Groundwater recharge in an arid karst area (Saudi Arabia)

HEINZ HOETZL
Department of Applied Geology, University of Karlsruhe, Kaiserstrasse 12, D-76128 Karlsruhe, Germany

Abstract For one of the most important and intensively used aquifers in the eastern part of Saudi Arabia, the Umm er Radhuma aquifer, it was uncertain whether the natural outflow of the big springs along the Gulf coast, estimated at more than 100 m³ s⁻¹, is only due to infiltration during former humid periods or if it is a result of recent groundwater recharge. The catchment area of this aquifer is formed by the outcropping Eocene limestones in an extended, but narrow belt, about 250 km west of the Gulf coast. In spite of the extreme arid conditions there, karstification favours the infiltration of the episodic rain underground. Within a research programme the infiltration conditions and the effects of recharge on the aquifer with its mainly fossil groundwater were studied using natural tracers. Detailed measurements of the soil retention capacity and the inflow to the karst shafts yield a yearly groundwater recharge of 44 mm over the last 16 years, contributing significantly to the aquifer. The total dissolved solutes and ionic groups as well as the intensity of hydrogeochemical processes were used as natural tracers confirming two main discharge "channels" from the outcropping area of the Umm er Radhuma limestone towards the springs. The results are very important for groundwater management to keep the balance between recharge and discharge in order to avoid the extraction of highly saline water.

INTRODUCTION

The Arabian Peninsula belongs to the extended arid belt of the lower latitudes of the Northern Hemisphere. In spite of yearly precipitation rates of less than 100 mm some prolific aquifers occur below the desert in permeable Palaeozoic, Mesozoic and Cenozoic rocks. They have recently become more and more intensively used for water supplies and irrigation of newly developed agricultural areas. Several investigations using isotopes proved the fossil nature of large parts of these groundwater resources, which infiltrated mainly during more humid phases in the Holocene and Pleistocene (Hoetzl & Zoetl, 1978; Jado & Zoetl, 1984).

Groundwater recharge still occurs under the prevailing arid condition, but of course in a limited range. This is not only the case in the shallow aquifers along the wadis, where rare extreme storm events cause floods, but it can be proved also for some of the deep aquifers by tritium contents in the shallower sections. The question of the importance of such actual groundwater recharge was specially raised for one of the most
prolific aquifers in the eastern part of Saudi Arabia, the Umm er Radhuma (UER) aquifer. What is surprising is the original natural outflow along the Gulf coast of more than 100 m³ s⁻¹ including some submarine springs and the springs of the island of Bahrain (Hoetzl et al., 1977). With regard to the present strong artificial yield the question of how far the original natural outflow was balanced by the actual recharge was raised.

In a joint research project of the King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia, the Austrian Academy of Sciences in Vienna, Austria, and the University of Karlsruhe, Germany, the groundwater recharge with special attention to the karstification of the UER aquifer was studied. An area of more than 1000 km² with outcropping UER limestones was selected as an example test site for this pilot project. The basis of the hydrogeological studies was a detailed survey of the geological and geomorphological structures. A consistent picture of the morphogenetic evolution could be deduced (Hoetzl et al., 1993). The subsequent report is based on these results and will deal with the use of natural tracers to prove the underground flow from the recharge area over a distance of 250 km to the discharge area at the Gulf coast.

HYDROGEOLOGICAL CONDITIONS

Geological frame

The area of investigation covers the central eastern part of the Arabian Peninsula (Fig. 1). It belongs to the Arabian Shelf platform which is built up by sedimentary sequences of Palaeozoic to Cenozoic rocks. These sequences surround the shield area in the west and dip slightly towards the east and northeast below the overthrust of the Zagros mountains (Powers et al., 1966; Chapman in Al-Sayari & Zoetl, 1978).

