SOME ISPTOPE HYDROLOGICAL STUDIES IN SOUTHERN AFRICA

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Abstract

Four case studies involving the use of the environmental isotopes ^{14}C and ^{3}H, in the arid to semi-arid Kalahari region of Southern Africa are described and general conclusions regarding the qualitative aspects of recharge and discharge characteristics of the systems are based on these measurements. In each of the studies, diffuse, local recharge was found to be the dominant recharge mechanism. Recharge via river beds was found to be limited at the regional scale. The balancing discharge mechanism for groundwater was found to be via evapotranspiration. Groundwater salinity and mineralisation as well as the regional hydrogeology are controlled by geological structure rather than lithologies or residence times and the absence of hypersaline groundwaters indicates that the aquifers are periodically flushed during pluvial periods, thus pointing to long-term hydroclimatic controls over the observed present-day hydrology.

Introduction

The Environmental Isotope Group at the Schonland Research Centre has been involved in ground water studies for the past 30 years and has pioneered and zone isotope hydrology in southern Africa. Some of the earlier studies were sponsored by the IAEA. More recently, the value of environmental isotope hydrology has become more generally realised and accepted. As central funding for research at Universities has been drastically reduced, sponsored research and commercial contracts have provided the basic funding for the group.

The four case studies presented here were conducted in the semi-arid to and Kalahari region and deal with three contrasting aspects of the hydrology of this thirstland. From this, some general conclusions can be derived for the region as a whole and other and zones.

Sources of recharge in Gordonia

The Gordonia area in South Africa forms the southernmost section of the sand-covered Kalahari thirstland. It is traversed by ephemeral river beds. Ground water yields and quality from the underlying hardrock aquifers are poor. Fresher ground water is found along the Kuruman River, and wells of higher yield drilled in the sand filling a palaeovalley, or trough, stretching some 40 km southwards from the river. The working hypothesis to be investigated was that, in the assumed absence of diffuse rain recharge, the fresh water in the trough is derived from bank infiltration during river flooding.

Radiocarbon measurements showed very recent water in the aquifers close to the river, sometimes with measurable trititun. Lower values were found in the trough, in the range of 33 - 77 pMC. Neither the ^{14}C values nor the hydrochemistry show consistent geographic trends away from the river. The stable isotope signal for ground water close to the river is much lighter than values observed further away in the trough. Isotopic and hydrochemical data therefore converge in showing that the river cannot be the source of ground water in the trough.

The range of ^{14}C values of ground water in the trough suggests active recharge. In the absence of clear regional influence of the river, diffuse rain recharge must occur. The question remains as to the stable isotope contrast observed. This is ascribed to the different types of rainfall occurring in the area. The river flows once every 10 - 15 years, during widespread monsoon-type rainfall periods, producing much above average rainfall for two to three years in succession.

During such periods, the vegetation becomes active and develops, thus largely consuming infiltrated water and preventing significant diffuse recharge. Rare localised convective rainfall events of extreme intensity, and different isotopic signal, falling during periods of vegetal dormancy, were postulated as being the source of the observed diffuse recharge. Such a model of and zone recharge has since become generally accepted.

In the extreme west of the area, where the mean annual rainfall drops to 200 mm, fairly shallow, highly saline and alkaline (up to 300 meq L^{-1}) ground water is encountered. Stable isotopes show that this water undergoes considerable evaporation before recharge. Carbon-14 values lie between 17 and 52 pMC, which, due to the extreme alkalinity, cease to reflect ground water residence time. The isotope signal and high mineralisation is interpreted as due to occasional widespread flooding of the area between the dunes, followed by evaporation and a concentration of solutes. Below the river bed, a fresh water lens is maintained by the occasional flooding, with high ^{14}C, measurable tritium and lighter stable isotope signal. This again underlines the localised nature of infiltrated river water.

Kweneng province

A regional rest level gradient, directed northwards, suggests ground water flow from the piezometric high in the south, long accepted to be a recharge area. However, the ground water chemistry is heterogenous, showing no regional systematics, in both concentration and hydrochemical type.

The Kweneng province of Botswana lies some 300 km to the northeast of Gordonia. The Carboniferous to Jurassic sediments, capped by basalt, are covered by tens of metres of Kalahari sand. The two sandstone facies of this succession are almost everywhere good aquifers. The area is traversed by a fault, with its downthrown side on the north.To the south, the lower sandstone subcrops and dips below increasing thickness of mudstone northwards. To the north of the fault, the younger Ntane sandstone subcrops beneath the sand cover. Wells are usually sunk into the first aquifer sandstones encountered.

To the south of the faultline, the radiocarbon values average about 50 pMC. Immediately to the north, very low radiocarbon values are found below the thick layer of mudstone, where ground water is trapped. Further to the north, values are again around 50 pMC. These results are interpreted as being generated by diffuse rain recharge where the sandstone subcrops beneath the sand cover. At a mean residence time of some 4000 years, an aquifer porosity of 10 % and a depth of penetration into the saturated zone of 60 - 80 m, a mean annual recharge of the order of 1- 2 mm is obtained.

