratification.

3. Serowe. The intensively faulted and intruded Karoo sequence forms a low scarp with thick Kalahari cover to the west of Serowe. Groundwater levels show a mound to the west of the scarp. Deeper and confined groundwater is fresher and Na-HCO_3 dominant; in shallower groundwater, salinities increase westwards with decreasing piezometric gradients. For the fresher groundwater of the mound, recharge estimates based on ^{14}C values, chloride balance, mound stability and modelling roughly agree (3 - 12 mm a^{-1}). Further west, ^{14}C recharge estimates are unchanged, all other tend to 0. Aquifer structure is therefore important in salination and chloride balance should be applied with caution.

4. Toteng/Sehitwa. In this extremely flat area, deep Kalahari Beds cover intensively faulted quartzite and arkose rocks. Groundwater gradients are low and ill-defined. Mineralisation ranges up to 15 000 mg/l, independent of the ^{14}C distribution which is continuous from 80 pMC to 5 pMC. Stable isotope values show some pre-recharge evaporation, but little geographic dependence. The actively recharged water therefore carries a palaeosalinity, which even in pluvials will be imperfectly flushed due to the structure.

5. Jwaneng. The highly productive Jwaneng mine well field produces Ca-HCO_3 dominant water in the Kweneng district with Na,Ca - HCO_3 ,Cl groundwater. Below the featureless Kalahari cover, the field taps a Karoo coarse sandstone delta which partly subcrops and becomes confined below increasingly thick mudstones north-westwards, with ^{14}C values increasing from 55 - 75 pMC. This apparent paradox leads to the concept of recharge in the south-east, producing flow lines north-westwards, boreholes progressively tapping only the upper aquifer. Leakage into the overlying aquitard, reversed during pumping, may explain the unusually low drawdowns observed over 12 years of increasing exploitation ($5x10^6$ m^3/a). Groundwater flow in the delta aquifer, as opposed to near-static conditions outside, is ascribed to ongoing recharge and its assymetrical structure.

Conclusions

1. In such factors as groundwater mobility, mineralisation and chemical type, as well as aquifer development, aquifer structure is of fundamental importance.

2. Diffuse groundwater recharge is ubiquitous and generated by exceptionally intense rainfall events (e.g. Uhlenhorst, Namibia (1961): 489 mm in 24 hours).

3. The contribution and influence of localised recharge sources (e.g. floods in rivers) is limited to their immediate vicinity.

4. The principal loss mechanism is evapotranspiration, even through tens of meters of sand cover.

5. Such losses imply increasing salination, which maybe reset during major recharge periods (pluvials), here too structure is of major importance.

6. Evapotranspirative salination disqualifies chloride balance recharge estimates. Although ^{14}C-bearing alkalinity also builds up, ^{14}C is more reliable, as radioactive decay and calcite precipitation act as sinks.