International Conf. on Water Resources & Arid Environment (2004)

Do we Adequately Understand the Potential Value of our Regional Aquifers?

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Abstract

The possibility of differences in hydraulic properties in depth in arid area regional aquifer systems is posed with the inference that aquifer potential can be over-estimated without adequate characterisation of these properties. The occurrence of effective modern recharge is questioned and the need to properly assess specific yield in the groundwater mining scenario is emphasised. The need to assess the added value of aquifers as storage facilities is discussed.

Introduction

The purpose of this paper is to ask questions about our knowledge of the regional sedimentary aquifers found in arid areas such as the Arabian Peninsula and North Africa. The aquifers are of fundamental value in the economies of the countries in which they occur and are thought to contain vast volumes of exploitable groundwater. They have been utilised locally and investigated regionally in several countries, however as yet they have not been extensively examined in detail under severe stressed conditions to which they will progressively be subjected with time. As stressing implies deeper progressive groundwater withdrawal, the paper questions whether there may be changes in aquifer character with depth and whether we may be over-valuing the aquifers in a traditional abstraction sense. With the increasing need for integration of water reserves, the added value of aquifers as storage facilities in supply strategies is discussed.

Restrictions on Aquifer Potential in some UK Aquifers

The traditional value of an aquifer lies in its ability to provide a sustainable abstraction yield. In temperate countries, where recharge occurs in reasonable amounts seasonally, assessments using ‘safe yield’ and conjunctive use scenarios can be devised based upon routine hydrogeological methodology. Many of the main sedimentary aquifers in these countries exhibit long-term hydraulic equilibrium and tend not to be substantially over-stressed in terms of abstraction-drawdown conditions. Periodically, however, drought conditions occur, stressing increases and some aquifers do not respond adequately to their forecast potential. Such stressing may pose problems for the water supply engineer, but can be of considerable value to the hydrogeologist in understanding aquifer hydraulic controls.

Routine groundwater resources assessments inevitably tend to be somewhat coarse, frequently with fairly large error margins. Bulk flows are assessed, using bulk parameterisation, and accepting reasonable annual recharge conditions, flow depth profiles need only limited definition. With stressing and head decline in an aquifer, however, flow controls at depth attain greater importance so that emphasis needs to be focused hydrogeologically upon any variations in aquifer hydraulic characteristic with depth.

In the United Kingdom (UK) important hydraulic controls in depth in principal sedimentary aquifers have been identified both in sandstones and limestones. Much of the work involved has come about because of aquifer stressing. The controls are seen in terms of decreases in both hydraulic conductivity (K) and storage (S) with depth and clearly signify decreasing aquifer supply potential with depth.

On Figure 1 a depth profile of hydraulic conductivity in Triassic Sandstones is shown, based upon a mixture of packer and core testing. The high K values are attributable to fracture/fissure presence at the shallower depths, indicated from CCTV logging in Figure 2, and are an irregularly distributed feature of the sandstones over wide areas. Clearly, such controls define a preferential shallow flow zone in the sandstone aquifer.

More marked aquifer characteristics contrasts are found in the main Cretaceous limestone aquifer in the UK. Examples of characteristics profiles are shown on Figure 3. The high characteristics values in the shallow zones are the result of typical concentrated shallow carbonate dissolution, such that although the limestone may be some 300m in thickness, the effective flow zone thickness can be only some 50m, or less.

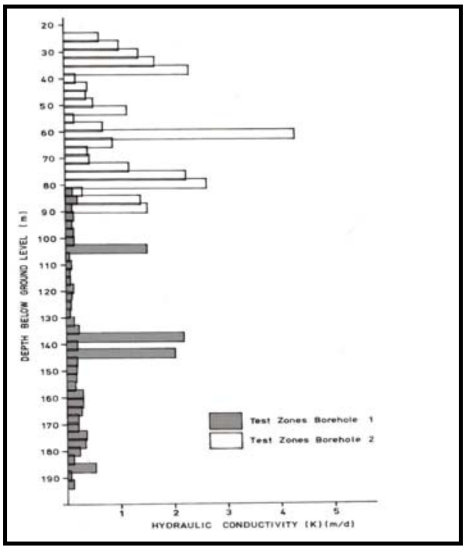


Figure 1. Example of a hydraulic conductivity profile in wells in UK .Triassic Sandstones

