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The Difficulties of Regional Groundwater Resources Assessments in Arid Areas

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Abstract

The paper discusses the hydrogeological characteristics of regional groundwater systems in arid areas. The difficulties of defining geological detail at large scales are raised and the importance of understanding lithological multi-layering and local structural aberrations. Emphasis is placed upon the variable character of hydraulic diffusivity within aquifer units and the importance of vertical hydraulic conductivity in intervening non-aquifer units. Recharge and discharges from the system are discussed together with the problem of representing groundwater flows in unstressed systems. The importance of using abstraction data for model calibration and the degree of calibration that can be expected are noted. It is concluded that the models produced allow bulk flow interrogation of the regional systems and afford general principles of groundwater management and supply protection to be pursued, but not local impact details. It is stressed that the groundwater resources represented should not be interpreted beyond the depths of abstraction accessibility.

Keywords: geology, hydraulic diffusuvity, models, resources portrayal

Introduction

The principles for the regional assessment of groundwater resources are well established. A range of techniques is used to set up the physical concepts of groundwater flows in systems, and the mathematical representation of the concepts, in order to provide some reasonable form of management of the utilisation of the resources. The representation simplistically entails the balancing of groundwater flows through a system in response to recharge, abstractions and river discharges. Management options such as ‘safe yield’ or ‘net gain’ principles can be applied, in which the recharge is balanced to water use and the discharge over specific time frames.

The accuracy of representation, and therefore the reliability of resources management forecasting however, can obviously prove problematical, as the commodity being assessed is unseen, remote and frequently unreachable. This is particularly the case in those systems with large spatial dimensions.

In the following discussion the application of standard hydrogeological analysis techniques and their interpretation in the context of major regional groundwater respect the manor in which the resulting resources assessments may be viewed.

Geological Definition

The regional groundwater systems in the arid areas are normally sedimentary so subject to the vagaries of deposition and structural control. The simplistic views of distinct uniform aquifer geometry are not necessarily applicable. Multiple lithological piles are the norm, frequently exhibiting facies variations. While aquifer units may be defined, they are separated, or merge into ‘non-aquifer’ (aquitard) units that allow the transmission of groundwater and have significant influences upon regional flows and resources. Further, importantly, sedimentary layering is a feature within most lithological units, as for example shown in Figure 1 for the Palaeozoic sandstones aquifer unit in Jordan.

To define the sedimentary sequences standard geological and seismic information is of considerable value, but obviously boreholes are of paramount importance and inevitably are of low density both spatially and with depth. Although boreholes may exist the databases for them are not necessarily consistent, or comprehensive. An example of the inherent low borehole density that occurs is shown on Figure 2 for the world’s largest arid regional groundwater basin, the Great Artesian Basin in Australia, and an indication of the difficulties of depth definition is given for the Murzuq-Ghadames basins in Libya, in Figure 3.

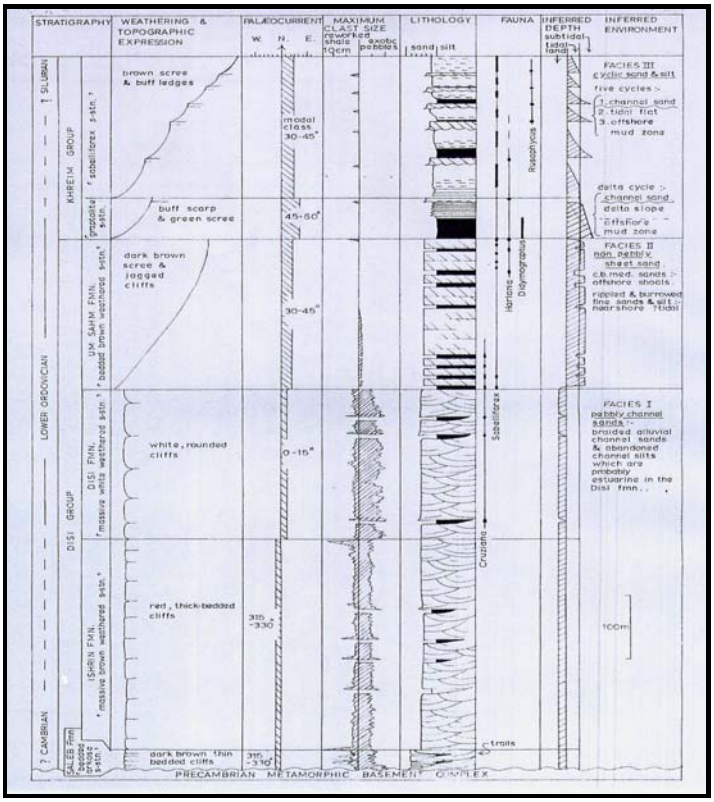

Figure 1. Sedimentary description for the Palaeozoic sandstone aquifer sequence in southern Jordan.

