البحوث

Managing Water Resources in Kuwait Using Underground Artificial Storages

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1 - Introduction:

Artificial groundwater recharge can be defined as the planned activity of man whereby water enters the aquifers with a rate exceeding the natural recharge. It is a well established technique around the world for augmentation of water supplies and the reclamation of wastewater. Less commonly it is used to displace or prevent the intrusion of bodies of polluted water, including saline waters, and for the storage or generation of heated water for energy conservation.

1.1 - Experiences in Artificial Recharge:

Artificial recharge is widely applied in different countries around the globe. However, few countries although depending on groundwater, have not yet adapted such a technique.

In the Netherlands atrificial recharge is used both to augment storage and for wastewater reclamation. Approximately 280.000 m^3/d are recharged through lagoons in the coastal dune sands at the Hague, Amsterdam and Castricum. The next stage is intended to be the recharge of deeper aquifers through boreholes using treated water from the Rhine (Joseph, 1981).

About 600.000 m^3/d of treated water are recharged into shallow aquifer in the Rhine and Ruhr valleys in north-west Germany. A further 40.000 m^3/d is recharged at Aesch, on the river Birs, through hybrid lagoon/well system (Joseph, 1981).

The French have an operational scheme on the Chalk at Croissy-sur-Seine, near Paris, where about 55.000 m^3/d are recharged through lagoons (Joseph, 1981).

The coastal aquifers of Israel are protected from saline intrusion by a system comprising more than a hundred injection boreholes. Most of water recharged is

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available later for abstraction. The Scheme has been in operation successfully for more than 20 years at an average rate of recharge of 240.000 m^3/d; the peak rate exceeds 500.000 m^3/d for a short spell each year (Harpaz, 1971).

Numerous schemes are in operation in the United States of America. In 1988, 558 of the 719 injection wells surveyed in 14 states were recharging aquifers. The others were being used for saltwater intrusion barriers, drainage and subsidence control (Bouwer et al 1990).

The following motivations are obtained by artificial recharge in US:

1 - Seasonal storage: this includes the use of aquifers for underground storage, where surplus freshwater is stored in aquifers during winter and retrieved back during the summer months, when peak water demands and low water levels in reservoirs place strains on the water system. This practice is applied in Virginia (Brown and Silvey, 1985), Nevada (Brothers and Katzer, 1990) and Florida (Kwiatkowski et al, 1990).

2 - Reducing the groundwater overdraft and replenishment of depleted aquifers: in Texas, the depleted water table of the Ogallala aquifer, which is pumped for irrigation use, is recharged with the surface water available from playa lakes (Brown and Keys, 1985). Also, in El Paso, Texas, a recharge project involving 38.000 m3/d was applied in order to reduce the mining of the underground reserve and to provide a secure water supply over the long term (Knorr and Cliett, 1985). In Eastern Arkansas, the declines in alluvial aquifer potentiometric head and potential groundwater shortage were augmented by means of artificial recharge (Masciopinto et al., 1991).

3 - To prevent saline water intrusion of the local aquifers: this scheme of artificial recharge is utilized extensively in San Francisco Bay, which provides a practical example of this application (Todd, 1987; Hamlin, 1987; and Bouwer, 1990). This practice has also been used for more than 35 years in Los Angeles to prevent saline intrusion in the local aquifers; between 200 and 300 Mliters/d is injected through 180 wells (Joseph, 1981). In Atlantic City, recharging the sand aquifer was used to increase the water in storage and reduce the potential for saltwater intrusion (May, 1985).

4 - The disposal of urban drainage water and flood control: artificial recharge is

used in smoothing out stream variations, which means pumping the flood runoff into the aquifer and releasing the water back in areas of low runoff. On Long Island, New York, more than 2200 lagoons are used for this purpose. Also, effluent recharge schemes are operated at Phoenix (Arizona), Pinellas Peninsula (Florida), and Leaky Acres (California) (Joseph, 1981). In Arizona, dry wells are used extensively for on site disposal of stormwater, and in certain industial areas as a conduit to groundwater for contaminated runoff and other wastes (Haney et al., 1988).

5 - Water quality and modification: in the Atlantic Costal Plain, about 8 million gallons of treated drinking water have been injected into an aquifer of poor water quality. Later, the water has been successfully recovered through a dual-well (Castro, 1994).

1.2 - General Background of the Study Area:

Kuwait, as most of the Arabian Gulf countries, has an arid climate. The mean monthly temperatures over Kuwait range from 48 C in July to 12 C in January. The relative humidity is generally low because of the prevailing hot and dry westerly winds; it varied monthly between 19% in June and 64% in January (Amer et al., 1990).