The Palaeocene to lower Eocene UER formation outcrops about 70 to 150 km east of Ar Riyadh in a relatively narrow (50 km) but very extensive slightly curved belt, which can be followed from the Rhub al Khali in the south to the Iraq-Saudi border over more than 1000 km (Bramkamp & Ramirez, 1958). The sequence consists of fossiliferous fine-grained recrystallized limestones with intercalated calcarenites and dolomites. They are underlain by Cretaceous marls and dolomites of the Aruma formation and superposed to the east by sandstones and marls of the Miocene.

The superposition of the Miocene marks an important erosion unconformity. After the deposition of the UER formation the sea drew back towards the Gulf, where thick marls and evaporites (Rus Formation) and limestones (Dammam Formation) were deposited during the Eocene. The western part of the UER became land and was exposed to strong karstification (Hoetzl et al., 1993). Its latter sedimentary cover was produced mainly by terrestrial accumulation processes during the Miocene. Since the upper Miocene the recent landscape has been developed under prevailing arid climatic conditions and repeatedly intercalated short wet (semiarid) phases with erosion processes. These more humid phases caused partly an exhumation and reactivating of the karst in the outcropping area of the UER, where nowadays a lot of collapse structures, dolines, open shafts and caves are to be found (Benischke et al., 1988; Edgell 1990; Al-Saafin et al., 1990).
The Umm er Radhuma aquifer

The UER aquifer has a thickness of 150 m to more than 250 m (Baciewicz et al., 1982; GDC, 1980). The basis is formed by the impervious Aruma formation. In the outcropping area, the As Summan Plateau with elevations of 350 to 420 m a.s.l., the unconfined water level lies down to 150 m below the surface.

Towards the east the aquifer is superposed by impervious sediments so that confined conditions occur in the main part down to the Gulf. The thickness of the mid and young Tertiary overlying sediments with intercalation of some less important aquifers reaches more than 250 m. The topographic position of the UER aquifer there with regard to the sea level of the Gulf depends on structural highs and depressions.
Along the north-south striking anticlines the UER comes close to the surface (BRGM, 1977).

The anticlines in the Gulf region are of great hydraulic importance. Due to the fractional deformation of the bedded rocks by the extension strain along the anticline axis water paths are generated even through the impervious layers. Therefore artesian springs occur along the anticlines forming the natural outflow of the deeper UER aquifer (Al-Sayari & Zoetl, 1978). Two of the biggest oases of the world, the oasis of Al Hasa and the oasis of Al Quatif, known from ancient times, owe their existence to such artesian springs.

**RECHARGE OF GROUNDWATER**

The outcropping area of the UER formation forms the As Summan Plateau, which is partly covered by the Ad Dhana sand dunes. The central part belongs to one of the extremely dry areas of the Arabian desert. The average annual precipitation there is around 70 mm, sometimes with two or three years in sequence without any rain. The average annual temperature amounts 25°C and the mean air humidity ranges between 58% in December-January and 21% in June-July.

For detailed investigation, the As Sulb Plateau, part of the As Summan Plateau about 150 km northeast of Ar Riyadh, with an area of 1400 km$^2$, was selected for pilot studies (Hoetzl et al., 1993). The meteorological station of Ma'aqala, a village in the centre of this area, gives a mean annual precipitation of 93 mm and a mean "Class A Pan" potential evaporation of 4496 mm for the period of 1974 to 1989. In spite of these values a groundwater recharge of 2 mm per year through the unfavourable sand dunes, with their high evaporation losses, could be proved by Dincer et al., (1974) with reference to thermonuclear tritium.

The UER formation there is only partly covered by sand dunes. Over wide ranges it is uncovered so that the karstified limestones are directly exposed (Felber et al., 1978). Numerous sinkholes and collapse structures, open karst shafts and corrosionally extended joints, mainly paleokarst features, are present. They favour infiltration conditions in these limestone areas (Al-Saafin et al., 1990).

During the episodic and then frequently strong rainfalls the surface runoff discharges over short distances into the next karst openings (Fig. 2). By this rapid inflow to greater depths the water is protected from further evaporation and leads to a significant supplement to the groundwater.