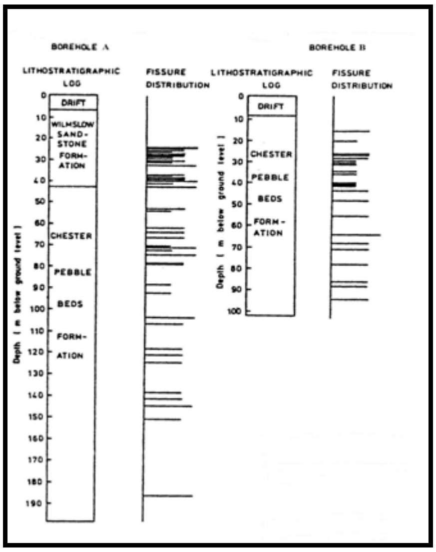


Figure 2. Fracture/fissure frequency in UK Triassic Sandstones

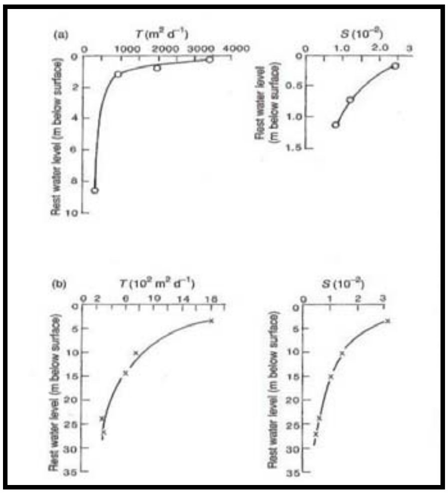


Figure 3. Transmissivity and storage profiles in UK Cretaceous Limestones.
a) Hampshire b) London Basin (Lloyd, 1993)

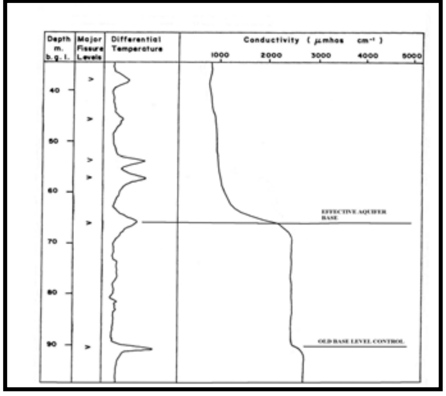


Figure 4. Fluid temperature- electrical conductivity log in Jurassic Limestones in the UK

On Figure 4, similar characteristics profiles are shown in UK Jurassic limestones, identified initially through fluid temperature-conductivity logging. The origin of the shallow preferential flow zones is thought to be partly a function of stress release caused by erosion, as much of the secondary porosity is bedding plane related, and dissolution through effective recharge over the last 6-7000 years, notably in the limestones. The features found in both unconfined and confined parts of the aquifers and are not peculiar to the UK.

Inferences for Arid Zone Aquifers

It may be claimed that the characteristics found in temperate area aquifers bear no relation to those of arid areas, particularly with respect to recharge influences. There may be some truth in such claims, however irrespectively, erosion is a universal feature and effective Holocene recharge has obviously affected many arid areas historically (Petit-Maire and Guo, 1996). It would seem reasonable therefore that hydraulic characteristics depth profiles in these arid areas need consideration, if the full value of aquifers is to be understood. It is particularly necessary in that groundwater mining is proceeding, inevitably as a matter of principle, in the regional sedimentary aquifers, and the consequent over-stressing is drawing water from increasingly deeper parts of the aquifers, which may have smaller specific yield values than found in the shallow zones.

The question of possible shallow preferential flow and storage zones in the major aquifers in the arid areas is raised not only because of over-stressing implications, but also because of the difficulty of reconciling perceived aquifer through-flows with any current effective ongoing recharge. In the unconfined regional aquifers of North Africa and the Arabian Peninsula, for example, precipitation is low and sporadic in harsh high evaporative environments. Significant direct recharge (in groundwater resources terms) is extremely unlikely, and although storm runoff events undoubtedly can contribute some recharge locally in wadi beds, their relatively infrequent occurrences appear insufficient to provide continual annual distributed inputs.