Rainfall is low and irregular in occurrence. The annual average is about 115 mm, which occurs essentially in the form of thunder showers mainly between November and April. On the other hand annual potential evapotranspiration is high, averaging about 2.266 mm/yr. (Amer et al., 1990), leading to a high negative deficit in the water budget, creating impossible conditions for perennial surface water systems to exist. Therefore, water demands in Kuwait are met mainly by brackish groundwater and seawater desalination.

Aquifers containing usable groundwater are restricted in Kuwait to the geological units of the unconfined clastic sediments (Kuwait Group), and the underlying confined limestone (Dammam Formation). Due to its relatively high TDS (3000-6000 mg/1) in Kuwait, groundwater is used mainly for non-domestic purposes (i. e., irrigation and industrial uses); in addition, it is blended with desalinated water for drinking purposes.

1.3 - Kuwait's Need for Artificial Recharge:

The purpose of artificial recharge varies in general, according to the actual need for it, from one place to another, and from one period to another. Based on the hydrogeological conditions of Kuwait, its water system operation, and water, three main issues were identified as follows:

1 - Sole dependency on desalination plants for potable water supply. The only source for potable water in Kuwait is sea water desalination. There is a danger that the desalination plants will lose part or all of their capacity in event of emergency conditions resulting, for example from sea water pollution (e.g. with crude oil) or accidental breakdown of desalinated plants due to mechanical failure or due to terrorist activities against these plants.

2 - Operating desalination plants at poor efficiency. All of the urban potable water comes from sea water desalination plants. These plants have fixed optimal operational capacities. Operation of desalination plants at other outputs results in sub-optimal efficiencies. Water demand, however, varies significantly on a seasonal basis, high in summer and low in winter. Hence, most of the year, desalination plants are operating at poor or low efficiency.

3 - Subjecting the aquifers to overpumping is creating a massive decline in their potentiometric heads. This decline is inducing sea water intrusion and upward leakage of the deep saline water leading to deterioration of the groundwater quality.

Thus, two possible types of storage are needed to solve the above stated problems. First, through short-term storage, seasonal water demand fluctuations could be overcome, where the excess desalinated water during winter is stored to be used later during the water peak demand in summer. Second, through long-term storage, part of the surplus of desalinated water could be placed in the aquifer to face water demand under emergency conditions.

However, since Kuwait is an arid country, with no rivers, canals or lakes to be used as natural storage, aquifers could provide the promised storage. Thus, the underground storage of freshwater in brackish aquifers by artificial recharge may be used as an alternative to a surface reservoir. Such a process would typically involve injection of freshwater, storage until needed and subsequent abstraction from the same well. Storing water underground has the adventages of: (i) being economically more feasible than surface storages because of the low cost of construction and maintenance, (ii) minimizing evapo-transpiration losses, and (iii) being relatively safe from pollution threats.

The prevailing climatic and hydrogeological conditions in Kuwait make the use of water spreading techniques to recharge aquifers impractical. This is due to the extremely hig evaporation rate, and to the dryness and relatively large thickness of the unsaturated zone which makes well injection the only possible method to recharge the aquifers in Kuwait.

Therefore, in this study the hydrogeological feasibility of using injection-wells in recharging the aquifers in Kuwait will be assessed, whereas other constraints (e.g. cost of injection) will not be considered.

2 - Methodology:

To assess the feasibility of using the aquifers in Kuwait as underground natural storages, three 3-D numerical groundwater flow and transport models were used. These were: regional, sub-regional, and single-well models. All these models are multi-layered consisting of the Kuwait Group (KG) and Dammam Formation (DM) aquifers (Al-Otaibi, 1997). The MODFLOW groundwater flow modeling package (McDonald and Harbaugh, 1988), and the three-dimensional transport code MT3D (Zheng, 1990) were used to solve these models. The lithological and hydrogeological classification of the main aquifers in Kuwait is shown in Fig. 1.

A) Regional Groundwater Hydraulic and Transport Model:

This model was constructed to model the aquifer system on a regional scale, covering Kuwait and adjoining areas of Saudi Arabia. The model domain (Fig. 2) was discretized into 73x70 cells having irregular nodal spacing (ranging from 2000 to 5000m), where $\Delta x = \Delta y$. This model was used in completing the following activities:

1 - Finding the more reliable aquifers parameters, determining the pre-development water budget, and predicting the aquifer response to the present and future groundwater abstraction.

2 - Ranking the sites available for artificial groundwater recharge through:

a) Simulating the aquifer hydraulic response to artificial groundwater recharge to determine the volume of water that can be injected at each site. The effect of well-clogging in reducing the well injection capacity, and creating an additional build-up inside the injection wells were considered.

b) Simulating changes in the native groundwater TDS during freshwater injection, and variations in the recovered water TDS during the recovery periods; hence, the freshwater recovery efficiency at each site can be estimated.

