Improvements of Methods of Long Term Prediction of Variations in Groundwater Resources and Regimes Due to Human Activity (Proceedings of the Exeter Symposium, July 1982). IAHS Publ. no. 136.

Problems of groundwater development in the Sana'a basin, Yemen Arab Republic

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ABSTRACT Until recently the hydrogeology of the Sana'a was little known. Studies in 1972 to identify a source of water supply for Sana's indicated that the Tawilah sandstone could meet the city's requirements to the year 2000 and beyond. Thus, all further work was directed in developing this aquifer. At the same time, local farmers who until recently relied on abstraction from shallow well, embarked on a programme of intensive exploitation by boreholes, which has remained largely uncontrolled. This has led to declining water levels which have placed the now completed wellfields at serious risk. Examination of the aquifer in the light of the present situation indicates that previous assessments of recharge by the throughflow method have significantly over-estimated the resource. Lack of data rather than hydro-geological techniques are considered to have been the major factor.

PHYSICAL ASPECTS OF THE BASIN

The Sana'a basin comprises an area of about $700km^2$. It is typically an intermontane semi-arid basin having an elevation of 2200m a.s.l. and surrounded by mountainous terrain rising to about 3000m. The morphology of the basin is spectacular, with deeply dissected valleys on the higher ground in contrast with the flat area of the Sana'a plain. The mountainous region comprises volcanics of Tertiary to Quaternary age (with some fine examples of volcanic necks and plugs), and the Cretaceous Tawilah Sandstone which forms an inner fringe partially surrounding the Sana'a plain. The plain is floored by a moderately thick succession of Quaternary alluvium comprising silts and clays but also sands, gravels and volcanic detritus.

GROWTH OF WATER REQUIREMENTS

Needs of the City of Sana'a

Sana'a the capital of the Yemen Arab Republic, has grown rapidly in the last 20 years. In the 1975 census, the population of the city was estimated to be 135 000 and is predicted to rise to 225 000 by 1985 and over 400 000 by the end of the century. Present water requirements are about 300 $l^{-1}s$ and will probably reach 1 000 $l^{-1}s$ in the year 2000.

Irrigation in the Sana'a Plain

Groundwater has been used for irrigation in the Sana'a plain since historical times. Traditionally, it was extracted by hand or animals from shallow hand-dug wells mostly in the alluvial plain. Only recently has mechanisation been adopted; initially centrifugal pumps, and later, as water levels deepended, line shaft and electro-submersible pumps. During a survey undertaken in 1972, some 1000 wells and boreholes were enumerated, many of them mechanised. It was estimated that about 150 $l^{-1}s$ were abstracted from the alluvial deposits in the Sana'a plain and some 65 $l^{-1}s$ from the Tawilah Sandstone in the tributary wadis. Since the early 1970s the increase in water use for irrigation has been rapid, particularly in the tributary wadi areas where the Tawilah Sandstone occurs at a shallow depth and ample groundwater supplies could be guaranteed at all locations. In a survey carried out in 1978 - 1979, it was estimated that abstraction by local farmers this sandstone formation was approximately 400 $l^{-1}s$. Unfortunately no similar survey has been carried out more recently but from the number of drilling rigs operating in the area in the last 4 years present abstraction could be in excess of 900 $l^{-1}s$. Although, the present situation is an admirable example of private enterprise, it has led to a steady decline of water level over the entire aquifer with very little hope of recovery.