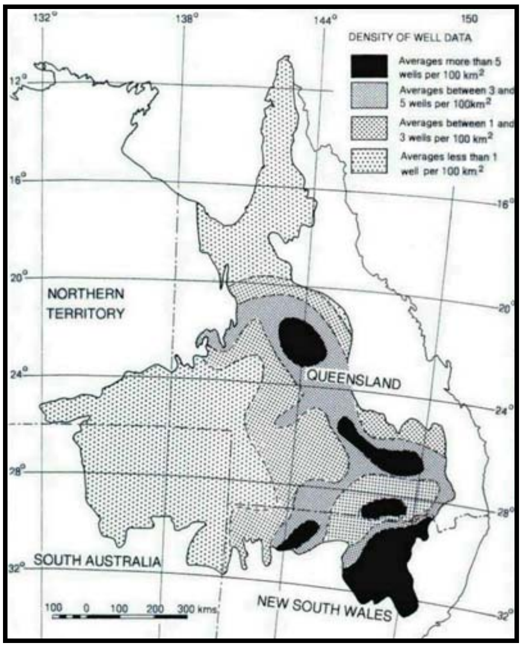

Figure 2. Well density in the Great Artesian Basin of Australia

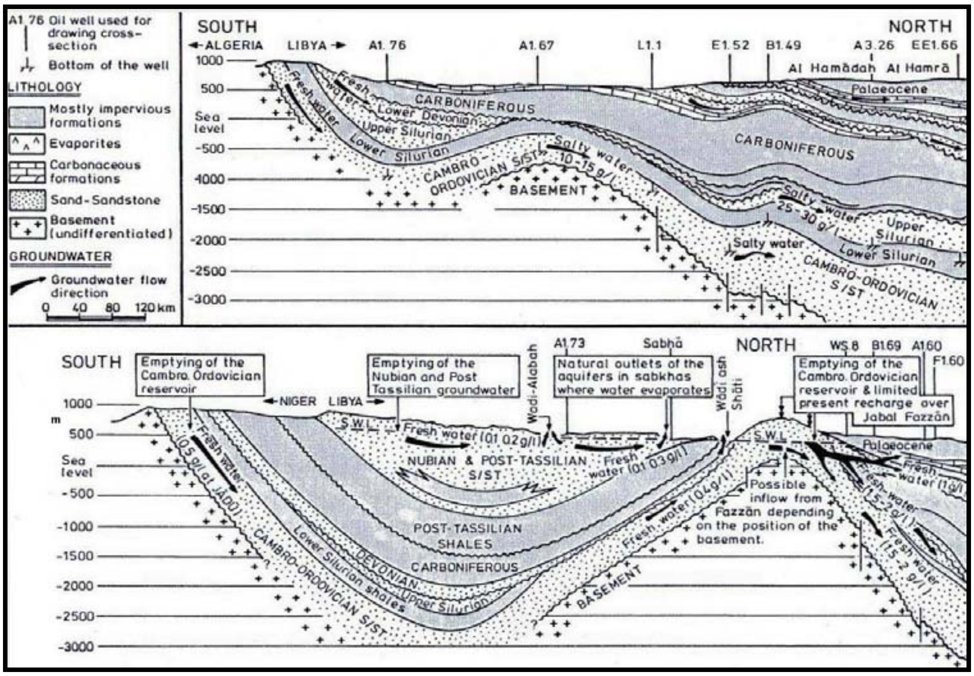

Figure 3. Groundwater system in the Murzuq-Ghadames Basins of Libya (after Pallas, 1980)

Spatial continuity of units is of fundamental hydrogeological importance so that a reasonable understanding of structure and structural control on sedimentation is essential. Regionally, the major basins appear structurally simple, but local folding and faulting can have considerable influences on groundwater flows and repercussions on resources management options. In Figure 4 faulting is seen as disrupting aquifer continuity in the Nubian Sandstone sequence in the southern western desert of Egypt and in Figure 5 a basalt dyke emplacement along faulting in the Disi Sandstones in southern Jordan controls the local flow pattern and poses serious drawdown enhancement problems for major abstraction. On Figure 6 anticlinal and facies changes can be seen to influence groundwater flows between the Umm er Radhuma aquifer and overlying units.

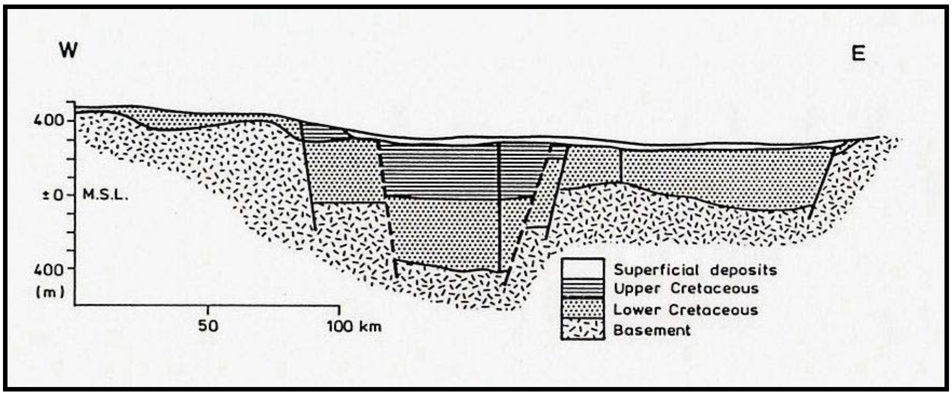

Figure 4. Fault displacements in the Nubian Sandstone groundwater system in the southern Western Desert of Egypt