B) Sub-regional Groundwater Hydraulic and Transport Model:

To obtain more reliable results and simulate the freshwater and recovery at the optimum sites (as selected using the regional model) in greater detail, it is necessary to construct a molel with smaller grid spacing. A sub-regional model was designed to cover most of the existing wellfields particularly, the two recommended sites for artificial groundwater recharge. The selected area to be modeled was nested on the regional model coarse grids. Then, this sub-regional model was modeled separately. The modeled domain (Fig. 3) was discretized using a rectangular mesh consisting of 80x176 cells with uniform spacing (where $\Delta x = \Delta y = 500m$).

This model was used to examine the management options available for storing-recovering freshwater in and from the aquifer for long-term and seasonal storage, where the optimum option can be selected.

C) Single-well Groundwater Hydraulic and Transport Model:

This model is needed to analyze the data of a freshwater injection-withdrawal experiment to identify and investigate the well face-clogging characteristics, to estimate the aquifer dispersivity, and to determine the recovery efficiency of the test.

The experiment was conducted using a single-well (SU-10) located in the Sulaibiya wellfield, that is completed in the Dammam aquifer (Mukhopodaya, 1994). The recharge water was potable; hence, the TDS was used a natural tracer since there was a contrast in its concentration between the recharge water and the brackish aquifer water. Subsequent to injection, which was conducted for about

30 days, the injected water was withrawn from the same well for about 90 days until the quality of pumped water reached the background level. Water level and tracer concentrations were measured at the test well during injection and withdrawal periods.

To represent the freshwater injection-withdrawals experiment in reasonable detail and to define the modeled area within meaningful boundaries, the technique of telescopic mesh refinement (Ward et al., 1987) was used to construct the single-well model. This was achieved through defining sub-regional boundaries within the regional flow model, which then define a new smaller problem domain. For more accuracy in defining the boundary conditions, the telescopic refinement done was in two steps until the model grids became small enough. The final design for the single-well model (Fig. 4) consists of 55x55 cells with irregular grid spacing. A very fine grid spacing (0.5 x 0.5m) was used at the center of the model to represent the location of the well. Away from this node, the grid spacing was gradually increased to reach 67.8m for the boundary nodes.

3 - Applications of Artificial Groundwater Recharge in Managing Water Resources:

The regional numerical groundwater flow and transport model was used to identify the optimum locations to store freshwater, and the sub-regional model was used to find the optimum management variables to inject and recover freshwater at the selected sites. These variables include: number and geometry of injection/recovery wells, injection/recovery rates, duration of injection required to create the intended quantity and quality of freshwater. Also, the recovery efficiency of the freshwater storing and recovery practice was identified. The Dammam Limestone was preferred to the Kuwait Group as the most appropriate aquifer for water injection. This is mainly due to less practical difficulties caused by well-face clogging that will arise from recharging this fissured aquifer compared with the clogging developed after rechargeing the granular Kuwait Group aquifer.

The Various sources of recharge water (desalinated water, treated wastewater, and runoff water) were ranked based on their dependability of supply, quality, compatibility with native groundwater and aquifer material, and expected conveyance cost. It was found that planning for artificial groundwater recharge in Kuwait should be based primarily on the availability of the desalinated water, and the treated wastewater be considered as an alternative, especially for surface recharge through spreading basins to improve its quality to meet the specification for water use.

3.1 - Seasonal Storage:

The current and proposed groundwater abstraction from the aquifers in Kuwait, as indicated by the simulation flow model, is seriously exposed to mismanaged development, where the groundwater is abstracted (or may be mined) regardless of the aquifer's safe yield. Because the TDS of the groundwater in the utilized aquifers is already high (ranges from 3000 to 6000 mg/1), any further deterioration will make these aquifers less usable in the future. By that time, any remedy will be impossible.

On the other hand, the urban demand for freshwater varies considerably between summer and winter months, resulting in operating the desalination plants under sub-optimal conditions. It was found that if the artificial groundwater recharge is practiced by integrating the aquifers and the desalinated water production together, the desalination plants can operate with their optimum capacity, irrespective of demands for freshwater, while the aquifer yield can be restored. Two benefits follow from this practice:

1 - Operating Desalination Plants at Optimum Capacity: This can be done through a seasonal cyclic storage and recovery of desalinated water. It is possible to store the excess desalinated water during winter months, and recover the stored water later during the summer to meet peak water demand. In addition, using the aquifers as a standby storage to meet the peak water demand, the establishment of new desalination plants can be postponed depending on the aquifer storage capacity and the number and capacity of injection/recovery wells. The optimum site to be used as a seasonal storage was found to be the Shigaya-B wellfield (Fig. 5). The main reasons for selecting this site are: (1) its capacity to store and recover large volumes of water within a short period of time; and (2) its location in a highly depleted area, thus, the aquifer head can be restored and the undesirable effects affecting groundwater quality can be reduced. The number of wells required to make the desalination plants operate at their optimum capacity year-round are 20 wells, where their theotetical optimum injection (during the injection cycles) and pumping (during the recovery cycles) rates are 7000 m3/d per well. The intitial recovery efficiency was found to be improved with the increasing number of injection/recovery cycles from 12% to about 48% obtained after 10 cycles.