The question of recharge to regional arid area aquifers has been an ongoing problem, for which probably there is no easy answer. In simple terms, because recharge in such areas is virtually impossible to scope quantitatively from hydrological (non-groundwater) studies it is determined indirectly through modelling of aquifer through-flow, which is dependent upon good aquifer characteristics understanding, notably transmissivity (T). If the latter is over-estimated then the through-flow and recharge inputs will be over-estimated likewise.

Independent inference for recharge is often sort through the use of groundwater isotope data. For example, on Figure 5 the interpreted tritium distribution for the Eocene Umm er Radhuma (UER) aquifer in Saudi Arabia is shown. The inference is of consistent distributed modern recharge in an area with an annual precipitation of only 150-175 mm. The questions are how universal spatially is the tritium signature and what are the associated modern carbon signatures? In southern Jordan, in the Cambro-Ordovician Disi (Saq) aquifer where annual outcrop precipitation reaches 100-150 mm, spatially irregularly distributed tritium values of up to 75 TU have been recorded as shown on Figure 5. The positive TU waters however, have modern carbon percentages of only 20-40 %. Such data indicate mixed 'origin' waters most easily explained by 'origin' layering in the aquifer and possibly suggesting preferential flow in the shallow depths. Unfortunately, as is often the case with groundwater isotope data the conclusions are not definitive. If we do not have a real quantitative understanding of recharge, what do we know about through-flows? Through-flows in arid regional systems are actually small when compared to temperate areas. For example, the major, 1000m thick, Cambrian-Ordovician sandstone aquifer in the Muzuq-Hamada basin in North Africa, that has an area of 864,000 km^2, has a through-flow of only some 400.10^6 m^3/year. This flow is attributed to head depletion of 1-3 mm/year in the approximately 200, 000 km^2 unconfined area, and not to modern recharge (Lloyd *et al.*, 1996). Taking a temperate example, the Triassic Sandstone aquifer in the Birmingham Do we area of the English Midlands, on the other hand, with an outcrop area of only 110 km^2, has an average through-flow of about 15.10^6 m^3/year: a recharge of 136 mm/year.

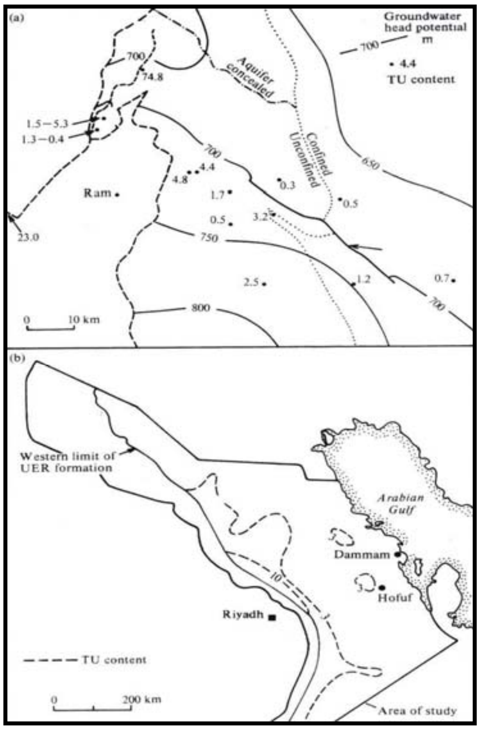


Figure 5. Tritium concentrations. a) Disi aquifer in southern Jordan (after Lloyd and Heathcote, 1985) b) Umm er Radhuma aquifer in Saudi Arabia (after Bakiewicz *et al*. 1982).

