

6 GROUNDWATER RECHARGE

Groundwater studies have traditionally been linked with geology, however, hydrogeology has become a subject in its own right, with its own techniques of analysis, but based initially on geological investigations. This chapter does not aim to cover the whole field, which would require a book on its own; various hydrogeological textbooks are available (e.g. Price, 1996; Rushton, 2003). It concentrates on the links between surface water and groundwater and how information from one field can help in understanding processes in the other. The example of groundwater recharge illustrates ways in which the study of the surface water balance can assist hydrogeological analysis, while the study of the base flow component of runoff can give information on groundwater storage. With the help of groundwater analysis methods, examples illustrate the way in which measurements of different components of the groundwater process make a more precise analysis possible.

PROCESSES OF GROUNDWATER RECHARGE AND DISCHARGE

In general, groundwater recharge from the surface occurs after the soil moisture store is filled, when excess water may either run off as river flow or else drain down towards the water table as groundwater recharge; it is possible for both processes to occur as a result of recharge from stream beds. In some environments, as in chalk or limestone, the recharge will dominate the destination of the net rainfall. In some conditions, or in areas where rainfall intensity is high, infiltration through the soil surface may be a limiting factor, but in general the balance between recharge and runoff will depend on downward percolation rates from a full soil moisture store. Measurement or estimation of this phase of the hydrological cycle is not easy, but some examples are discussed later.

It is possible to assess the timing and quantity of recharge from a study of the fluctuation of the water table or piezometric surface, which can be measured in observation wells. This is particularly true where recharge is highly seasonal, because the rainfall or the potential transpiration is seasonal and therefore the net rainfall is seasonal. It should be noted that the rise in water level due to recharge is not the same as the depth of water recharged; the coefficient of storage is the ratio between increased water content and water depth of recharge, which depends on the aquifer material. In the case of a confined aquifer, where the water is held under a pressure which increases as the piezometric level rises, the storage coefficient is much smaller than in the case of a free water surface, typically 0.001 against 0.1.

The flow through an aquifer can be illustrated by a water table map, on which the contours of equal water table elevation are drawn. The direction of flow is perpendicular to the water table contours, from areas of higher to lower elevation. The rate of flow through the aquifer can be estimated by Darcy's law, which states that the flow is proportional to the gradient of the water surface and also the permeability of the aquifer

material, which is expressed as cm day^{-1} , or as $\text{m}^3 \text{ day}^{-1} \text{ m}^{-2}$ of aquifer, per unit gradient. This flow rate is not the same as the velocity of the water itself, because the flow pathway does not include the whole aquifer. The permeability may be estimated from the material of the aquifer, or tested in a laboratory, but can be measured more precisely by an *in situ* pumping test.

Groundwater flow will emerge at a lower level than the water table, either as river flow, spring flow or even through the coastline directly to the ocean, as sheet flow or through offshore wells. The groundwater discharge may be deduced by estimating the groundwater component of river flow, the outflow at springs or with more difficulty the outflow to the ocean.

SUMMARY OF TEHRAN STUDIES

The rate of groundwater recharge may be estimated or measured at different stages of the flow cycle: by estimating the recharge itself, the flow of groundwater through the aquifer, or by estimating the discharge from the aquifer to a river or spring. These three approaches are introduced by means of successive studies of the groundwater resources of Tehran.

Successive investigations of this major aquifer, described as the source of one of the largest developments in the world, have taken advantage of increasing data availability and advances in integrated modelling techniques. Initial information on aquifer recharge from rivers, on flow through the aquifer based on water table gradient and aquifer dimensions and permeability, and on seasonal water table fluctuations, was used to make preliminary estimates of groundwater availability.

As measurements of river inflows, well level fluctuations and aquifer properties were accumulated, together with estimated distributions of abstractions and aquifer recharge from external domestic supply, information became available for modelling. In the first stage an electrical analogue model was constructed to reproduce the average values of aquifer recharge, flow through the aquifer and abstraction. The analogues between flow through an aquifer and electrical current through a network of resistances, between aquifer permeability and electrical conductivity, and water level and voltage head, were used to construct a steady state model of the aquifer and to simulate wellfield abstraction at various locations and deduce the long-term effect on levels of different rates of pumping.

Once a further period of records had been collected, it was possible to assess a time series of recharge over a spatial grid from river flows and from water supplies; this information was included in a dynamic model of the aquifer, based on computer-based mathematical modelling. Water level data covering a seven-year period were summarised by a 64-node series, and recharge from streamflow and imported water, rainfall, *qanat* flows and abstraction were calculated for each node on a monthly basis. The mathematical model represents the response of the aquifer in terms of water levels and water flows to patterns of recharge and abstraction, given the aquifer characteristics of transmissivity and storage coefficient for each grid square. Transmissivity coefficients were first optimised over a period when cumulative level changes were small, and storage coefficients were optimised using the complete time-varying model. Once the model results were reasonable over the period of observation, the model could be used to assess the effect of wellfield abstraction over time. Thus increasing levels of information were used in a series of models of growing sophistication and precision.

Initial study of the Tehran aquifer

In 1957 when very little information was available in the form of measurements, it was necessary to estimate the annual quantity of water available from the local aquifer for supply to the city of Tehran (Sutcliffe & Rangeley, 1960b). The original water supply for Tehran was derived from underground resources by means of a number of subterranean galleries known as *qanats*. These (Fig. 6.1) consist of a tunnel sloping gently uphill from the point where the water supply is designed to emerge, upstream to a "mother well" below the water table in a source area. Vertical shafts are constructed at regular intervals to provide access for construction and repair, and these reveal the course of the *qanat* on air photography. The majority of the *qanats* emerged in the historic city core, where water was traditionally distributed in surface channels along the streets. At the time of the study the *qanats* had been supplemented by a number of drilled wells around the expanding city.

Further resources had been derived since 1933 from the River Karaj to the west by the construction of an aqueduct. The Karaj and another large river to the east of Tehran, the Jajerud, were being developed near their outfalls from the Alborz mountains by the construction of reservoirs, but the flows of these rivers were also used for irrigation on the plains to the south. It was therefore important to know what could be supplied from the local aquifer, which had already been developed to some extent by individual industrial and domestic water users.