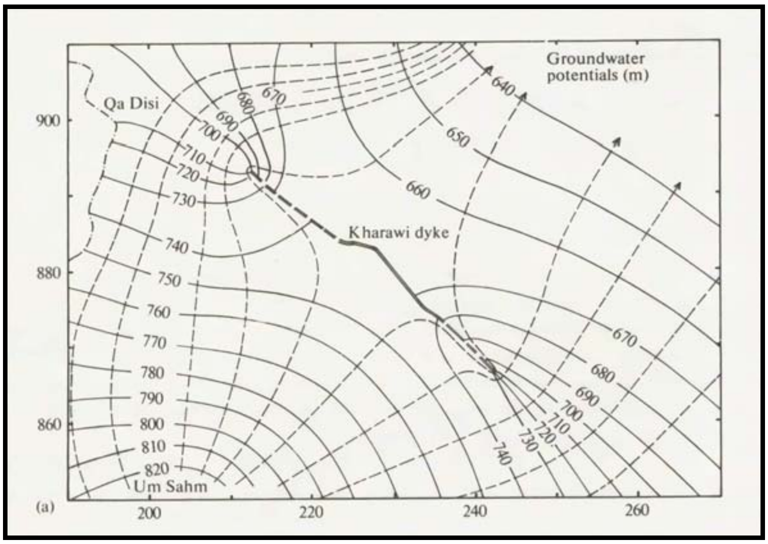

Figure 5. Dyke emplacement along a fault forming a barrier to groundwater flow in the Palaeozoic sandstone groundwater system in southern Jordan (after Lloyd, 1969)

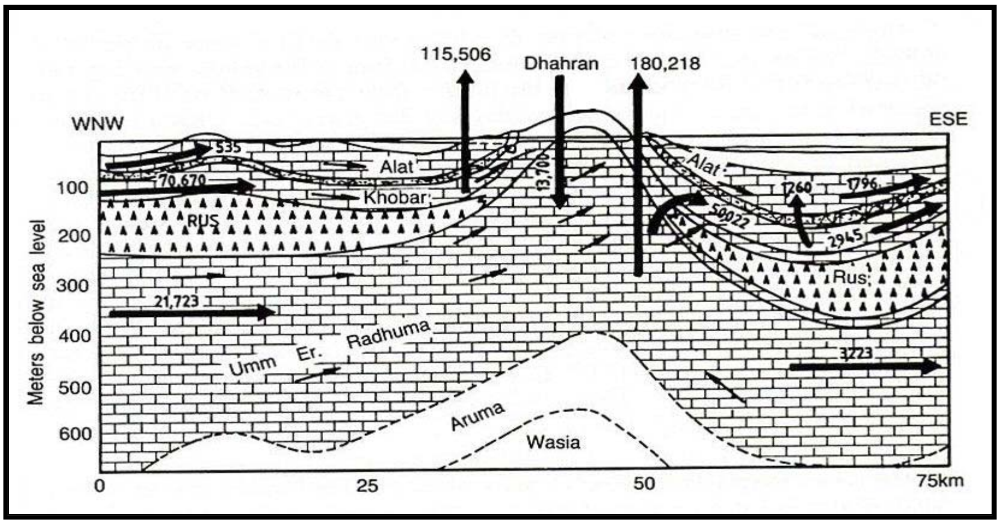

Figure 6. Anticlinal influences on sedimentation and facies changes leading to groundwater cross-flows from the Umm er Radhuma aquifer unit to overlying units (after Abderrahman and Rasheeduddin, 1994)

The maxim is that without proper geological interpretation, hydrogeological interpretation is very questionable. In the regional basins, despite the intelligent use of satellite imagery, geophysics and boreholes it is inevitable that geological interpretations will have limited accuracy, particularly in the deeper sections, and that for the completion of the requisite base geological models, there is considerable reliance upon professional judgement.

The geological model allows the commencement of the understanding of the conceptualisation of the groundwater flow paths in a system and the definition of the aquifer units. This conceptualisation can eventually be tested through mathematical flow modelling, for this however, some understanding of the ground hydraulic characteristics is essential.

Hydraulic Characteristics

To determine groundwater throughflows it is obviously necessary to determine a three-dimensional portrayal of hydraulic diffusivity. This requires an assignment of hydraulic conductivity and storativity values. Such values are traditionally derived from pumping-tests.

To give some idea of the difficulties inherent in establishing a hydraulic characteristics database it is interesting to note that for the major Saq Sandstone and associated aquifers in Saudi Arabia, which cover an approximate area of 370,000 km^2, the data point frequency is about one value per 10,000 km^2 (BRGM, 2006) and in the Umm er Radhuma (UER) and associated aquifers, also in Saudi Arabia, covering an area of some 350,000 km^2 the frequency is about one value per 3,900 km^2 (GTZ, 2006). In the latter case, which concerns dominantly limestones, the transmissivity range is immense 34-25,900 m^2/day. It is important to point out therefore that irrespective of any of the comments below, dealing with diffusivity complexity, the starting point for understanding flow in the regional basins is likely to be severely constrained in terms of hydraulic parameterisation availability.

A common problem in thick, large-scale systems is the dependence on single boreholes for hydraulic characteristics determination. Although some justification can be claimed for transmissivity (T) interpretations, storativity calculations are not possible. Irrespectively, apart from the unconfined Neuman (1972) approach, classical pumping test analyses only provide a uniform hydraulic conductivity (K) interpretation and importantly, do not allow any determination of the vertical component (K_v). Where possible, small scale modelling of wellfields, rather than individual well complexes, may give dependable results, if such wellfields are present.