Within the pilot studies (Hoetzl et al., 1993; Al-Saafin et al., 1990) detailed measurements of the soil retention capacity and the inflow to the shafts (Fig. 3) were carried out. Several small catchment areas dewatering towards one of these karst shafts were studied and the erosion access channels running to the shafts were equipped with gauging stations and automatic recorders. The results proved a groundwater recharge rate of 47% of the average precipitation. Estimations for the last 16 years compared with the meteorological station of Ma'aqala result in a yearly average of 44 mm. Though it is difficult to generalize these data for the whole UER outcrop it proves a considerable amount of recharge to the UER limestone aquifer, clearly more than was previously assumed.
TRACING OF THE UNDERGROUND FLOW

Discharge conditions

The investigation in the As Sulb Plateau confirmed considerable groundwater recharge into the outcropping part of the UER aquifer (Al-Saafin et al., 1990). A very rough
Fig. 3 Sinkhole with weir and automatic recorder in the access channel and meteorological station to determine groundwater recharge.
estimation based on the recharge rate and the size of the outcropping areas (more than 30 000 km²) comes to more than $10^9$ m³ per year, which seems to be of the same magnitude as the total outflow from the natural springs (Hoetzl et al., 1978). This supports the assumption of a hydraulic balance between recharge and discharge.

The springs are located mainly along the Gulf coast and in the Al Hasa area about 250 and 200 km east of the recharge area (Hoetzl et al., 1977; Job, 1978). While the difference in the topographic elevation comes to more than 300 m, that of the pressure heads is close to 200 m, resulting in a hydraulic gradient of about 1%. Age determinations with radiocarbon gave a mean residence time for the spring waters of 10 000 to 20 000 years BP, indicating an infiltration in the early Holocene or late Pleistocene (Hoetzl & Zoetl, 1978). Referring to the distance of the recharge area results in an average velocity of about 10 to 20 m per year.

**Chemical characteristics of the unconfined aquifer**

With regard to the low velocities, artificial tracer techniques are not an appropriate investigation method, even for short distances. Therefore attention was drawn to the natural chemical composition to find some correlation with the discharge behaviour. Published and unpublished data from consultant and governmental reports were studied (BRGM, 1977; GDC, 1980; Italconsult, 1969; Job, 1978; MOAW, 1983; Wakuti, 1971). Additional analyses were performed for water samples of the As Sulb plateau (Hoetzl et al., 1993). Some of the data are shown in Figs 4 and 5. There are only a few wells available, so that the interpretation of the ionic distributions is restricted.

Analysis of groundwater from the wells in the unconfined region of the UER revealed lower concentrations of the dissolved content in those areas where the upstream

![Fig. 4 Distribution of the ions in the unconfined water of the Umm er Radhuma aquifer, As Sulb Plateau (S = Shawyah, H = Hizwah, M = Ma'aqla, AA = Al Aytaliyah).](image-url)
catchment area is not covered by sand dunes and/or Tertiary sediments. In general the increase of mineralization was connected with a change in the ionic composition from calcium-sulphate to sodium-chlorite water (Fig. 5). Increasing concentrations and alkalization proved to be an effect of smaller recharge rates and longer residence time. Tritium, though only with very low concentrations, is to be found more frequently in less mineralized water, while highly mineralized waters are generally without any tritium content.

From the few wells in the pilot area only trends of the chemical development depending on recharge and transport processes could be deduced. For a systematic evaluation of the further flow direction there were too few observation wells available.
However, even the first results were helpful for the interpretation of the further discharge behaviour.

**Chemical characteristics of the confined aquifer**

The map of the piezometric contour lines (Fig. 6), evaluated from data of water wells and exploration boreholes (MOAW, 1983), shows more or less north-south oriented lines, indicating a general hydraulic gradient towards the Gulf coast.