At the same time as the hydrology of the aquifer was being investigated, the alluvial geology of the Tehran area was studied (Knill & Jones, 1968). The area of Greater Tehran lies between the volcanic deposits of the Alborz mountains to the north, the complex sequence of limestones and igneous rocks of the Sepayeh ridge to the east, and limits defined somewhat arbitrarily by the River Kan to the west and the city of Rey to the south. There is evidence that the ridges of the Sepayeh continue below the city, with a depression within the bedrock floor reaching a depth of about 700 m to the north of the city. The alluvium underlying the Tehran plain has been divided into four groups ranging from an older, folded group of probable Pliocene age, overlain by flat-lying Quaternary gravels, sands, silts and boulder beds. North of the city (Fig. 6.2) the

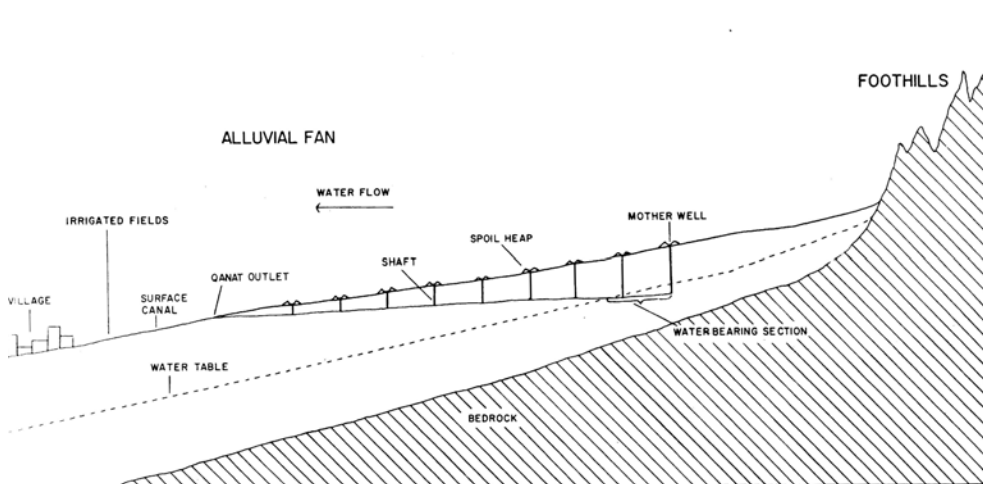


Fig. 6.1 Diagram of a qanat (from Beaumont, 1971).

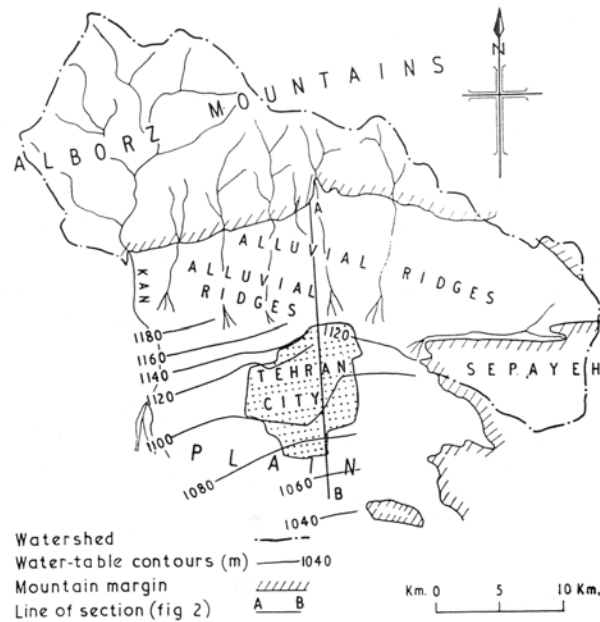


Fig. 6.2 Tehran aquifer (from Sutcliffe & Rangeley, 1960b); cross-section A-B is shown in Fig. 6.3.

plain is broken by a number of alluvial ridges, formed from the older beds contorted into anticlinal folds with steep or vertical bedding, which are aligned from east to west. The younger alluvial beds overlie the old beds unconformably and slope gently towards the south or form flat-lying deposits infilling depressions. Recent gravels occur within the river beds and their gravel fans.

The aquifer is extensive and unconfined within the alluvial beds underlying the Tehran plain. It derives water from a segment of the mountains to the north, draining towards the plain above the city. In the northern part of the plain a number of ridges of old folded alluvium with relatively poor aquifer characteristics, form a barrier to lateral movement of groundwater, which is restricted into passages between the ridges. Several watercourses cut through these ridges and spread out as wide gravel fans to the north and west of the city centre. The main water-bearing formations lie to the south of these ridges and slope gently towards the south and a number of salt lakes. The western boundary of the aquifer was taken as the River Kan (Fig. 6.2); to the west along the base of the mountains, this aquifer was used for local irrigation.

Estimates of recharge

A water balance study of the southern slopes of the Alborz range revealed a close relationship between precipitation and elevation (Fig. 3.6). The annual mean rises from 160 mm at an elevation of 1000 m to 630 mm at 2170 m. Precipitation occurs during the colder months (October–April) and the basin water loss is thus much smaller from the mountain area than from the plain. The main recharge of the aquifer derives from precipitation at high elevation, which runs off mainly as snowmelt through rivers and watercourses which debouch onto the plain. Several streams have cut through the alluvial ridges in narrow channels and all spread out into wide gravel fans and braided



Plate 6.1 Alluvial fan of the River Farahzad, northwest of Tehran.

channels once they reach the flat plain (Plate 6.1). Recharge clearly enters the aquifer through the gravel beds and fans. There was also significant artificial recharge in the area of the city from domestic and industrial sources.

The estimation of infiltration from surface sources was reasonably simple, because it was clear from reconnaissance that a large proportion of the mountain precipitation and runoff found its way into the aquifer. At the time the River Kan and the smaller streams were not monitored, but the precipitation on their local basins was estimated from the regional relation between precipitation and elevation. It was also possible to estimate the runoff from this precipitation by comparison of the water balance of several adjacent measured rivers, including the Karaj and Jajerud.

Some discharge measurements were made on the Kan during the study, and showed that a fairly high proportion of its flow passed the city in a defined channel; it was clear that much of the recharge from this river took place near the alluvial fan to the southwest of the city. The proportion of the Kan runoff recharging the aquifer to the east of the river above the city was estimated at 15% from measurements and observation. The smaller streams, on the other hand, were observed to fan out to the north of the city (Plate 6.1), and it was deduced that a large proportion of the runoff recharged the aquifer. Estimates were made (Sutcliffe & Rangeley, 1960b) of the recharge as a proportion of runoff; based on observation of the topography, these ranged from 40 to 80%. A nominal 10% of the precipitation, of about 200 mm, on the plain above the city was added to give a total estimated annual recharge of $67 \text{ m}^3 \times 10^6$.

In the unusual conditions of this semiarid area, this estimate provided a useful check on the subsequent estimates made by other approaches. The proportion of inflow reaching the aquifer must often be uncertain, though with rivers that disappear within the study area it was relatively simple. In other cases measurements of inflow and outflow could provide useful estimates.

Flow through the aquifer

At the time of the initial study (1957) no archive of well records or water-table map was available, so the first step was to compile these essential tools. With the assistance of local drilling contractors, some 225 existing wells were traced and visited. Initial

depths to water table had been logged and were compared with the observations of the owners or mechanics of the wells, many of which were fitted with gauges. Levels at different dates were consistent over the area; a few records of depth over time were found, and one long-term record suggested that little change had occurred up to that time. This meant that the water-table map compiled from observations at different dates should be representative. Water samples were taken and analysed, while a number of estimates of seasonal fluctuations of the water table were obtained at the wells.