In thick aquifers it is frequently impossible to test the full thickness so that normally the parameters determined for the shallow sections are projected throughout the whole section. For modelling purposes this is necessary, but can prove very problematical. The effects of compaction-decompaction, structural dislocation and cementation can cause variable impacts on the parameter distributions, often with decreases in values with depth. In Figures 7a an example of change in porosity with depth is shown and in Figure 7b the processes of cementation in deep burial (after Giles *et al.,* 1998).

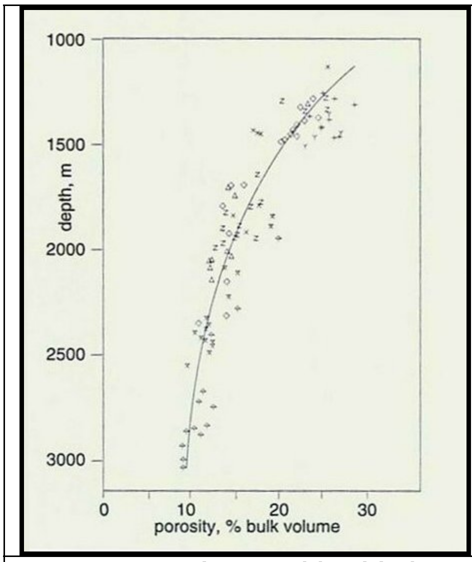

Figure 7. a. Porosity decrease with burial depth

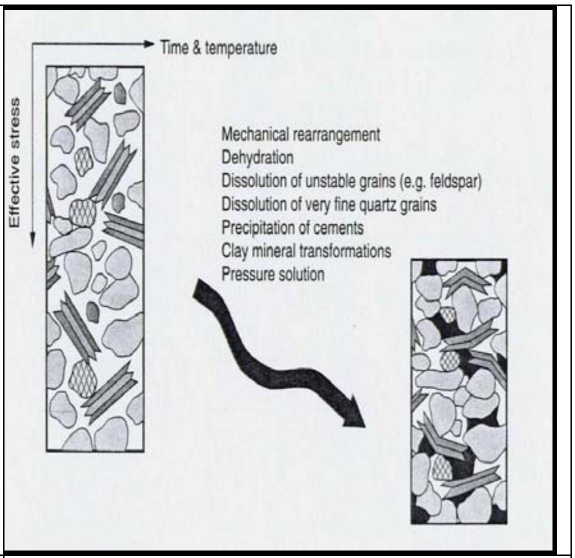

Figure 7b. Porosity decrease in sandstones due to cementing etc.

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In Figure 8 the hydraulic characterisation for a thick sandstone aquifer in the UK is shown, indicating the hydraulic implication variations that can occur. The bedding plane features in the upper part of the unit have enhanced permeability and specific yield because of decompaction and some cement dissolution. Permeability layering throughout is a feature.

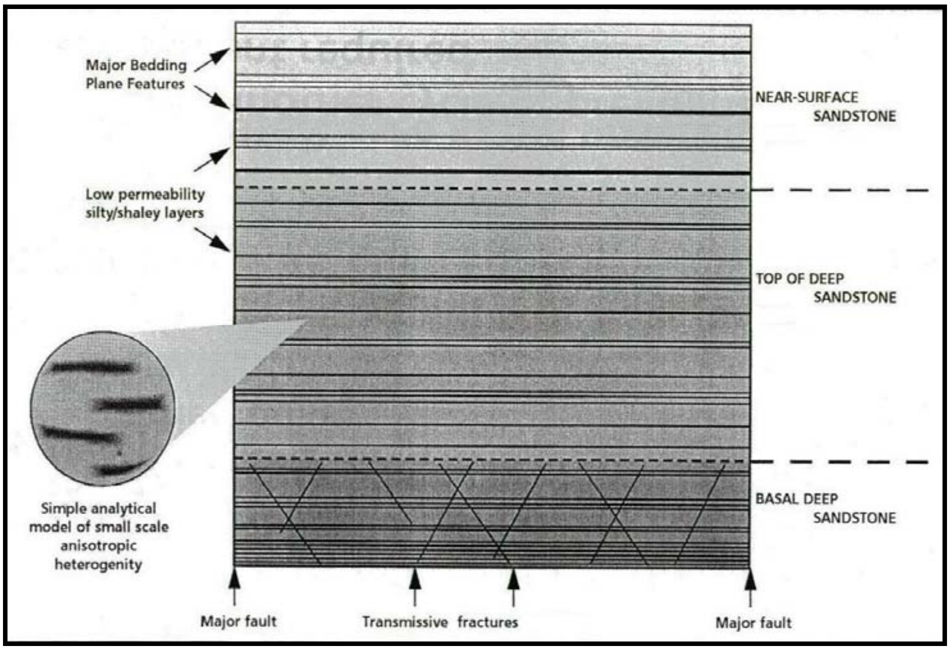

Figure 8. Hydraulic charicterisation of a thick sandstone aquifer in the United Kingdom

For the deeper sections of systems such as the ‘basal deep sandstone’ in Figure 8, conventional pumping tests are not normally applicable so that reliance has to be placed upon small scale core analyses and/or drill stem testing (DST). In Figures 9 and 10 hydraulic data from spot coring in a deep sandstone borehole are shown. The analyses have been carried out to assess $K_{v.}$ The data are few because of costs but do indicate the type of variability that can exist through a thick section (700m). Interesting the distributions in Figure 10 show no convincing correlation between porosity and K_v. This is attributed to variations in pore throat sizes.