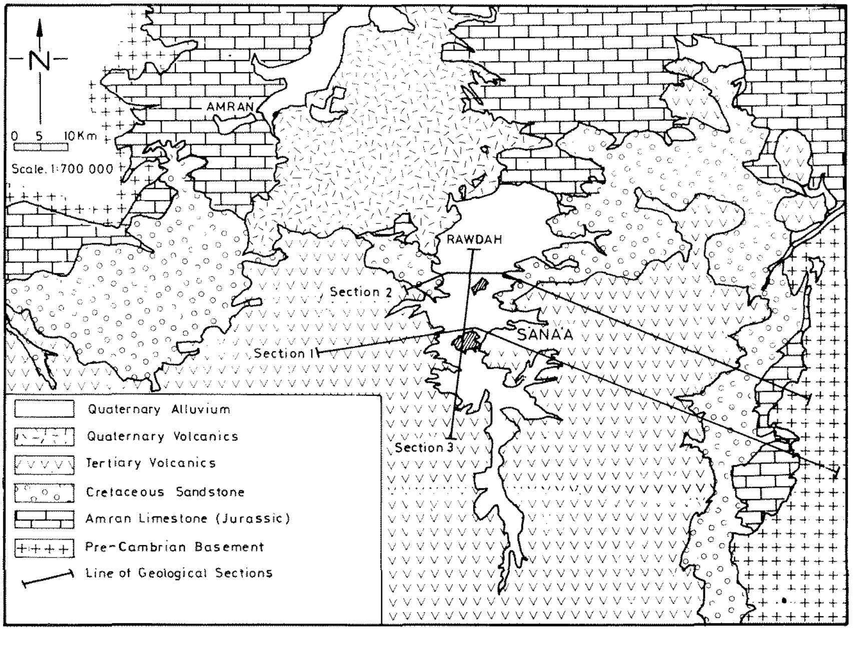

FIG.1 Regional geology of the Sana'a basin.

HYDROGEOLOGY

Geological framework

Figs. 1 and 2 show the regional setting of the Sana'a plain and the distribution of the main formations. The evolution of the Sana'a basin is only known in general terms and is summarised below.

Following a period of peneplanation in the late Palaeozoic, the beginning of the Mesozoic era was characterised by the formation