The detailed water-table contours showed that several individual groundwater flows enter the northern part of the main aquifer from different sources. Flows derive from the Kan River and from the fans near the Kan to the south of the alluvial ridges, and also pass through the gaps in the ridges to the south of the northern Shemran basin. The same areas provide the sources of most of the *qanats* supplying the city; these sources were located with the help of the city's chief *qanat* engineer and marked on air photographs and maps (e.g. Knill & Jones, 1968). South of the alluvial ridges the flows coalesce with a hydraulic gradient of about 1:120 (Fig. 6.3).

The information derived from water quality investigations can also provide useful hydrological insight by giving information on the processes at work. For example, samples of water obtained from over 100 boreholes throughout the Tehran plain were analysed; those obtained below the city, especially from relatively shallow boreholes, clearly illustrated the effect of downward drainage of wastewater by the presence of a mound of high total soluble salt values below the city. This artificial recharge within the city centre was also evident from a mound in the water table. Similarly, tongues of relatively fresh water through the Qolhak gap in the alluvial hills to the north of Tehran confirmed the routes by which groundwater flows through the aquifer.

Whereas recharge depends on surface water flows, which vary from year to year, groundwater flow through a large aquifer should be relatively steady, as annual

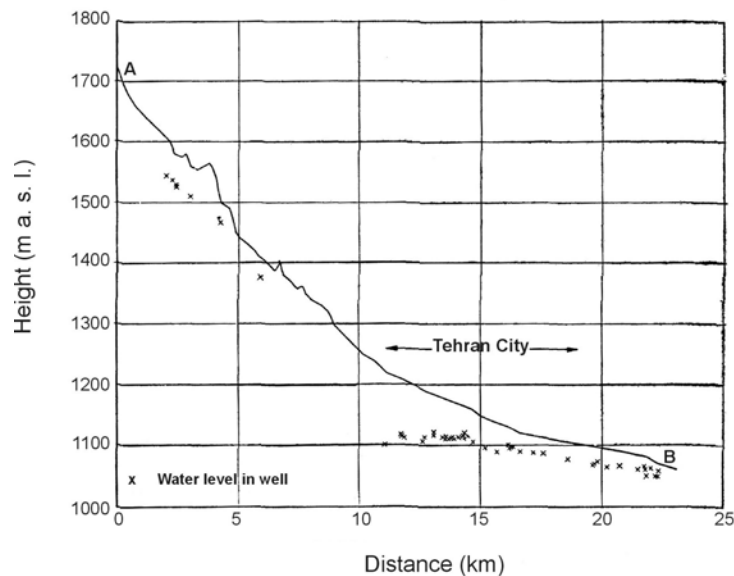


Fig. 6.3 Cross-section of Tehran aquifer; location of transect A–B shown in Fig. 6.2 (from Sutcliffe & Rangeley, 1960b).

fluctuations will be damped out within the aquifer. Thus estimates of flow through the aquifer, based on measurements of gradient and aquifer properties, should represent the long-term average resource. The information from a large number of wells showed that the hydraulic gradient in the main aquifer was uniform, which with the geological evidence suggested that the aquifer was fairly uniform horizontally.

This in turn suggested that the transmissibility of the aquifer, or the permeability multiplied by the depth, should also be fairly uniform and could be reasonably estimated from a small number of tests. The time for the study precluded the drilling of sets of wells for orthodox pumping tests, but during the visits to recently drilled well-sites, several were found where hand-dug shallow wells had been replaced by adjacent deep boreholes and modern pumps. The owners readily agreed to allow their wells to be used for testing.

Three pumping tests were carried out at sites of this type; the deep well was rested and then pumped for periods of up to 48 hours while the water table was observed in the nearby shallow wells. This was followed by an equal recovery period when the deep well was rested. In the absence of automatic recorders this entailed a shift system of observers using locally made electrical sounders (Plate 6.2), but the tests provided data which accorded with theory. The outputs of the pumps were measured either directly by V-notch or by volumetric methods. Drainage was a problem as the pumps were not normally used continuously; at one site where the output was passed into street drainage to avoid recycling, a check revealed that a small lake had been created to the delight of the local children.

The drawdown and recovery records at the observation wells were analysed using the graphical Theis curve and straight line methods (Wenzel, 1942; Brown, 1953). The plotted results (Fig. 6.4) fitted the straight line solution very well. In one case, in the south of the city, two observation wells were used at 21 and 108 m from the pumped well. In addition to the analysis of drawdown and recovery levels in each well, the final drawdown values were used for an equilibrium solution. The results for transmissibility



Plate 6.2 Observing water levels during a pumping test northwest of Tehran.

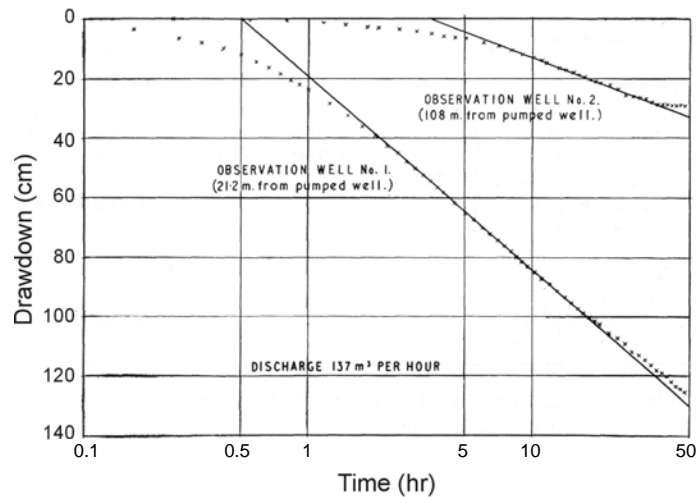


Fig. 6.4 Pumping test in southern Tehran (from Sutcliffe & Rangeley, 1960b).

were reasonably consistent except for those derived from the far observation well alone. A second test in the south of the city gave a similar result for transmissibility, while one in an isolated basin 10 km north of the city centre gave a lower value consistent with the steeper gradient in the area. Values of the coefficient of storage were also obtained from these tests. The typical value of transmissivity, in the unit current at that time, was 72000 Meinzer units (US gals/day/foot width/unit gradient) or $895 \text{ m}^2 \text{ day}^{-1}$. The corresponding coefficient of storage was 0.1.

Because the pumped well did not extend to the base of the aquifer, the calculated transmissibility was adjusted to $1020 \text{ m}^2 \text{ day}^{-1}$ to allow for partial penetration of the aquifer, using depths given by geophysical survey. This transmissibility was multiplied by the hydraulic gradient and the effective width of the aquifer (20 km), to give an estimated annual groundwater flow of $62 \text{ m}^3 \times 10^6$. It was considered that this method of estimation was the most direct and involved the fewest assumptions. It is the most generally applicable method of estimating the available groundwater resources in a short period of investigation.