2 - Increasing the Aquifer Yield: At the same time, the depleted aquifer heads are restored to a certain degree using the cycle of water injection/recovery. For example, recharging the Shigaya-D wellfield at a rate of 1840 m3/d per well using 24 wells on a seasonal basis was found to raise the DM aquifer heads at the major cones of depression by 80, 20, 10, and 7m at the recharged site, Shigaya-B, Umm Gudair, and the Sulaibiya wellfields, respectively (Fig. 5). Thus, the aquifer yield at the water wellfields is increased, and the possibility of groundwater quality deterioration due to seawater intrusion or upward leakage of saline water from underlying layers is reduced.

In general, to maximize the benefits from artificial groundwater recharge in increasing the aquifer yield, it should be practiced in conjunction with groundwater abstraction. To achieve this objective the Kuwait region was, in this study, divided into three zones, each showing a different degree of response to groundwater abstraction and/or artificial groundwater recharge. These zones were arranged laterally in the direction of the regional groundwater flow (Fig. 5): up-gradient zone (Zone A), down-gradient zone (Zone C), and Zone B in between these two zones.

Zone A: The water injection in this zone was found to cause a reduction in the natural groundwater inflow recharging the whole system. Thus, the wellfields in this zone (Umm Gudair and Shigaya-C) were excluded from use for artificial groundwater recharge. However, this zone is the most suitable location to produce groundwater because it is recharged with a relatively good quality water (TDS ranges from 2500 to 3000 mg/1). Hence, the abstraction from this zone will induce the lateral groundwater inflow to the aquifer system. Also, with optimum constant pumping rates, a pseudo-steady state drawdown in the aquifers heads could be reached in this zone.

Zone B: This zone was found to be the optimum location for cyclic injection/ recovery of water because the aquifer heads in this zone are very depleted. Thus, during the injection cycles the resulting increase in aquifer heads and the improvement in water quality will be maximized over an extensive area.

Zone C: This zone is located close to the Arabian Gulf coastline, which is the discharge zone of the aquifer system. This means that the recharged water will flow towards the Gulf. Also, the implemetation of artificial recharge in this zone will increase the aquifer heads on a regional scale. However, the specific benefits for the zone itself will be valuable in halting seawater intrusion. Groundwater abstraction from this zone should be minimized to avoid such undesirable effects.

3.2 - Long-Term Strategic Storage:

Storage and recovery of a sufficient volume of freshwater is feasible option to meet the shortage in freshwater supply that may occur during emergency conditions. The Shigaya-A wellfield was found to be the optimum site to be used as a long-term underground strategic reserve. This is mainly due to its high recovery efficiency, and the sufficient depth of the aquifer potentiometric head at this site, which allows the buildup in water head inside the injection well if it is clogged. Emergency conditions were assumed to persist for 270 days. Three different scenarios for the emergency to occur were assumed in this study. They are classified according to the degree of severity, ranging from a limited deficit in freshwater resulting from a limited failure of one or two desalination plants, to a total loss of the desalination plant's capacity and of the surface reservoir capacity. The optimum management variables required to store a sufficient volume of freshwater to fulfill the shortage in freshwater supply during each scenorio were separately indentified as follows:

Scenario A: Very limited mechanical failure or terrorist action against one or two desalination plants was assumed. Under this scenario, the available storage and the capacity of desalination plants would be adequate to replace the lost portion of freshwater, and there was no need for artificial underground freshwater storage in this case. However, under the other two scenarios, underground artificial storage was necessary.

Scenario B: Total loss of desalination plants is assumed to occur, but the surface reservoirs were still available. Under this scenario, a volume of 53.2 Mm^3 of freshwater had to be injected into the aquifer to be able to recover 9.7 Mm^3 (Which is the freshwater demand during emergency conditions). This means that the recovery efficiency is 18.2%. This was done using 20 wells with an injection rate of 1750 m^3/d per well for about 4.16 year. The optimum spacing of the wells, under which the maximum injection rate and maximum recovery efficiency can be obtained, was found to be 1000m.