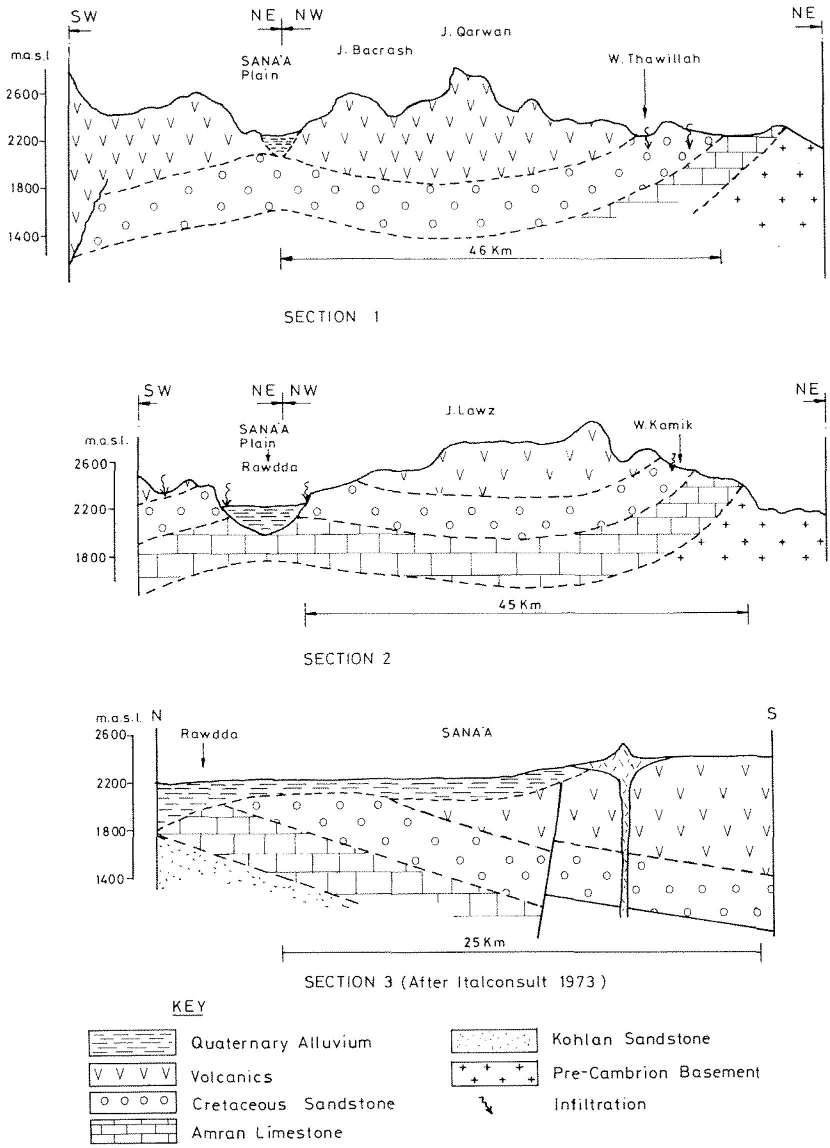

FIG.2 Interpretative geological sections.

of basins which, in Trias and early Jurassic times were filled with continental sediments of fluvio-lacustrine origin - the Kohlan Series. Further subsidence in the Jurassic led to a widespread marine transgression resulting in the deposition of the carbonates of the Amran Series, well exposed in the Amran basin north of Sana'a. In the late Jurassic, marine conditions gave way to a continental environment with the deposition of lagoonal sediments, clays and gupsum in the centre of the basins and coarse clastics at the edges. During the Cretaceous, continental conditions became resulting in the deposition of the Tawilah Sandstone Group. In the Palaeocene a narrow sea spread over the centre of the country, including the Sana'a basin which led to the deposition of the neritic sediments, clays and silts, of the Mejd-Zir series. Tectonic movements in the early Tertiaries connected with the evolution of the Red Sea rift led to broad folding (the Sana'a pericline was formed at about this time) and block faulting. The result of the general uplift was the removal by erosion of Jurassic and Cretaceous sediments, especially in the centre of the country. Tectonic activity was accompanied by intensive volanicity, including the intrusion of dykes, which started locally at the end of the Cretaceous and became widespread during the Tertiary period. The Trap volcanics date from this period. The extrusion of lavas protected the Cretaceous sandstone from further erosion. Some volcanic activity continued into the Quarternary but deposition in the Sana'a plain appears to have been of a fluvio-lacustrine nature which led to a considerable thickness of clay and silts in its central part. Geophysical evidence suggests that the depression in the Sana'a plain may be of tectonic origin but this can only be confirmed by further exploratory drilling.

Groundwater reservoirs

The hydrogeological studies of the early 1970s concluded that the Tawilah Sandstone was the only groundwater reservoir in the region having the potential to satisfy the future needs of the city of Sana'a. The Quaternary sediments with their high clay content were considered poorly productive - athough they have been extensively used for irrigation in the plain and forthe domestic supply of Sana'a and surrounding villages. The Trap volcanics and Quaternary basalts were also found to be generally unproductive, this being consistent with the characteristic random nature of fracturing of such rock. The Amran Limestone in the Sana'a plain occurs at depth (about 400m) and has not been penetrated by boreholes. Exploration in the Amran area and elsewhere in Yemen has shown this formation to be generally unproductive, attributed to its argillaceous nature and lack of extensive fissuring. The Kohlan Sandstone, which is thought to underlie the Amran Limestone in the Sana'a plain, also occurs at depth (about 600m) and has not been penetrated by boreholes. The groundwater potential of this formation is unknown although, it is known to give rise to large springs at outcrop northwest of Sana's.

TAWILAH SANDSTONE AQUIFER

Extent of the aquifer

Although the Tawilah formation is known to be fairly extensive, perhaps covering the entire region of central Yemen, the extent of the aquifer is only known locally within the Sana'a plain. Fig. 2 shows largely interpretative sections of the aquifer which highlight its tectonic setting and hydraulic extent. The northern limit of the aquifer is fairly well known with the aquifer wedging out in the northern part of the plain. South of Sana'a, it plunges into considerable depth (about 600m) under a volcanic and alluvial cover. A major fault zone (indicated by geophysical surveys) and a volcanic plug probably restrict the aquifer in this direction. To the west, the aquifer continuity is again locally interrupted by volcanic plugs and probably faults and almost certainly a similar situation occurs in the east (not shown in the sections).