With burial and compaction fracturing is frequently an influence upon hydraulic diffusivity, as indicated for the ‘basal deep sandstone’ in Figure 8. The influence however can be extremely random as aperture sizes on fracture planes and aperture interconnections vary as a function of dislocation intensity, cementation etc. On Figure 11 hydraulic conductivity values for fractured aquifer based upon sectional testing (DST), shows that the fractures do influence K but that in some sections high K is present, but few fractures. This may be a primary K influence, or a fracture aperture size influence.

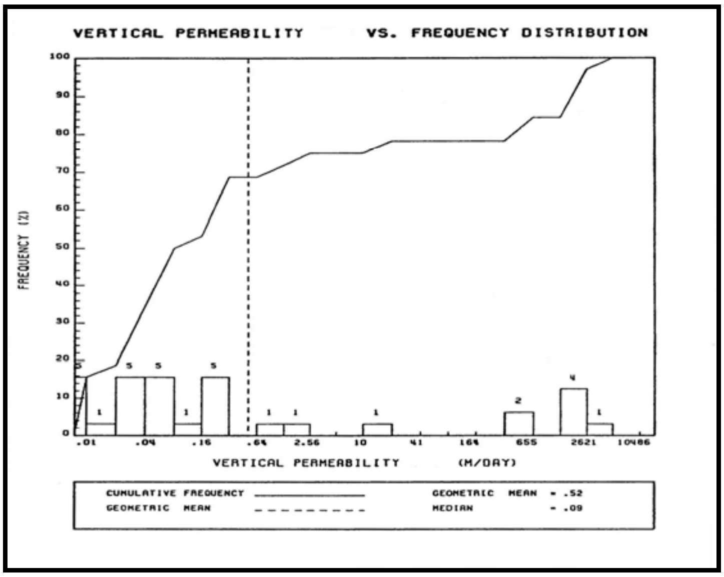

Figure 9. K_v frequency determined from laboratory core testing in Palaeozoic sandstone from Libya (after Brown & Root, 1993).

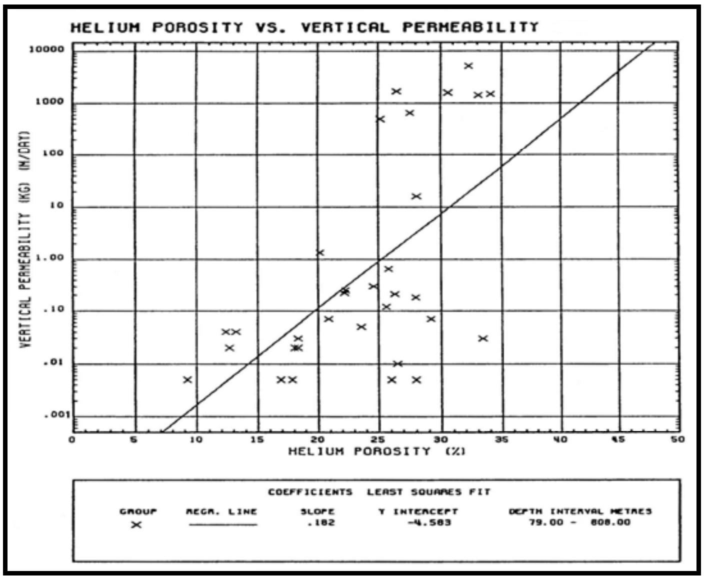

Figure 10. Porosity – Kv correlation determined from laboratory core testing in Palaeozoic sandstone from Libya (after Brown & Root, 1993).

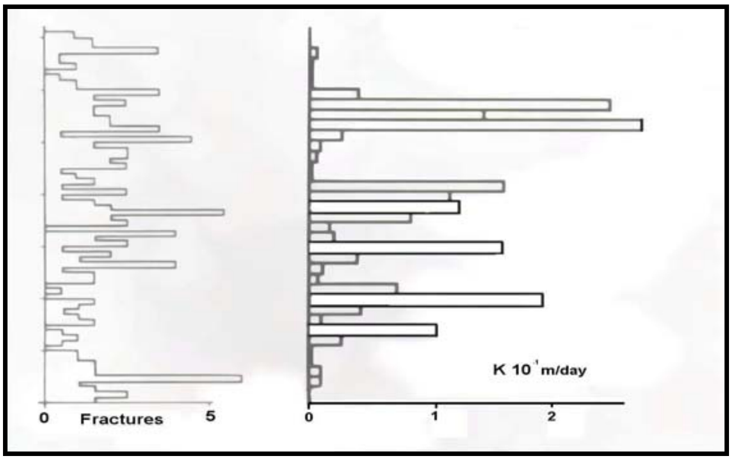

Figure 11. Hydraulic conductivity distribution in depth in fractured ground based upon DST analyses

Hydraulic diffusivity in carbonate sequences provides the most serious challenge. Dissolution controls aperture in most limestones and cannot be easily defined through any rules. Regional limestone systems tend to have been subjected to more than one phase of dissolution and it is likely that the latest phase is the dominant influence on diffusivity with some of the earlier phases backfilled with sedimentary debris, or cementation. Unfortunately, this is not always the case. In some of the simpler limestone systems diffusivity zones can be determined, for example in the London Basin in the United Kingdom (Water Resources Board, 1972), but usually reliance has to be placed upon limited testing, professional judgement and abstraction simulation as discussed below.