Scenario C: Total loss of the desalination plants capacity and of the surface reservoir capacity is assumed to occur. Under this scenario, where freshwater supply was completely lost, more water had to be stored (about 115.32 Mm^3) to recover 21.9 Mm^3 of freshwater to meet freshwater demand during the period of the emergency. This involves the use of 40 injection wells with a rate of 1500 m^3/d per well over 5.26 years. The optimum spacing for these wells was found to be 1500m.

4 - Conclusions and Recommendations:

From this study, it was found that artificial groundwater recharge using wells is a beneficial way to manage groundwater in arid regions, especially in providing a strategic reserve of freshwater for emergency conditions and in increasing the yield of depleted aquifers. Also, artificial groundwater recharge can be used to provide short-term storage to balance the seasonal fluctuation in operating the desalinted plants, which will save the operational cost of these plants and postpone the establishment of new ones. For the hydrological situation in Kuwait, a number of conditions should be addressed to maxmize the benefits of Aquifer Storage and Recovery:

1 - To predict the size of the expected shortage in freshwater, the daily domestic consumption per capita has to be known. Also, the portion for drinking and cooking use has to be identified for better planning in creating such storage.

2 - To create a long-term freshwater strategic reserve for emergency use, the pro-

posed site for this purpose is recommended to be used initially as a seasonal cyclic storage (for about 3-5 years). This will help in improving the recovery efficiency at this site with the successive cycles of water injection/recovery. Consequently, the volume of freshwater that needs to be injected to create the required freshwater storage for emergency use will be less.

3 - The recharge wells should be constructed as Aquifer Storage Recovery (ASR) wells to permit them to be used for dual purpose (i.e., for abstraction as well as recharge). This design also will help to develop the injection wells (if they became clogged) periodically without much effort and loss of time.

4 - To increase aquifer yield through artificial recharge, future modeling studies should allow for water density variation, to fully identify the saline water front movement and its effect on groundwater quality in the coastal well-fields. Hence, the optimum locations for water injection to halt sea water intrusion can be identified.

5 - In this study, the only source that was considered for recharge was desalinated water. However, for future studies, the treated wastewater could be considered based on its availability and its compatibility for recharge. Thus, artificial groundwater recharge may be practiced in a continuous manner to provide a sustained recharge source to increase the aquifer yield in the long run, regardless of the fluctuation in operational schedules of the desalination plants. This also requires the identification of the areas that are suffering from water quality deterioration due to the upward leakage of the deep saline water. This will, in turn, require more representative water quality samples taken at different depths in the aquifers, and a quantification for the upward leakage coming from the underlying saline aquifers. These data were not available for the present study. Therefore, it is recommended to take these into consideration in future studies concerned with increasing the aquifer yield through artificial groundwater recharge.

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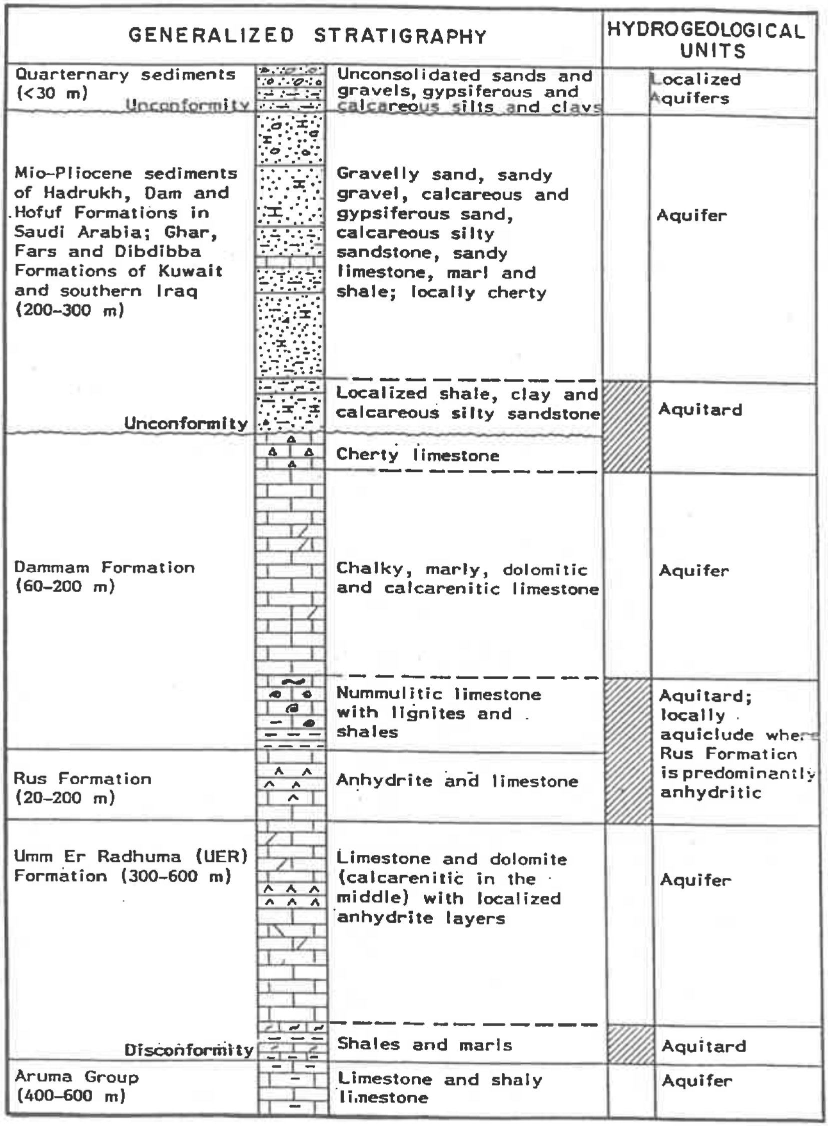