Water table fluctuations

Where recharge is highly seasonal, another method of estimation can be based on the observation of annual fluctuation of water levels within the aquifer. In the Tehran region, the precipitation occurs during the winter months, much of it in the form of snow. As the runoff is concentrated during the spring snowmelt, the recharge of the aquifer is highly seasonal and reflected in the fluctuations of the water table. Periods of recharge are followed by periods in which the outflow is equal to the rate of change of storage, which can be estimated from the product of the fall in water level, the coefficient of storage and the area of the aquifer. The rate of change of storage during the period of decline must be extended to cover the full year to estimate the annual recharge.

One or two records were available at the time of the study to confirm the seasonal pattern, but no network of measured wells had been established. However, questioning

of mechanics at the wells revealed that where estimates were given, these were reasonably consistent and suggested that the seasonal range varied from about 4 m in the north of the main aquifer to about 1 m in the south of the city. As the recharge occurs during the first four months of the year and is followed by eight months of discharge, the seasonal range was increased by 50% to give the annual outflow. From the dimensions of the aquifer and a storage coefficient from pumping tests of about 0.1, the annual recharge was estimated at about $75 \text{ m}^3 \times 10^6$.

Comparison of estimates

The three estimates were based on different approaches: recharge from surface sources, flow through the aquifer, and water-table fluctuations. As far as possible, the three estimates were made independently, and yet gave annual figures of similar magnitude. Each of them could be criticised as depending on sparse evidence, but it was considered that a mean estimate of annual flow of about $70 \text{ m}^3 \times 10^6$ was reasonable.

At the same time it was recommended that, because the groundwater resource was important to the city, regular observations should be undertaken. It was suggested that the flows of the rivers and streams feeding the aquifer should be measured, that the River Kan should be measured at two locations, upstream and downstream of the main aquifer, and that a network of well levels should be monitored and systematic pumping tests carried out.

Development of analogue model

When the investigation was followed up in 1970–1973, sufficient records had been collected to provide estimates of the average behaviour of the Tehran aquifer, which was taken to cover a wider area than before. Estimates were made of the average rainfall over the Tehran region, the surface water inflow and the distribution of recharge, and of the water imported from the Karaj and Jajerud rivers and its distribution over water supply areas. Surface outflows to the south were also taken into account, and evaporation losses over the area were estimated. *Qanat* inflows and outflows were assessed, and were found to have increased significantly. An independent estimate of the transmissivity distribution was based on maps of recharge and water table, and a digital model was used to reconcile the transmissivity estimates, by providing successive transmissivity distributions which reduced the error in the water balance from that derived from pumping tests and geology.

These estimates were used to construct an electric analogue model of the aquifer (Cole, 1973). In this model the aquifer was represented by a two-dimensional network of points connected by resistances which reflected the transmissivity of the area, water levels were represented by voltage heads measured at these points, and groundwater flows were modelled by electrical currents through the network. The transmissivity distribution through the aquifer was derived from a number of pumping tests, extrapolated and adjusted to fit the hydrogeological evidence; the storage coefficients were derived from the tests and the aquifer lithology and were represented by capacitors. The levels at the boundaries of the aquifer were represented by voltages at corresponding points in the model, and the resistances ensured that the voltage network corresponded with the levels in the aquifer. The *qanat* system was represented by a number of “snake and ladder” circuits. Once the aquifer had been modelled in this way,

it was possible to model the extraction of groundwater from a wellfield at any point by extracting a current at the equivalent point and observing the change in voltage which was equivalent to the drawdown. This steady state model of the aquifer, which was finally constructed on a 1×1 km grid, and provided with surface inflow and rainfall on the basis of an average year, enabled wellfield planning to be made without extensive trial drilling. The effect over time of wellfield abstraction could be tested on the analogue model. The effect of importing water or of diverting the River Kan could also be tested. Although it would be unusual to develop an analogue model nowadays, as computer-based models are relatively straightforward, analogue models have the advantage as an operational groundwater management tool in that they are comparatively simple to understand.

Development of dynamic model

About five years later again, the available measurements had accumulated to an extent that it was possible to derive a dynamic as opposed to a steady-state model of the aquifer. This time-varying model was designed to simulate the behaviour over a period of time rather than calculate an average condition. In order to make the adjustment of aquifer parameters simpler, computer-based mathematical modelling was used on this occasion. In order to monitor the behaviour of the wellfield, the aquifer was divided into 64 grid squares of 4×4 km, and the well levels recorded in 200 wells over a time span of 84 months were used to give monthly water levels for each grid square. The flows of the northern streams had been measured for seven years, and gaps in the record were filled by correlation with the flows of the larger rivers. Flow records of the streams at sites along the channels were estimated from gauged flows in order to deduce recharge from streamflow. It was possible to assess recharge on a spatial grid taking account of river flows in time and space. The import of surface water from the Karaj and the Jajerud had increased dramatically during the period of study, and the increasing water supply over the years from these imports and the resulting recharge to the aquifer were taken into account. Records of water supply were available from the supply network, and its distribution and use over the city could be deduced from sample billings which showed consumption. The residual water supply which was returned to the aquifer was deduced from a design study of surface sewerage systems, so that the inflow to the area, the recharge of the aquifer and the water level response of the aquifer could be compared with wellfield abstraction records and records of artificial recharge.

A number of channels draining from the lower end of the study area were measured and their outflows summarized. Recharge from rainfall, abstractions and discharges of *qanats*, and well abstractions, were calculated from periodic measurements or estimates and allocated over the nodes of the model and each month of the study period.

A dynamic mathematical model (Smith & Piper, 1978) was developed to represent the response of groundwater flows and well levels within the aquifer system to varying patterns of recharge and abstraction. Using the series of recharge and abstractions deduced above, the model reproduces the resulting changes of water level, using the parameters of the system: the transmissivity and storage coefficient of the aquifer over each grid square. The equations of groundwater flow and storage are represented by partial differential equations linking flows through the aquifer. The estimated flows

depend on hydraulic gradients and aquifer transmissivity, while changes in storage are based on changes in head and storage coefficients, taking account of recharges and abstractions to and from the aquifer. In the model the continuous aquifer is represented by a rectangular grid of nodes and time is divided into discrete intervals. The partial differential equations are approximated by simultaneous equations expressing flow and storage changes between adjacent nodes and time intervals. These finite difference equations were solved iteratively to give a time series of predicted water levels for each node. These predictions, using the aquifer parameters found in the earlier study described above, diverged from the water levels observed at many of the nodes and a programme of optimisation was undertaken. Transmissivity parameters were first optimised, using a steady-state digital model over two periods when change of storage was minimal; a weighted mean of these parameter values was accepted. The differences between the initial and final transmissivity parameter values were expressed non-dimensionally, and the pattern of changes was mapped according to the grid of nodes (Fig. 6.5); the pattern of change was considered consistent with recent hydrogeological interpretation. Storage coefficients were optimised using the complete time-varying model. Scrutiny of the aquifer parameters was based on prior knowledge of the aquifer; limits were placed on the permissible values of the storage coefficient. The optimisation was based on defining an error function to measure the fit of the predicted to the observed water levels and then changing the parameter values to minimise the error function.