Overall it has to be acknowledged that the hydraulic parameter distributions for aquifer units in regional systems, is inevitably extremely limited.

While the hydraulic parameterisation of aquifer units poses problems this pales to insignificance when the characteristics of intervening 'non-aquifer' units are considered! Groundwater transmission across 'non-aquifer' units in regional systems is a major influence on heads and flows. One of the most important factors therefore is the K_v of such units. Pumping test analyses are available (Kruseman and de Ridder, 1990) that purport to provide K_v, but are difficult to apply to thick 'non-aquifer' units and are frequently give ambiguous results. To generate discernable flow through a thick 'non-aquifer' unit in most cases will require more time and abstraction stressing than usually achieved in pumping tests. The response shown in Figure 12 illustrates this point in that the calculated breakthrough time is some 30 days for a wellfield abstracting a massive 1 million m^3/day (MCM/day). Unfortunately, the only way forward is to examine the K_v indirectly by modelling of relative heads and flows through a system. The practice, while inevitable, can lead to non-unique solutions because of the interplay of various poorly defined parameters, as discussed below.
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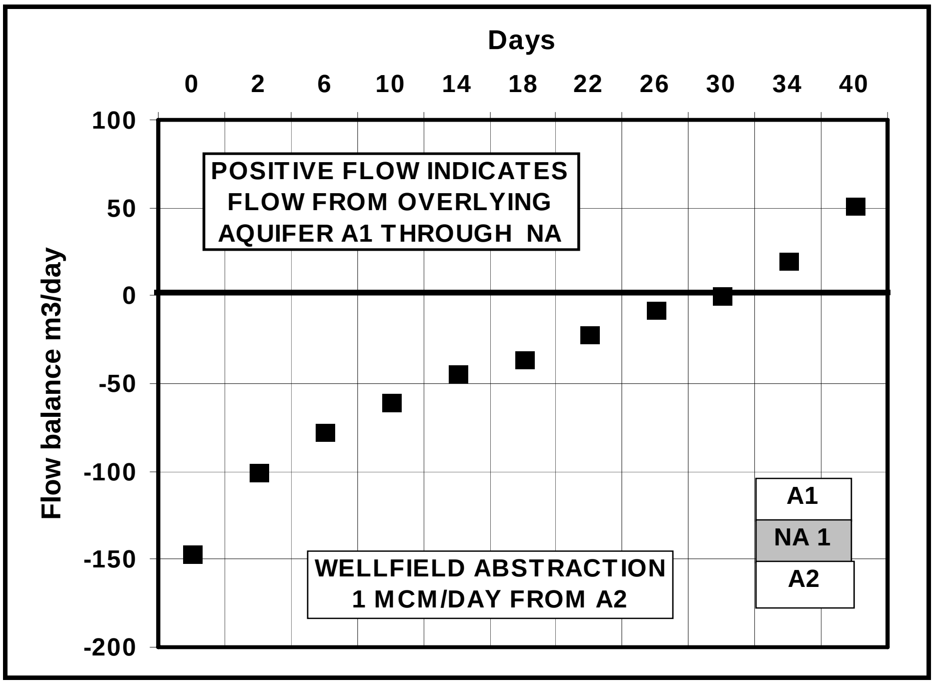

Figure 12. Calculated part flow balance for abstraction from 'aquifer 2' being compensated by cross-flow from 'aquifer 1' through 'non-aquifer 1' as part of the Tazerbo wellfield studies in Libya (NA1 thickness ~ 50-80m, $K_v = 10^{-4}$ m/day)

Flows and Gradients

A considerable amount has been written about recharge in arid areas (Lerner *et al.*, 1990) and need not be repeated here. Recharge directly from precipitation through the soil profile is generally not considered to occur so that the recharge that may occur is indirectly from flood runoff transmission losses, or ponding infiltration. Surface flow modelling is normally used to determine flood amounts and transmission losses based upon the stochastic generation of storm rainfall amounts, ground slopes and character, flow channel features and ground unsaturated moisture movement. The models are well founded (e.g. US Conversation Service, 1968; Wheater *et al.*, 1991a,b), however are heavily dependent upon good rainfall synthesis, and coefficients, which are extremely poorly known for the very varied ground conditions found in arid area surface catchments. Considerable difficulties are usually encountered in matching calculated transmission losses to groundwater hydrograph responses (Travers Morgan, 1993). This is attributed to the complex processes operative in and below braided channels in arid areas, some of which are illustrated in Figure 13.

Indirect recharge is thought to be small and is difficult to verify. In some systems modelling indicates that such recharge is necessary, in others its presence, if it exists, is masked by abstraction impacts and in some cases it not thought to be of any significance at all (Lloyd *et al.*, 1997).