Fig. 1: Generalized stratigraphy and hydrogeological subdivision of the tertiary sediments of Kuwait (after Mukhopadhyay et. al., 1996)

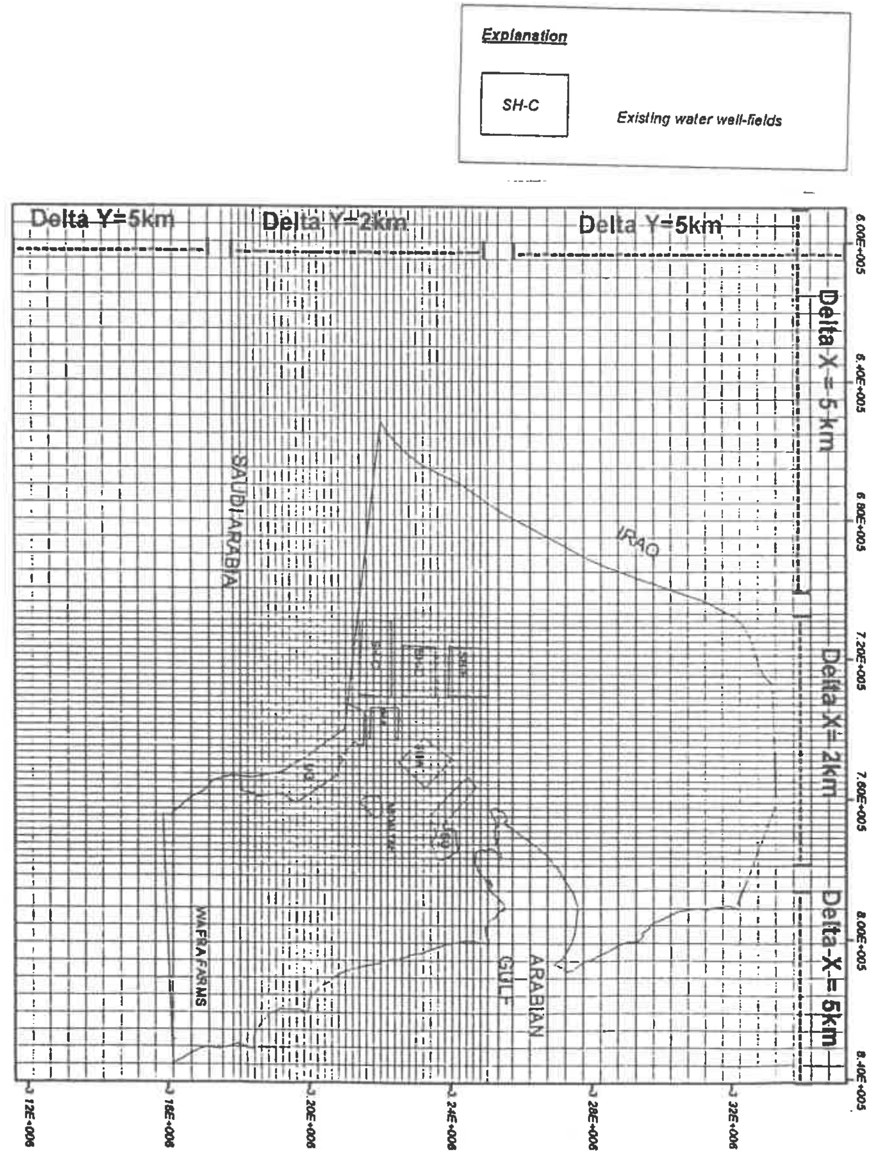
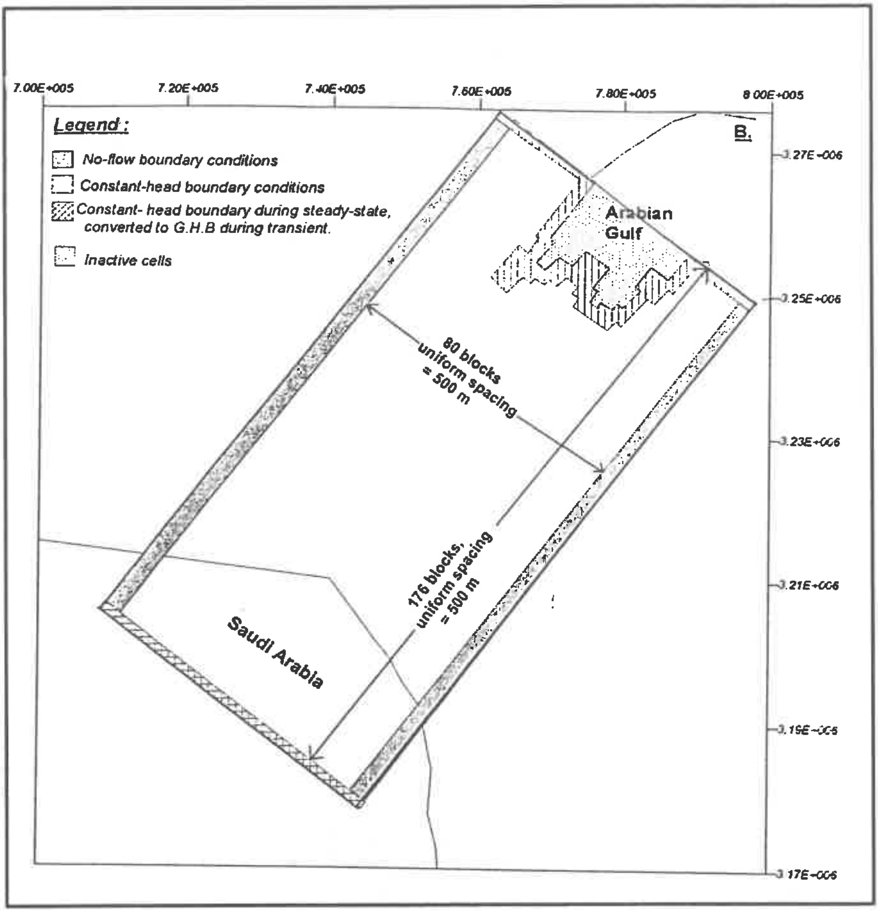