Through-flow is obviously a function of groundwater gradient and transmissivity. Regional gradients may be reasonably defined, although complications may exist approaching aquifer discharge areas. does, however pose problems. One of the major difficulties of defining hydraulic parameters and the resultant flows in the regional basins is the large depth and area scales involved. The depths required for drilling constrain the practice of using observation wells for aquifer characteristics testing so that reliance is extensively placed upon single well testing that is questionable for transmissivity interpretation, and unacceptable for storage interpretation. Interpretations assume that inflow to a well is uniform throughout the well depth and no account is taken of possible preferential flow zones

The large aquifer areas involved inevitably mean a limited spatial database and the need for considerable approximation. Further, the concentration of information tends to be in the shallower parts of the aquifers where erosional stress release and active flow conditions are likely to have been preferentially prevalent historically. In such areas the hydraulic characteristics may be of a higher order of magnitude than those down the hydraulic gradient, and at depth.

If we have difficulty in easily defining recharge and through-flow, what about natural discharge, which is often a conclusive control in temperate areas in the form of perennial springs and river flows? The groundwater flow systems in the regional basins have been reasonably defined conceptually as shown for central and eastern Saudi Arabia in Figure 6. However, it would be interesting to know how the aquifer characteristics distributions and flow controls relate to the postulated Pliocene-Pleistocene palaeo-river evolution along geological strike and subsequently dip (Al-Sulaimi and Pitty, 1995) and the Quaternary base levels of the Arabian Gulf described by Weijermars (1999).

The need to understand the inter-relationships in the multi-aquifer flow systems is well established. The problem is that cross boundary flows between aquifer units are extremely difficult, if not impossible, to determine. Conditions become even more complicated if the type of aquifer characteristics decreases in depth, described above are present. While heads may be discernable the controlling bulk vertical hydraulic conductivity can only be estimated through flow inferences. Cross-boundary flows dominate many of the regional discharge zones with flow to sebkhas, and /or to the sea, a common feature. Inevitably, our understanding of these complex environments is very limited.

The task of understanding the regional basin groundwater systems quantitatively is considerable. In simple terms, because of the environment and the scale of the aquifers involved, we lack understanding of recharge-depletion, hydraulic parameter depth profiles and the flow mechanisms controlling natural discharge. Such a dearth of understanding could easily lead to the over-estimation of the long-term value of these systems in terms of viable abstractions.

It could be argued that understanding of flows through the systems are of less consequence than understanding storage distributions, as most of the groundwater withdrawn in major abstractions will be from storage. As noted above, if storage parameters are found to decrease with depth, and/or down the hydraulic gradient, then clearly, aquifer value will be curtailed.

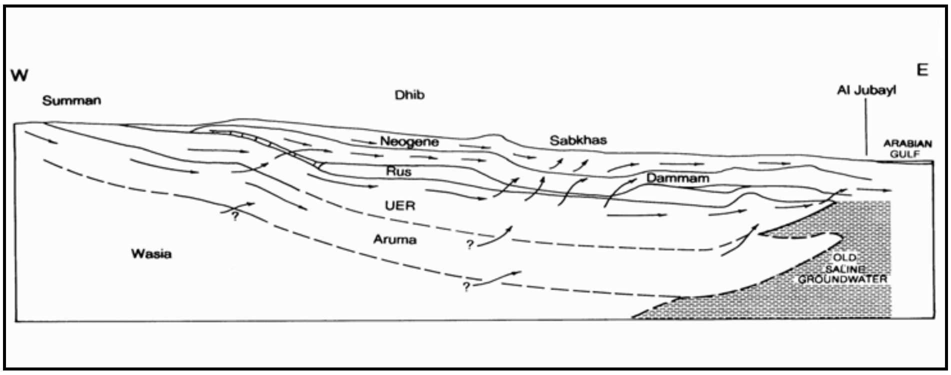


Figure 6. Conceptual multi-aquifer flow system in central and eastern Saudi Arabia.