A more detailed impression of the discharge direction can be achieved by comparing the contour lines of total dissolved solutes (Naimi, 1965). Following the data of the Ministry of Agriculture in Ar Riyadh (MOAW, 1983) two special water paths can be observed (Fig. 6). They are distinguished by lower concentrations as a result of relatively high recharge rates. The first preferential underground flow channel comes from an area south of Wadi Shaba, where wide areas with uncovered UER limestones are exposed. The other preferential flow comes down from the As Sulb plateau, crossing the Wadi Miyah and continuing from there towards the Gulf, where the main flow reaches the coast near Al Qatif only few kilometres north of Dammam. Therewith a part of more than 400 km of the UER outcropping zone is dewatering to a relatively small area of the...
Gulf coast. In spite of the long distance and obviously long travel time, the mineralization of the groundwater in these two preferred "channels" remains below 2000 mg l\(^{-1}\) dissolved constituents.

The distribution of the dissolved components for the whole aquifer shows similar effects as was observed in detail for the pilot area. In the central part between the two preferential channels higher mineralization occurs. This may be explained by the fact that the outcropping area behind the limestones is largely covered by sand dunes, causing higher evaporation effects and an increase in mineralization.

The tracing of the recharge flow towards the spring is also supported by the individual chemical components. The composition within the two observed preferential channels always shows lower sodium and chlorite concentrations then in the neighbouring aquifer parts. On the other hand there is an increase of alkalization and chlorination towards the springs. The distribution of the samples within the cationic and anionic diagrams (Fig. 7) shows a clear trend starting with samples from the As Sulb Plateau, followed by samples from Wadi Miyah on the half way to the Gulf and finally samples of the Al Quatif oasis along the Gulf coast. This documents that not only the individual chemical components can be used as natural tracers but that also the intensity of the hydrogeochemical processes can be applied to find regional correlations.

The different sources of the water in the two "preferential channels" could be proved. Though on its way from the recharge area towards the springs the waters become higher mineralized, the ionic composition of the two branches indicates a different geochemical development. It can clearly be shown that the springs in the Al Quatif area discharge mainly water from the As Sulb Plateau, while the springs of Al Hasa are fed by the water from the Southern As Summan Plateau.

Additional indications to trace the long-term flow within the UER aquifer are to be expected from isotopic data. The stable isotope data known from the literature (Al-Sayari & Zoetl, 1978) could be supplemented by the data of the As Sulb area (outcrop of UER). In the deuterium-oxygen-18 diagram (Fig. 8) the samples show characteristic clusters along lines parallel to the recent meteoric water line. Starting from shallow Wadi aquifers, continuing with the deep unconfined UER aquifer towards the confined waters of the springs in Al Hasa and Al Quatif, the distribution indicates the trend to slightly increasing \(\delta^{2}H\) values and decreasing \(\delta^{18}O\) values.

Regrettably, there were not enough radioactive isotope measurements available, but as far as they cover a characteristic profile section they show a good agreement with the chemical results. Tritium is usually missing even within the unconfined part of the UER aquifer. \(^{14}\)C data for the spring water at the Gulf coast gave mean residence time of 12 000 to more than 20 000 years; compared with the few values of the intermediate section there is no clear age distribution according to the distance from the recharge area.

**CONCLUSIONS**

Chemical components of the water composition have proved themselves as useful natural tracers to interpret slow aquifer discharges over extremely long distances (more than 200 km). As tracers, single ionic components, groups of ions, including sum-parameters, their relative distribution and certain geochemical processes, can be applied. Very helpful additional information for the interpretation of the long-term underground
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Discharge can be derived from the isotopic composition.

Both chemical and isotopic tracers were used to interpret recharge and discharge conditions of the Umm er Radhuma aquifer, one of the most prolific groundwater resources of the Arabian peninsula. In spite of the extremely arid conditions considerable active recharge could be proved for the underground flow by the tracers. These confirm the hydraulic balance between the recharge and the natural outflow feeding the large springs along the central part of the Gulf coast. The knowledge of this hydraulic system is of essential importance for groundwater management to avoid salt water intrusion from the aquifer margins as well as from the sea.
Fig. 8 Distribution of the stable isotopes in the groundwater of shallow wadi aquifers and the UER aquifer, Eastern Saudi Arabia.

REFERENCES


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