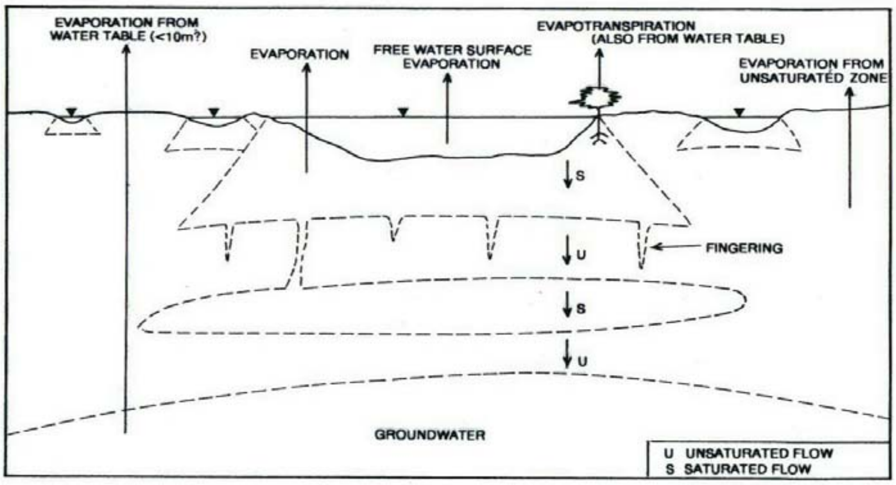

Figure 13. An illustration of some of the complex processes operative in indirectrecharge from surface flows in arid area channels (after Lloyd, 1995)

The natural discharges of the regional systems in arid areas pose immense difficulties. Some systems cross international boundaries causing data access problems, as for example the Saudi Arabian Saq aquifer, which discharges in part to the Dead Sea and the Azraq lakes in Jordan (BRGM, 2006). For the most part the systems discharge to sebhkas (evaporation losses) and/or the sea. Unlike temperate areas the discharge conditions negate any direct flow measurements and are thus a serious drawback to system understanding.

Sebkha discharges can be a large component of a system's flow. For example, sebkha evaporation accounts for about 30% of the flow balance for Palaeozoic sandstone aquifer of the large Murzuq-Gadames basin (Figure 3) in Libya (Lloyd *et al*., 1997). In most instances relevant data for the determination of sabkha evaporation does not exist. Calculations using classical climatic evaporative data are thought to considerably over-estimate losses judging from lysimeter studies in Australia (Lloyd, 1986). It is to be hoped that more distinctive and regional estimates may be obtained using the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) satellite imagery (Bastiaanssen *et al*., 2002) currently being developed for regional evapotranspiration estimation.

Groundwater discharges to the sea obviously have to be assessed through modelling using mixed density codes, which even with very good environmental head controls provide only approximate answers.

The absence, or presence of a very small recharge component, and a lack of understanding of discharge volumes in the arid regional systems place a heavy reliance on the calculations of system throughflows in flow balance determinations. These obviously depend upon the basic relationships between hydraulic conductivity and head gradient. In view of the discussion on hydraulic diffusivity given above throughflow calculations can be open to considerable question. Because of the parameter interplay and complexity in the regional systems uniqueness in determining throughflow is not necessarily achieved. Clearly, a range of permutations of parameters may lead for example to similar gradients as shown in Figure 14.

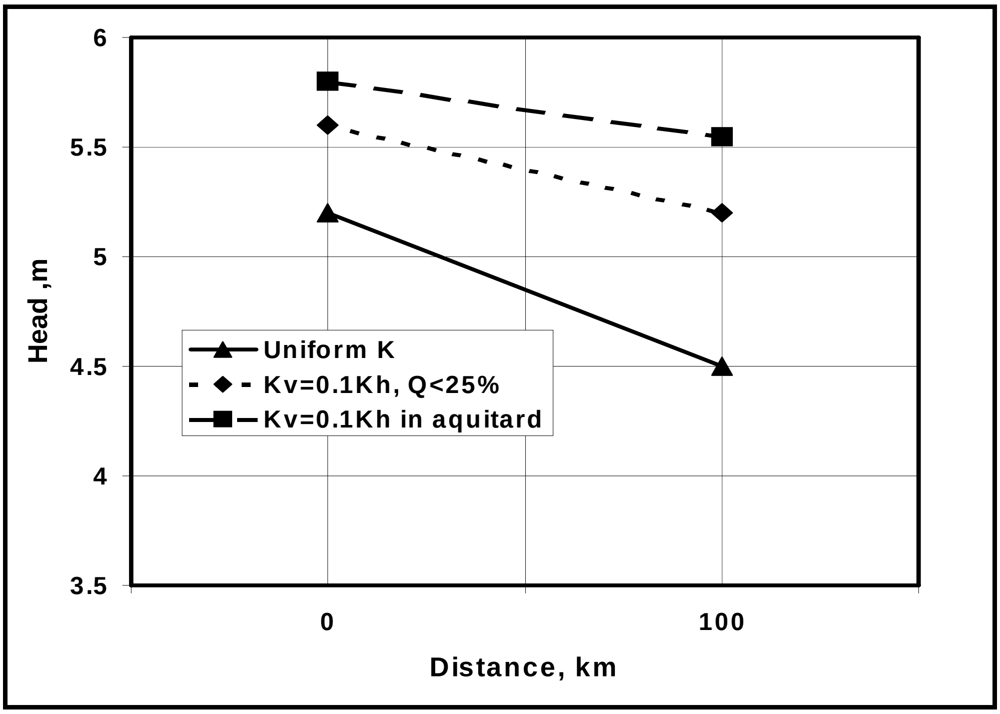

Figure 14. An example of the style of gradient similarity obtained by varying flow and hydraulic conductivities in an aquifer-aquitard (non-aquifer) system