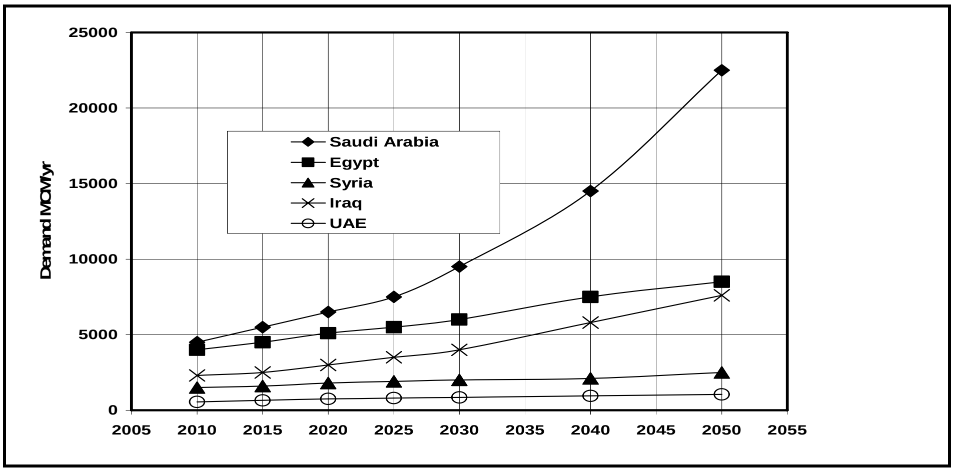
There is no easy answer to the problems we face. It goes without saying that in any planning scenarios robust safety margins are essential. Extensive hydrogeological investigations could help improve understanding, but it is probable that intensive studies on a regional basses would prove unrealistically expensive. Targeted studies should prove of value with reliance increasingly placed upon mathematical modelling. It is imperative that better estimates are obtained for aquifer parameters.

With advancing groundwater mining and drawdown, the opportunities do exist for comprehensive re-testing, hydrogeological Logging (in addition to classical geophysical logging) and modelling with emphasis on major abstraction areas and wellfields. If there are doubts about storage (specific yield) values, then these may be resolved from careful wellfield modelling and should help in assessing whether head depletion in unconfined areas is a major driver in through-flow, and whether large modern recharge volumes need to be invoked. Further testing and modelling should also help establish if changes exist in hydraulic characteristics with depth.

As abstraction continues and drawdown increases it is important that modelling is frequently tested against good monitored data, both hydraulic and hydrochemical. Only by frequent interrogation of modelled systems, which Unfortunately historically, has not always been the case, will it be possible to track any changes in potential groundwater resources, and be possible to assess aquifer value in terms of abstraction. The need for continual assessment is essential, as inevitably the demand for water in the arid areas will increase, as illustrated by the projections in Figure 7 for domestic supplies.

Aquifers in Water Supply Stratagies

If we look at the use of aquifers we can divide their value for discussion into two major spheres of activity: the rural sphere and the urban sphere. The two can impact upon each other, but in terms of groundwater management and aquifer use they offer some different strategy opportunities.



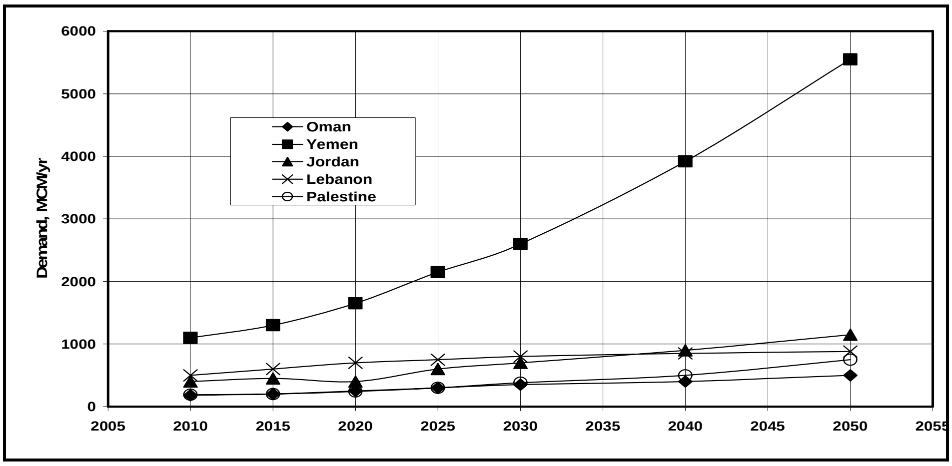


Figure 7. Annual domestic water demand projections for selected arid areacountries (after ESCWA, 2001).