Figure 2: Irregular finite-difference grids used in the regional model.



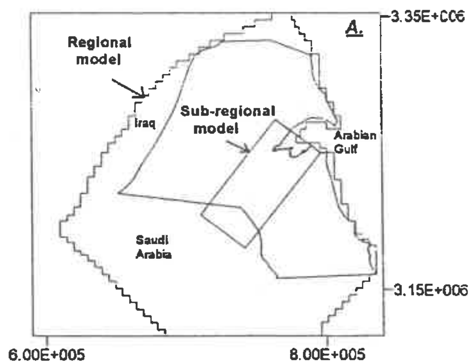


Figure 3: (A and B): (A) Location of the sub-regional model relative to the regional model.
(B) Domain discretization and boundary conditions of the sub-regional model.

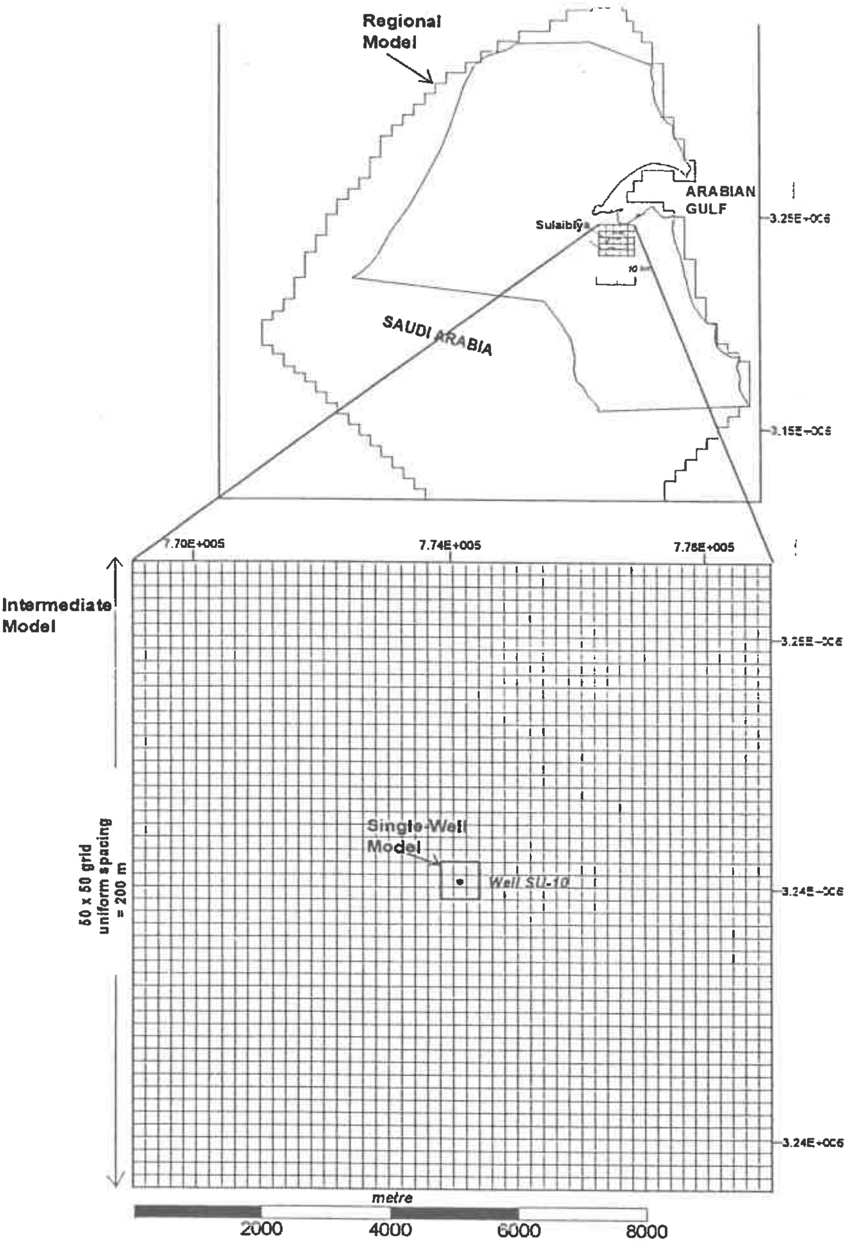