Once the behaviour of the aquifer over time had been satisfactorily reproduced in the model, the effect of various forms of exploitation of the wellfield could be studied and monitored in time as well as in the long-term average case.

Thus the accumulation of records of the different variables involved in the hydrological behaviour of the Tehran region enabled more sophisticated methods of analysis to be used. On the other hand it could be argued that the analysis was similar

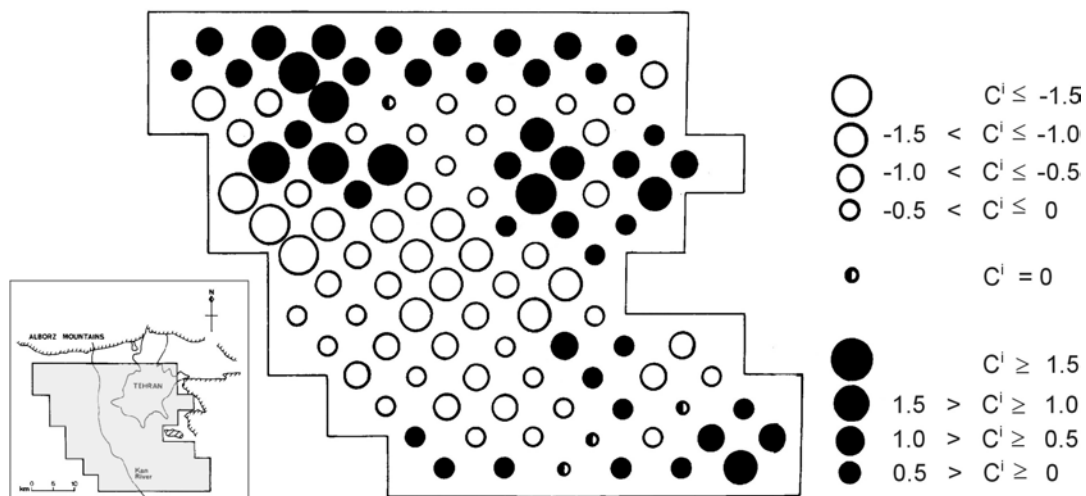


Fig. 6.5 Non-dimensional adjustment of transmissivity values in the Tehran model (after Smith & Piper, 1978).

to the original reconnaissance study of recharge, flow through the aquifer and water level fluctuations. The essential difference was that the various processes were studied in an integrated fashion, and the studies were based on actual observations of stream flows rather than estimates, records of well level fluctuations rather than verbal estimates, and a number of aquifer test results to enable the variation of the aquifer to be represented. Finite element models have now largely superseded finite difference models due to the ease with which grids of different sizes can be handled; nevertheless, the basic physical principles have not changed.

Example of joint exploitation of an aquifer

In 1957, at the same time as the initial study of the Tehran aquifer was being carried out, a complementary investigation was made of the water balance of the Varamin plain of about 1000 km², which is a continuation of the Tehran plain to the southeast (see Fig. 3.6). The interest of this example (see Fig. 6.6) is that it was in a less developed state than the Tehran area, and the water balance had not been disturbed from its historic state. It was fed by the River Jajerud, which drains about 1800 km² of the Alborz mountains and contributed about $400 \text{ m}^3 \times 10^6$ river flow annually at the apex of the alluvial fan. At the time preparations were being made to construct a reservoir at Latiyan on the Jajerud, to store water for the control of irrigation on the plain and to divert water to the city of Tehran.

Although the northern agricultural villages near the outfall of the river were supplied with irrigation water by a network of canals, the villages in the southern part of the plain were largely supplied by a series of *qanats* feeding a large number of small irrigation ditches. The whole area supported some 240 villages, which depended on wheat and barley, cotton and vegetables. At the time, only a few drilled wells had been established to provide water for industrial purposes, so the area was essentially in its natural state. As the average rainfall at Varamin was only 170 mm, the main contribution to the water balance was the river inflow. Estimates were made of the direct river contribution to the aquifer, and of canal seepage by means of successive flow measurements using locally-made Parshall flumes spanning reaches of canals, and also pond tests in which seepage was measured from short lengths of canal isolated by steel plates. Recharge from rainfall and irrigation was estimated.

However, the extraction of water from the aquifer was effected by over 200 *qanats*, and the balance could be estimated from their outflow. These *qanats* were typically about 15–20 m deep at the motherwells, and their channels had a gradient of 1:2000, compared with a ground slope of about 1:300; the length from motherwell to exit was about 2–5 km. Measurements of outflow were made at a sample of 100 *qanats* out of over 200 sites located from air photography. Velocities were measured by current meter (Plate 6.3), except for the smallest where floats were used; the measurements were made in late October, so the results were conservative, though seasonal variations were not thought to be extreme varying only with water table level at the motherwell. The total flow was estimated from these measurements at about $5 \text{ m}^3 \text{ s}^{-1}$ or $160 \text{ m}^3 \times 10^6 \text{ year}^{-1}$.

In general terms the hydrology of the Varamin plain was in equilibrium, with the river inflow being used successively for irrigation and the surplus draining into the aquifer by seepage from canals or irrigated areas and then being abstracted by *qanats* for further irrigation.

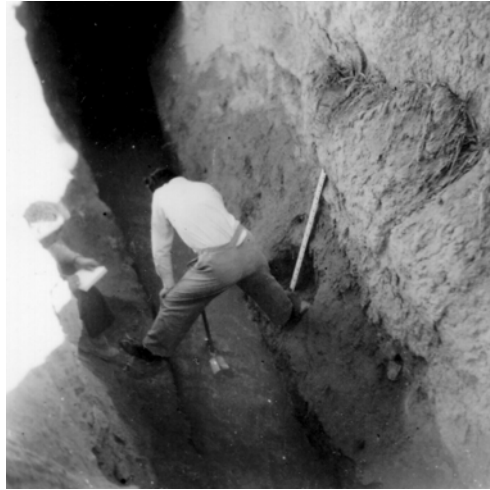


Plate 6.3 Observation of qanat flow on the Varamin plain, southeast of Tehran.