Rural Sphere

The rural sphere is dominated by irrigation use with comparatively minor public supply requirements. In national arid area terms irrigation use far exceeds any other groundwater use. On Figure 8 the total annual abstraction data for Saudi Arabia is shown for the period 1971-2000. Irrigation probably accounts for in excess of 95% of the volume.

Irrigation operations and irrigation water use are outside of the scope of this paper. Suffice to say that agricultural survival is obviously ultimately dependent upon controlled abstraction either through indirect means such as subsidy restrictions, or more directly through abstraction licensing.

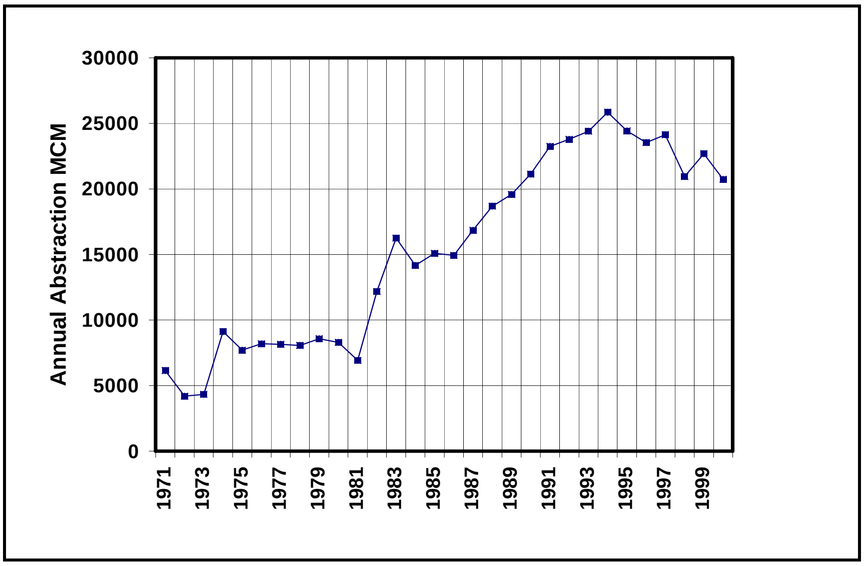


Figure 8. Total annual groundwater abstraction in Saudi Arabia.

Transfer schemes, such as the Great Man-made River Project (McKenzie and Elsaleh, 1994) in Libya are unlikely to prove to be a panacea for major irrigation schemes, so attention has to be focussed upon *in situ* aquifer potential, with all the parameter realisation difficulties noted above.

In concept, although irrigation usually is the major national groundwater user, the strategy for the rural sphere is straightforward, in that, apart from more reliance possibly upon local brackish water, either blended, or directly, the use must be tailored to the available abstraction within whatever timeframe is decided by government. The aquifer value is therefore in the traditional abstraction sense and its utilisation requires standard management techniques. This is easy to say and it is accepted that in practice essential socio-economic factors must be accounted.

Urban Sphere

The urban sphere is seen as including the main population and industrial areas with the immediate surrounding agriculture support zones. Such an environment provides the opportunity to realise the added value of aquifers as storage facilities: a practice that is gaining momentum, and needs careful consideration in arid countries as part of long-term water resources planning.

Arid urban areas typically use groundwater directly, may have access to stored surface water and in the wealthier countries use desalinated seawater and/or desalinated groundwater. The by-products from the water use are mains losses and other uncontrolled returns to the ground, and wastewater.

On Figure 9 a possible strategy for an urban sphere is shown for discussion and assumes that water supply is based upon an integrated system.