The thickness of the sandstone in the Sana'a plain is variable. In the northern area it is about 100m thick, eventually wedging out further north; in the central and southern areas the thickness increases along the direction of dip to about 400m. Boreholes in the area exploit almost the entire aquifer thickness in the northern plain but only about 60% in the southern areas, thus leaving some groundwater storage untapped.

Hydraulic properties

About forty boreholes (excluding local boreholes) have been drilled in the Sana'a plain, but only a few aquifer tests have been carried out. Transmissivity and storativity are only known from about ten sites where satellite piezometers were drilled adjacent to production boreholes. Aquifer tests at these sites together with yield tests of production wells have shown the aquifer to be highly anisotropic with transmissivities ranging between $10m^{2-1}d$ and $500m^{2-1}d$. The primary permeability of the sandstone appears to be low (perhaps less than 0.05 $m^{-1}d$) but this has been enhanced locally by fracturing to give values of about $1m^{-1}d$ or more. The variation of permeability with depth is not known, but from limited data, it appears that it decreases with depth though the evidence is largely sketchy. The aquifer anisotropy has been attributed mainly to the effects of fissuring caused by faulting and fracturing associated with the intrusion of volcanic dykes in the Tertiaries. In general, it has been demonstrated that the aquifer is most productive in the smaller east-west tributary wadis which run perpendicular to the main north-south Sana'a plain. It is probable that these wadis represent zones of structural weakness where intense fracturing through faulting and intrusion of dykes has occurred.

Geological evidence suggests that groundwater in the aquifer is stored under water-table conditions in areas where the sandstone outcrops or where it occurs at shallow depth. In the southern part of the Sana's plain, where the sandstone is overlain by a considerable thickness of alluvium, water is stored under confined conditions with water levels rising to about 100m above the base of the confining bed. Unfortunately nothing is known of the type of storage in the aquifer at large. It is perhaps reasonable to assume that confined conditions pertain in most of the aquifer with the thick volcanic beds acting as the confining stratum. Storage coefficients appear to be of the order of 10^{-4} (for the portion of the aquifer under confinement) and about 1% for the phreatic areas.

Aquifer piezometry and groundwater movement

The piezometry of the sandstone is fairly well known locally along the fringes of the Sana'a plain, but little known regionally. From this limited knowledge, it appears that groundwater moves from the surrounding high ground towards the Sana'a plain (Fig. 3). In the absence of regional information, the local piezometry has been extended to encompass a wider area, on the assumption that it reflected the general pattern. This view, however, is somewhat difficult to reconcile with geological evidence which tends to suggest a southerly direction of flow for at least one part of the aquifer (Fig. 2; Section 2 and 3). Hydraulic discontinuities through faulting and volcanic intrusions complicate further the flow pattern. Thus although the inference from Section 1 (Fig. 2) is one of groundwater movement from the western outcrop towards the Sana'a plain, hydraulic discontinuities may prevent such movement from taking place.