Resources Models

The first prerequisite of a groundwater flow model is a robust geometry. This requires an acceptable spatial representation of the geology within the practical operative size of the model. As a result, in regional systems with their multiple lithological distributions, a degree of simplification is necessary. Juxtaposed units with comparable hydraulic characteristics tend to be amalgamated to produce a practical set of hydraulic layers. For example, in the BRGM (2006) Saq aquifer study 13 model layers were derived from some 50 recognised geological units. Importantly, as the regional system was being represented, no account could practicably be taken of the type of hydraulic diffusivity variations discussed above, if present.

As noted above the initial object of modelling is to balance flows. From the forgoing discussion however, the paucity of recharge with recharge induced head responses and the usual lack of river, or spring discharges seriously compromises arid area regional groundwater calibrations, particularly in systems that have not been significantly stressed by abstraction. Interestingly, as demonstrated by GTZ (2006) for the UER system the natural groundwater flow in a regional system can be out of balance, because of changing climate (reducing recharge) and flow inertia.

Abstractions, if properly monitored, together with drawdown, can provide the controls that greatly assist model calibration. Unfortunately, all too often monitoring is limited and recourse to indirect measurement is necessary. Major abstractions are normally related to agriculture so that with cropping knowledge and evaporation data, crop use in the form of evapotranspiration, can be determined. Regional evaporatranspiration assessments using the (NOAA-AVHRR) satellite imagery noted above in Saudi Arabia with energy algorithms have proved very positive (Water Watch, 2006). Obviously, however the application of abstracted groundwater to crops can prove very inefficient and in many instances over-application will occur. In order to determine reliable total abstraction therefore a considerable amount of representative agricultural field study is necessary. A lack of understanding of application inefficiency can prove very detrimental to the eventual groundwater modelling.

Regionally, head distributions are the criteria by which models tend to be judged for the arid area systems, although distributed flow balances are equally important. Calibrations are inevitably coarse because of all the unknowns noted above and the simplification intrinsic to such large-scale system models. Providing gradient trends are satisfactory 'absolute' head calibrations are not essential. Figure 15 gives an example of the standard of head calibration acceptable, demonstrating some quite marked difference between field and model values, but with reasonable trend agreement. It also shows the commonly found lack of field data. Head residuals (difference between field and modelled heads) are also frequently relied upon to judge calibration. Their value lies in demonstrating areas of the model where accuracy may be questionable and revision may be necessary

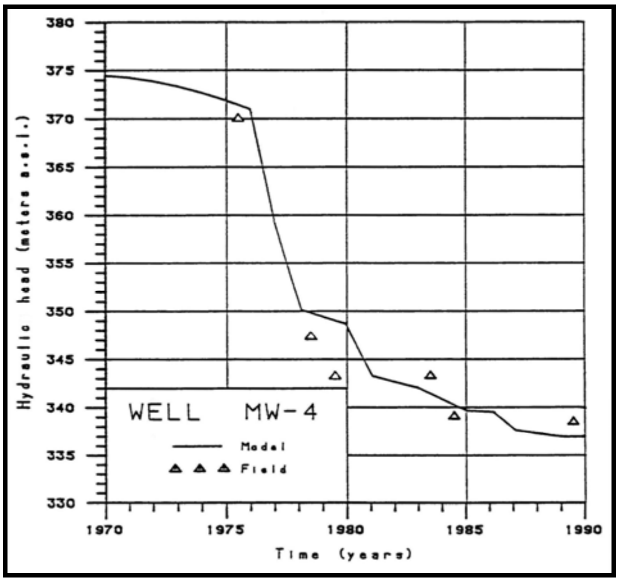

Figure 15. Example of model head calibration from Murzuq-Gadames basin calibration in Libya (after Lloyd et al., 1997)

Conclusions

From the forgoing discussion it is clear that to produce an acceptably calibrated model in an arid area regional groundwater system requires considerable hydrogeological ingenuity. The paucity of data and the simplification that are dictated by practical model sizes mean that the models produced can only provide a broad understanding of the manor in which groundwater flows through a system. They can provide an important understanding of bulk flows and the prediction of the impact of the abstraction of bulk flows. The models should allow general management principles to be examined and decisions about supply protection, but will not provide definitive local detail. Because of the paucity of recharge and surface flows the classical management principles of ‘safe yield’ and ‘net gain’ cannot be used and groundwater ‘mining’ philosophies obviously have too be applied.

In judging the groundwater resources of a system the models are all embracing but in reality provide a synthesised portrayal of that part of the system that is accessible in terms of data measurements. The resources defined therefore can only be viewed within the context of the groundwater accessibility. To countenance resources beyond the depths of accessibility is extremely dangerous as has been indicated by the discussion of hydraulic parameters above. Further, because of the ‘cone of depression’ hydraulics of groundwater abstraction only a limited volume of the groundwater within the depths of accessibility is abstractable.

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