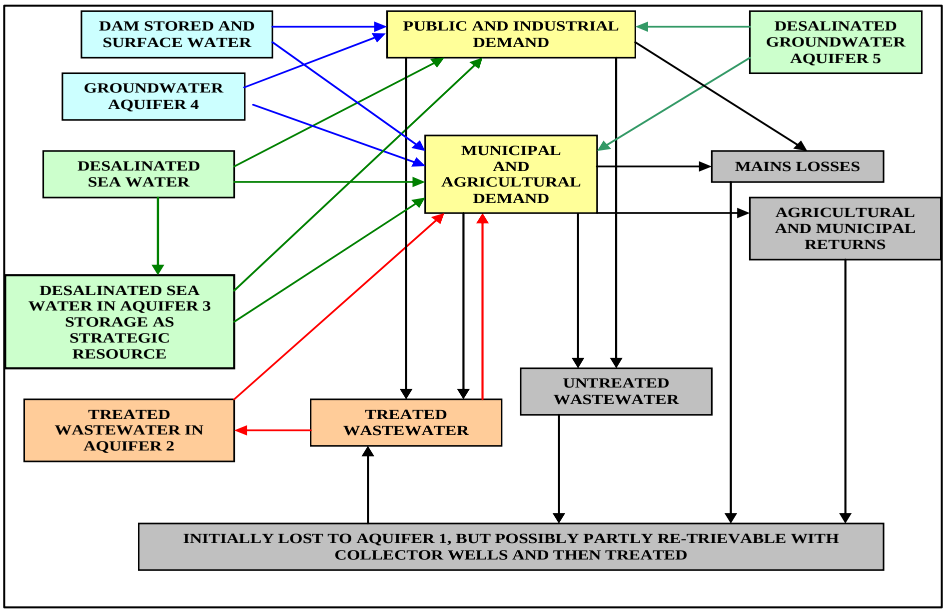


Figure 9. A possible water resources strategy in the urban sphere (aquifer refers to specific separate aquifers, or separated aquifer areas).

The generation of wastewater is continual, but seasonally variable. In the Figure 9 strategy it is suggested that treated wastewater is used to support agriculture in the urban sphere and municipal land irrigation, the requirements for which will not be constant. Inevitably, there will be a phase difference between wastewater supply and use, with a need for storage facilities. An obvious storage possibility is an aquifer.

There are many constraints that need to be overcome before aquifer storage and retrieval can be implemented. The hydrogeological aspects alluded to above need definition.

Social aspects need consideration, in terms of such issues as land rights, historical water use, supply compensation etc., and there are likely to be large infrastructural costs. However, until adequate studies are carried out we will not know whether such projects are feasible. Further, because water supply situations are progressively worsening as a result of increasing demands coupled with resources stressing, it is important that an understanding of aquifer storage feasibility is undertaken as soon as possible.

The other storage factor suggested in Figure 9 is the use of aquifers for the storage of desalinated water as a strategic resource, to offset difficulties of temporary plant and pipeline malfunction. In many arid countries desalination is increasing and becoming more efficient and cheaper. With effective systems in place the seasonal variations in demand will mean that for certain periods desalination plants will operate below capacity. During these periods there would be the opportunity to generate desalinated water for aquifer storage within the urban sphere. As with aquifer use for wastewater, hydrogeological, social and infrastructural assessments will take time, but sensibly should be initiated sooner rather than later.

Some initial studies have been carried out in the Arabian Peninsula. In Qatar well injection has been tested in the Umm er Radhuma with good efficiency results using fresh aquifer water (Entec,1994), however in Kuwait, as part of a desalinated water recharge study, Al-Awadi *et al.* (1995) have shown that while fresh and brackish water do not adversely affect hydraulic conductivity in the Dammam aquifer, fresh water recharge could mobilise adverse chemistry from the aquifer matrix. Mukhopadhyay *et al*. (2000) suggest that the recharge of desalinated water to the Kuwait Group could lead to some carbonate dissolution in the aquifer and that K reduction is a possibility, because of montmorillonite-illite swelling.

The very limited sample cited shows that success is not guaranteed which it could be argued makes the early initiation of aquifer storage studies even more imperative. Further, although the emphasis in this paper is on regional sedimentary aquifers, there is no reason why alluvial aquifers could not be used as storage facilities under the right hydrogeological conditions.

Conclusions

There is a sense that recharge is over-estimated in many arid regional sedimentary basin studies and that there is insufficient understanding of aquifer characteristics such that through-flow in aquifer units may also be over-estimated. If the aquifers bear any similarity to many temperate zone aquifers there could be decreases in hydraulic conductivity and storage with depth that would significantly reduce aquifer value in the long-term under groundwater mining scenarios.

Stringent controls on abstraction are obviously required with continual review of resources potential. In urban spheres the value of aquifers as storage reservoirs for wastewater and desalinated water needs urgent appraisal.

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