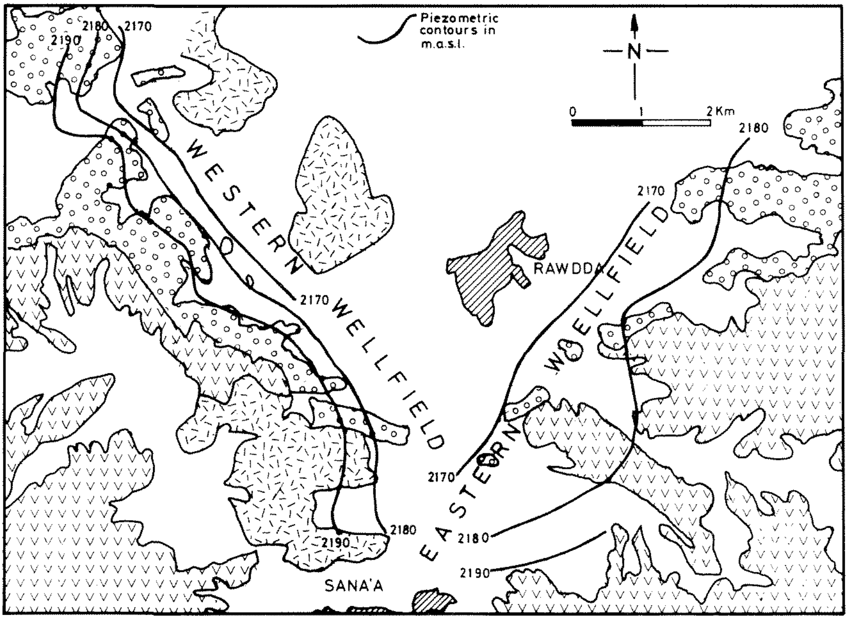

FIG.3 Piezometry of Tawilah sandstone in the Sana'a Plain.

Water level fluctuations

Monitoring of water levels in thq Sana'a plain commenced in early 1972 when abstraction from the sandstone aquifer was small. Water levels then were on average 40m below ground whereas now are in excess of 60m and falling. The 10 year record shows a consistent decline of water levels ranging between 0.5 and 2m year^{-1}. In the vicinity of pumping centres, the rate of lowering is greater and approaches 6m year^{-1}. There is no doubt that the depression of water levels in the pumped areas represents the hydraulic response of the aquifer to abstraction. It is, however, also clear that there is an underlying long-term trend of falling water levels, related to withdrawals being greater than replenishment.

GROUNDWATER RECHARGE

Mechanisms of recharge

It has been postulated (Italconsult, 1972) that the bulk of the recharge to the sandstone occurs on the plateaux and mountains surrounding the Sana'a plain by a process of deep percolation, i.e. downward movement of infiltrated water through the volcanic overburden. The same hypothesis assumes that the Sana'a plain behaves as a drain where all lateral inflow through the sandstone converges and replenhes the alluvial deposits. It is difficult to imagine deep percolation occurring, particularly in view of the large thickness and nature of the volcanic deposits. On the contrary, it rather appears that the overburden would prevent any replenishment from reaching the aquifer except perhaps in localised areas of deep fracturing. It is therefore considered that recharge to the aquifer occurs primarily in the sandstone outcrop areas or where the alluvial cover is thin. The exact mechanism by which infiltration occurs is not known but is thought to be similar to that of many arid countries with extreme topography and a rainfall pattern of short intense storms. In such areas, wadi catchments with their efficient drainage pattern act as collectors of surface runoff which is discharged into the wadi courses. Because the latter are generally flat and floored by sandy soil and fractured sandstone, large quantities of surface runoff infiltrate into the aquifer through streambeds, over short periods which rarely exceed a few days.

Estimation of recharge

To estimate recharge in such complex environment with very limited information is indeed a formidable task. The conventional rainfall/infiltration and runoff/infiltration techniques, although mathmatically the simplest area, the most difficult to apply in the absence of reliable and long term data. Rainfall data mainly exists for Sana'a and even there the record is discontinuous. Rainfall occurs in two short seasons, April - May and July - August. From synthesized records, the mean annual rainfall is about 330mm but actual records in the last 15 years indicate a mean of approximately 270mm. Annual evaporation exceeds rainfall, being about 2900mm. Recharge therefore occurs during major rainfall events which last only a few days. From the scanty record, about 70-80% of the annual rainfall (approximately 200mm) occurs over a period of about 20 days, corresponding to an effective rainfall of about 40mm. Runoff is thought to be small (no measurements exist) probably about 10mm. From these gross assumptions, it appears that infiltration into the aquifer within the tributary wadi areas (about 75km^2) of the Sana'a plain is about 30mm which corresponds to an annual rate of recharge of 2.25 10^6 m^3 or 75 ls^{-1}. A similar calculation for the entire northeastern sandstone outcrop (625 km^2) indicates an annual quantity of recharge of 25 10^6 m^3 or 790 ls^{-1}, this amount being an upper estimate as it assumes infiltration occurs over the entire outcrop area.

From the decline of water levels over the last decade, it is clear that abstraction has exceeded replenishment even during earlier years when exploitation was small. In this respect, water level fluctuations appear to confirm the tentative estimates of infiltration.