Jwaneng mine well field

This well field was established in the Kweneng just to the south of the fault line. The hydrogeological system tapped was interpreted as being a delta or alluvial fan of very coarse sandstone and a highly developed aquifer. As elsewhere in the area, the sandstone which

subcrops beneath the Kalahari cover dips northwards below increasing thicknesses of mudstone, confining the ground water. The mudstone thickness increases rapidly north of the fault line. As in the rest of the area there was a slight natural piezometric gradient northwards, before exploitation started.

Wells are high yielding (up to 30 L s^{-1}). Initial estimates of drawdown had to be repeatedly updated as the wellfield was performing much better than predicted. The chemistry of the wellfield water is of the Ca,Mg - HCO_3 type, which suggests that ground water is actively recharged. In the surroundings, the chemical type is Na,Ca,Mg - Cl,HCO_3. However, on account of the 20m+ sand cover, it was postulated that recharge occurs some 50 km south of the wellfield, where the sand cover disappears.

Isotope data on the wellfield boreholes showed no measurable tritium. Radiocarbon values increase from around 50 pMC in the south-east to some 79 pMC in the north-west, i.e. where the ground water is most confined. Somewhat to the north of the wellfield, deep village boreholes tapping the same aquifer have vanishing ^{14}C values.

The only model which fits this apparently contradictory set of data is to assume diffuse recharge to the unconfined section of the aquifer. Boreholes increasingly intersect the shallow flow lines in a N-W direction, giving higher `C values. The deep boreholes to the north show that the flow has ceased there: water therefore has to enter the mudstone aquitard. During exploitation, some 107 M3 a-' at present, the cone of reduced pressure in the aquifer spreads and water in the aquitard will flow back into the aquifer. This may explain the apparent increase in the effective storage coefficient with progressive exploitation. Simple residence time calculations show long-term recharge of the order of 5 mm a^{-1}, which accounts for some 20% of present-day abstraction.

Toteng-Sehitwa grazing lands

The Toteng-Sehitwa Tribal Grazing Lands ranching area of the northern Kalahari some (7400 km^2 in extent, annual rainfall 350 to 450 mm) presents particular difficulties in geohydrological interpretation on account of i) the generally poor quality of the ground water and ii) the absence of clear regional rest level trends revealing ground water dynamics. It is sand-covered and extremely flat in the east, but rises in the west, where the underlying late Proterozoic sediments are exposed above the sand in isolated hills. In the west, ground water levels conform to the rising surface topography, gradients levelling out to 0.0002 in the Kalahari deposits. The regional piezometric baseline lies inside the study area, to the north west.

The aimlessness of the hydrological system is reflected in the observed isotope values and hydrochemical types, which show few regional trends. Somewhat more positive stable isotope values in the extreme north may reflect historical transgressions of the Boteti River. Much of the ground water of the area reflects a degree of evaporation before infiltration. This can be understood in terms of the few larger and numerous smaller pans or ephemeral playa lakes which characterise the area. Total dissolved solids range from 500 to 52 000 mg L^{-1}. The few cases of very low mineralisation are confined to the western rock outcrops.

The ^{14}C frequency distribution suggests that there is a continuum of mixtures between old and younger ground water, of unconfined (up to 85 pMC, sometimes with measurable tritium (0.5 - 2 TU)), to confined (~ 10 pMC) conditions, all in the thicker Kalahari deposits, where the $\delta^{13}C$ values become less negative and more uniform. Values > 90 pMC are found in rock outcrops. In general, there is no correlation of dissolved solid and radiocarbon concentration.

Environmental isotope and hydrochemical data show qualitatively that the area as a whole is receiving ongoing rain recharge much higher than the poor ground water quality and drainage would suggest. Recharge is however difficult to quantify, as the effective porosity of the aquifers is as yet poorly known.

These conclusions suggest that continued exploitation should improve ground water quality by removing salinity from the aquifer. The historical record of many supply boreholes showed an improvement of water quality with time, as predicted.

Conclusions on the arid-zone hydrology of the Kalahari

- In each of the studies, diffuse local recharge is found to be the major hydrological driving mechanism.
- The influence of surface features such as river beds is found to be very limited on a regional scale
- Regional sub-surface water movement is found to be at best a second-order effect, except where local structure enables limited lateral displacement
- Ground water mineralisation is a function largely of structure, rather than of lithology or residence time.
- The only balancing output mechanism is evapotranspirative losses from the saturated zone. Similar loss mechanisms have been invoked in north-west Africa for the existence of large scale depressions in the phreatic surface.
- With the exception of western Gordonia and parts of the Toteng-Sehitwa area, the absence of hypersalinity suggests that the aquifers are periodically flushed during "pluvial" episodes. The effectiveness of such resetting of the ground water mineralisation will be reflected in the present-day hydrology, which in turn is structurally controlled.

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