The area was studied in 1967, 10 years later, by Beaumont (1968). By that time the abstraction from wells had greatly increased; the total discharge was estimated at $145 \text{ m}^3 \times 10^6$ per year, and the water table was dropping from that recorded in 1957. He reproduced a map of the *qanats* from the 1957 air photography, which showed clearly the pattern of abstraction (Fig. 6.6). When he visited the area only two years later, in 1969, large numbers of *qanats* had been destroyed after heavy rains and had been replaced by well production (Beaumont, 1971).

The passage of water from the river channel of the Jajerud through the irrigation channels and *qanats* of the Varamin plain, and the successive use of water in irrigation and waste flow, until its emergence in the salt lakes of the desert fringe, were also illustrated in successive changes in water quality from low to very high salinity.

Variation of abstraction with time

This example of the Varamin plain from 1957–1969 illustrates the fact that the balance of a groundwater system may vary dramatically with time, especially during periods of technical change. In the case of the Tehran aquifer, it was possible to estimate the increase of abstraction over time, as the construction of the wells was relatively recent in 1957. Nearly all the wells had been drilled in the previous eight years, and the growth in abstraction could be deduced from the dates of construction. The diversions from the river had also been monitored, so that the increase in abstraction and import of water could be taken into account and the estimated flows of *qanats* included.

WATER RESOURCES OF BAHRAIN

In the case of the water resources of the island of Bahrain, inflow to the aquifer was supplied by historical groundwater recharge in the mountains of Saudi Arabia which depended on significantly higher rainfall in the distant past. The piezometric levels fall from northwest to southeast over the island, and these levels had been falling over the recent period before an investigation in 1967. One aim of the study was to determine the cause of the decline in levels; this involved a comparison with historical abstractions.

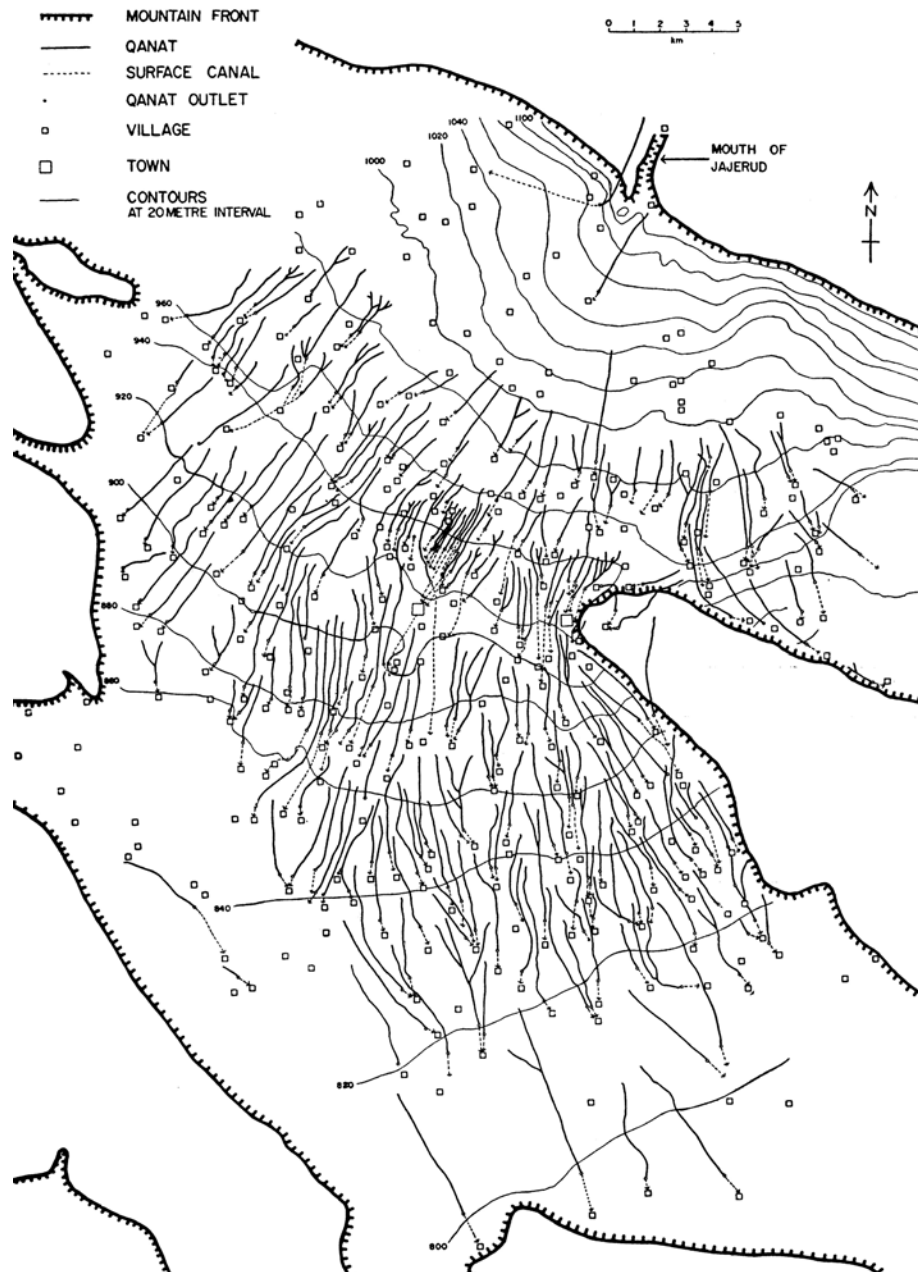


Fig. 6.6 Varamin plain: contours and locations of qanats (from Beaumont, 1968).

Fortunately, two previous studies could be drawn on to provide estimates for earlier dates. In 1923, before any well abstraction had begun, the only abstraction from the aquifer had been from natural springs, both on the island where date plantations were maintained from a few large springs whose yield had been measured, and from offshore springs whose output was measured subsequently. After exploratory drilling

had revealed the potential of the aquifer, well construction had started in 1924 and had increased rapidly after 1947; a survey in 1953 had led to an inventory of wells and yields which provided historical evidence of abstraction based on the dates of construction. By 1967, the number of wells used for irrigation had increased to the extent that it was simpler to estimate the abstraction from the irrigated area, as described in Chapter 4. This series of snapshots of the abstraction could be compared with the decline in the water table.

A study of the water resources in 1967 focussed on the balance between the groundwater inflow, which derived from recharge in Saudi Arabia and flowed through the brown crystalline limestone Dammam Formation aquifer (Willis, 1967) under the sea, and the abstraction for domestic and urban use and for crop irrigation. It was necessary to deduce a history of water abstraction on the island for comparison with the declining groundwater levels. The early water supply had come from springs which provided drinking water and also supplied irrigation water to extensive date palm plantations in the northeast of the island. There were also submarine springs off the eastern coast which had been known for many years.