Groundwater inflow to the Sana'a Plain

In the absence of reliable hydrometeorological data, previous investigators (Italconsult 1972; Howard Humphreys & Sons, 1977 and 1979) have estimated recharge by calculating the inflow into the Sana'a plain using the Darcy equation. The method provides an estimate of long term replenishment but has the disadvantage of not distinguishing between this and short term variations which may or may not exceed the long term mean. Ideally, the Darcy equation can only be applied for steady flow in isotropic confined aquifers where an orthogonal flow network of equipotentials and flow lines can be constructed.

Estimates by the method using the locally observed piezometry in the Sana'a plain, indicated total inflows of about 50 10^6 m^3, 20 to 30 10^6 m^3 for the western sandstone outcrop and 33 10^6 m^3 for the eastern area (Fig. 3). These were taken to represent the mean long-term recharge to the sandstone. Considerations in connection with the hydraulic continuity of the aquifer, the regional direction of groundwater flow and the concept of deep percolation, appear to cast doubt as to the appropriateness of the method. Notwithstanding the limitations imposed by poor data, which can also seriously affect the estimates, it now seems that previous hydrogeological concepts have probably been erroneous. Contrary to the previous view, it is postulated that groundwater recharge occurs only locally in the smaller wadis, tributary to the Sana'a plain, and that lateral inflow from distant sources is unlikely.

AQUIFER DEVELOPMENT

Wellfields in the western and eastern areas have been recently completed with a view to providing initially 9.5 10^6 m^3 per annum, increasing to 19 10^6 m^3 in a few years. It is now almost certain that mining of the sandstone reservoir has been occurring for some time. At the present rates of withdrawal of 30 10^6 m^3 per annum (mainly for irrigation), the life service of the wellfields has been placed at serious risk. There is no doubt that even at this late time some benefit can be derived by effective control of private abstraction. Given, however, the practical difficulties of enforcing conservation measures, it appears that the ultimate deterrent would be an economic one forced on farmers by mounting extracting costs as water levels become deeper. The life of the wellfield can also be extended to a limited degree by deepening of some of the existing boreholes nearer to Sana'a where the aquifer is thickest. For the present, a reliable assessment of the useful life of the wellfields is not possible. From the recently observed rate of lowering of water levels, periods of up to 15 years seem reasonable but perhaps at lower rates of exploitation than originally envisaged. More hydrogeological data including exploratory drilling of a regional nature assisted by a digital model of the aquifer will be required before accurate estimates can be made. Isotope studies to determine the age of groundwater and hence replenishment, will also be useful. As regards the future of water supply to Sana'a, attention should be directed to exploring by boreholes the as yet unexploited Kohlan Sandstone which is thought to exist at depth in the Sana'a plain.

GENERAL PROBLEMS OF ASSESSMENT OF RESOURCES

In as much as the present situation in the Sana'a plain has arisen as a result of uncontrolled exploitation, the hydrogeological aspects of the groundwater reservoir, especially as regards the assessment of recharge are equally pertinent. In particular, these aspects are relevant in the application of perfectly proper techniques in complex hydrogeological environments using imperfect and limited data. It is often the case that errors in the assessment of groundwater resources do not stem from the lack of hydrogeological techniques but from lack of data. Time and the cost of carrying out comprehenshive investigations are invariably the major constraints. When, however, the viability of large schemes depends upon a proper understanding of the groundwater reservoir, it is prudent that both time and money are expended in obtaining the required information. It is recognised that very often water supplies need to be developed quickly and at as low cost as possible. Nevertheless, reluctance to commit necessary expenditure and to allow sufficient time for the investigatory phases can result in premature assessment of resources which may lead to failure of schemes involving high capital expenditure.

ACKNOWLEDGEMENTS The author is grateful to the Director of the National Water and Sewerage Authority of the Yemen Arab Republic for permission to publish this paper. He is also indebted to Mr. A.K. Al Fussail and the hydrogeological section of the Authority for their assistance.

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