Figure 4: Embedded grids of the intermediate model, and the nested area of the single-well model.

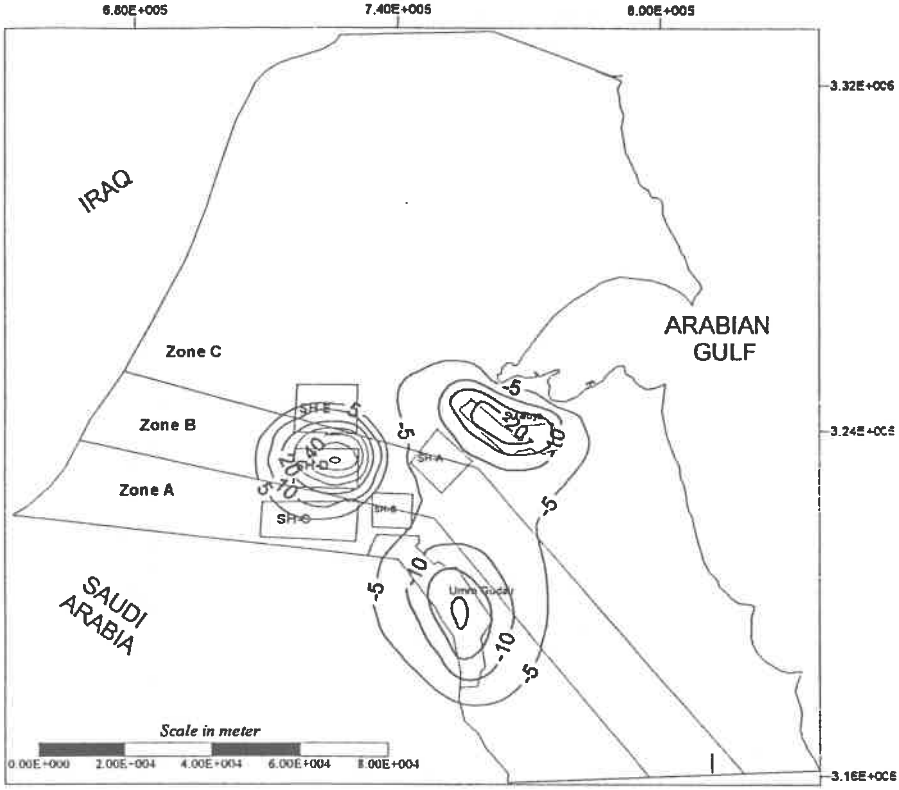


Figure 5: Simulated changes in the Dammam aquifer potentiometric head during the seasonal injection cycle at Shigaya-D wellfield as predicted for 2005, while groundwater is produced from other well-fields. (+) buildup, and (-) drawdown, (in meter).