Several of the land springs had been surveyed and the yields of the main 15 springs measured in 1923. This information was compared with a wider survey of springs in 1953 to estimate a total annual yield in 1923 of $70 \text{ m}^3 \times 10^6$, with an addition of $10 \text{ m}^3 \times 10^6$ for the submarine springs. After 1924 a number of wells were drilled for water supply and irrigation, and a survey of some 300 wells had been carried out in 1953 to estimate the total abstraction. It was estimated that the annual well production was $60 \text{ m}^3 \times 10^6$, of which 70% was for irrigation. At the same time surveys of the land springs gave a total yield of $42 \text{ m}^3 \times 10^6$ and the submarine springs $10 \text{ m}^3 \times 10^6$ to give a total annual abstraction at that time of $112 \text{ m}^3 \times 10^6$.

By 1967, when another estimate was made (Sutcliffe, 1967), the number of drilled wells had reached almost 800, and the measurement of even a representative sample would have been a large task. The abstraction for urban and industrial water supply was measured, but the largest component was the abstraction from springs and wells for irrigation of date palm plantations. This component was estimated from the areas of irrigation and the transpiration from the date plantations, which was estimated to be similar to open water evaporation, as described in Chapter 4. Allowance was made for channel losses and leaching or drainage requirements. This estimate from the water balance, together with measured municipal and industrial use, led to the total annual abstraction of $122\text{--}147 \text{ m}^3 \times 10^6$.

The increased historic abstraction was further studied using the dates of construction and the positions of the wells drilled since 1946, and it was noted that the locations of abstraction had changed over the years. The effect of abstraction on Bahrain was reinforced by more recent abstraction in eastern Saudi Arabia. Comparisons suggested that the growth of abstraction was responsible for the recorded fall in well levels over the island.

The water quality was observed to deteriorate from northwest to southeast, in the same direction as the fall in water level. There was evidence that the water quality had also deteriorated over the years, and date plantations over parts of the island had been abandoned as a result. This has been attributed to leakage between the deeper aquifer and the sea through the overlying aquifer, leading to sea water intrusion as levels fell.

INDIRECT ESTIMATION OF GROUNDWATER RECHARGE

It is not easy to separate groundwater recharge from direct runoff as a residual of the rainfall:evaporation balance. One attempt to do this was made by Penman (1950) for the Stour basin above Stratford Mill in East Anglia, between Cambridge and Felixstowe, England. This basin is mainly sited on chalk with a variety of surface drifts, so that basin outflow is derived from groundwater rather than from direct runoff. Net rainfall could be assumed to recharge groundwater when the water content of the soil layer was at field capacity. He developed a simple model with a soil moisture store whose effective depth or root constant was related to vegetation rooting depth; for this purpose the basin was divided into areas of shallow-rooting grass and deep-rooting woodland, with root constants of 125 and 200 mm respectively, and riparian areas with unlimited supply. Net rainfall recharged each store and overflowed to groundwater when storage exceeded field capacity; when the soil moisture reduced to wilting point the evaporation was assumed to reduce to 10% of the potential rate. The estimated groundwater recharge over the period of record, 1933–1948, after river outflow had been deducted, was compared with the water level in a deep well in the chalk which had been observed over a number of years. It was found that the well fluctuations were closely related to the estimated storage (Fig. 6.7), with a lag of about two months, and a storage coefficient of about 0.01.

This simple model was tested on the experimental basin of the Ray at Grendon Underwood (Mandeville *et al.*, 1970), set up by the Institute of Hydrology, UK, to provide reliable records of a small basin. The study showed that it was possible to derive reasonable estimates of runoff from rainfall using this model. The Penman model also formed the basis of the estimate of mean soil moisture deficit in different parts of the British Isles (Chapter 5), which was used to estimate net rainfall in flood studies.

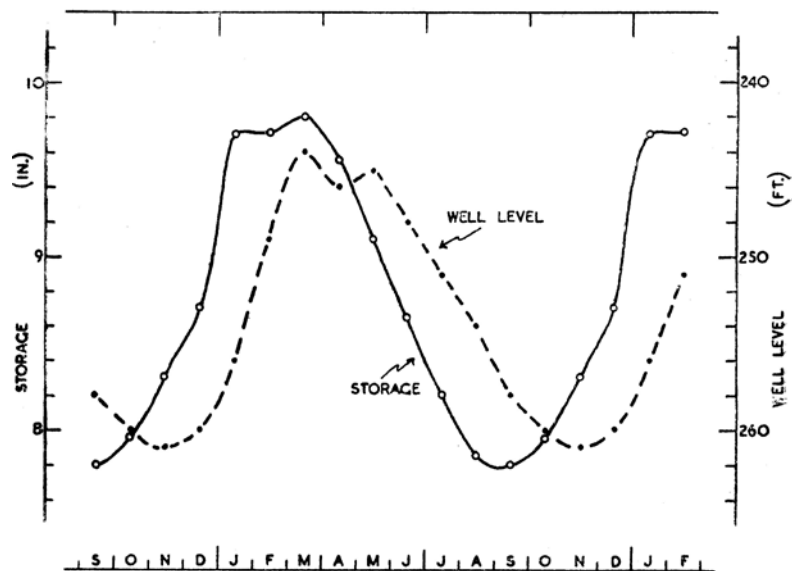


Fig. 6.7 Stour basin: mean monthly values of storage and well level, 1933–1948 (from Penman, 1950). Note: 1 inch = 25.4 mm; 1 foot = 305 mm.

Groundwater recharge in the Betwa basin

A similar model was used to study the water balance of the Betwa basin in central India (see Chapter 8), where it was hoped to estimate the groundwater recharge from the surplus; however, it was necessary to measure groundwater recharge directly as it was small by comparison with surface runoff.

In addition to the soil moisture network which was set up to monitor the water balance (see Chapter 5), two experimental sites were established in order to investigate the downward flux to groundwater directly. Experiments were set up on one site with deep soil (over 7 m) and one shallow soil site (2.4 m) (Hodnett & Bell, 1986). Duplicate sets of instrumentation were established (neutron probe access tubes, tensiometers at 0.2 m intervals to 2.4 m depth, and dip wells to measure water table depth). At each site, one plot was used to monitor soil moisture movement under natural conditions. The other plot was used to study hydraulic conductivity by the instantaneous profile method (Watson, 1966) with the plot covered by a black polythene sheet when the soil profile had been wetted to saturation. The hydraulic conductivity was calculated from the measured water flux and the potential gradient, and was related to matric potential and water content. It was shown that the conductivity decreases markedly with declining moisture content, and that downward flux is associated with cracks and fissures in the soil. Once the storage is filled by the rise of a perched water table, vertical percolation to deeper aquifers is very low. However, in shallow soils, especially under uncultivated grass and scrub where shrinkage fissures may reach the deep aquifer in weathered basalt, recharge is likely to be relatively unrestricted.

Thus it is possible to measure groundwater recharge directly, and such measurements can be important in establishing the processes involved in different environments. However, it is perhaps simpler to study recharge indirectly by measuring the aquifer response, especially in climates where the recharge is highly seasonal and therefore easier to observe. This technique was also used in the Betwa basin as well as the direct measurement based on soil moisture techniques.

Abu Dhabi and Oman

An extreme example where it was possible to deduce the water balance in a rapid reconnaissance, in February 1969, is given by a remote area (Plate 6.4) in the Al Hajar al Gharbi extension of Jebel Akhdar northeast of Buraimi/Al Ayn, on the border between Oman and Abu Dhabi. What could be termed "surface water villages" were concentrated along the watercourses where river flows could support permanently irrigated date palms and seasonally irrigated winter wheat. It was clear that the date palms relied on the baseflow or groundwater component of flow, while the wheat was irrigated from the seasonal rise. At lower elevations "groundwater villages" were located below the recharge sites where the groundwater flow through the alluvium was tapped by traditional tunnels (*aflaj*, sing. *falaj*, the Arabic equivalent of *qanats*) and wells.

A number of streams were observed to leave a range of volcanic rocks which are relatively impermeable, where soil formation and vegetation are almost absent. Most of the storm rainfall is likely to run off along the streams, where deposits of gravel and recent sediment provide storage which, with storage within the mountain range, appeared sufficient to maintain perennial flow where the streams leave the mountains



Plate 6.4 Irrigated date palms within Jebel Akhdar, Oman.



Plate 6.5 An aqueduct carrying an irrigation channel over a stream, Oman.

for the alluvial plain. Near this point there was usually a village relying on surface irrigation channels leading off the stream above a small stone and mortar embankment, which apparently had to be renewed after floods. These channels were well constructed and included aqueducts (Plate 6.5) to cross tributaries. Each village had a dense plantation of date palms, with winter cereals growing in fields downstream which were

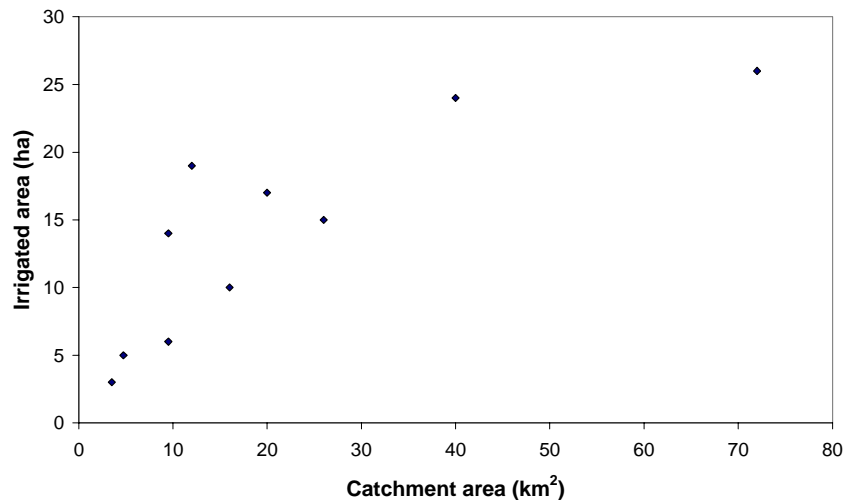


Fig. 6.8 Oman: comparison of basin areas and irrigated areas.

irrigated from extra flow available seasonally. Below most of these surface water villages were terraced fields which could be cultivated in years of heavy rains. There is a reasonable relation between the perennial irrigated areas of these surface water villages and the catchment areas upstream (Fig. 6.8).

Once the streams leave the main range they tend to enter deep gorges, up to 30 m deep, incised within the gravel plain which slopes gently to the west. Series of sedimentary deposits were exposed in the sides of these gorges, and the flow which passes the first set of villages is likely to percolate rapidly into these sediments. Once the streams reach the gravel plain the beds become difficult to distinguish in the mass of cobble outwash. To the west of this plain the channels draining the main range pass through an outcrop of limestone ridges and it is evident that floods pass through these channels. A small number of larger villages, including Buraimi and Al Ayn, are located within these gaps. These western or “groundwater” villages tap the subsurface flow by means of tunnels or *aflaj* which have their sources in or near the *wadi* bed. The flow is distributed in lined channels to date plantations. In the case of Al Ayn the total yield of seven *aflaj* was measured and found to be about 320 l s^{-1} or $10 \text{ m}^3 \times 10^6 \text{ year}^{-1}$, corresponding to a depth of 3.2 m over the date plantations of 3.15 km^2 .

In this arid area it was evident that most of the runoff had its source in the main range and that most groundwater recharge would occur during floods at sites where the watercourses left the mountains for the alluvial plains. At the time there were no measurements of rainfall or runoff, but it was possible to establish that there was also a reasonable relation between the total area irrigated in the eastern and western villages depending on specific streams, and the area of the main range contributing to the total runoff. The irrigated areas could be assumed to use about 3–4 m of water, which was equivalent in terms of the linear relation to 40–55 mm of runoff from the mountain areas. The rainfall in the mountains was likely to exceed the rainfall at Sharjah, which averaged about 100 mm, but it was clear from this brief reconnaissance that a significant proportion of the likely runoff from the mountains was already being used. In other words an efficient system of water use had developed over the centuries, with

villages using surface and sub-surface water in two stages: at the margin of the main range and subsequently in natural gaps in the ridges downstream. The combination of perennial and annual crops no doubt make it easier to adjust to variations in water supply. Recommendations were made for the measurement of rainfall and runoff at selected locations, but it was clear from a visit to the area, even before measurements could be made, that there were unlikely to be large unused resources in the area.

Subsequent detailed investigations were later undertaken in another sector of the Jebel Akhdar, including rainfall and runoff measurements in *wadis* and *aflaj*. A mathematical model of *falaj* behaviour was developed (Parks & Smith, 1983) which was used to compare rainfall data with modelled outflow from a *falaj* whose channel and aquifer dimensions were known. This suggested that recharge occurred along the whole *wadi* channel following rainfall in the highlands and a flood wave down the *wadi*. The flow down the *wadi* quickly becomes exponential, with a recession constant related to aquifer dimensions and characteristics; thus flow modelling can provide similar information on aquifer characteristics to a pumping test. The important difference between these *aflaj* and the *qanats* studied near Tehran and the Varamin plain was that these *aflaj* drew on relatively narrow bands of groundwater flow. The *qanats* of the Varamin plain were able to tap a much wider aquifer which was supplied from a major river. Nevertheless the principle of aquifer abstraction is similar.

CONCLUSION

The processes involved in groundwater recharge are as amenable to water balance analysis as other components of the hydrological cycle. Moreover they may be approached in several ways: as the outcome of a recharge from soil moisture storage or from stream inflow; from the estimation of flow through an aquifer; or from evidence of seasonal water level fluctuations in an aquifer. The analysis may be based on a simple balance estimate, or on modelling of a stationary process, using average values, or on dynamic modelling of a variable process.