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Strategic water reserve using aquifer recharge with desalinated water in Abu Dhabi Emirate

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ABSTRACT

United Arab Emirates (UAE) as well as other countries in arid region mainly relay on desalinated water for domestic water supply. The challenges facing UAE, however, is the vulnerability of desalination plants to pollution and emergency conditions. There should be available alternatives for reserving freshwater sources for emergency and peak demand conditions. Aquifer storage and recovery (ASR) technique has been proposed as a cost-effective large water storage alternative that can help to meet the needs of domestic sector in crisis/emergency situations. ASR technique is used to store excess desalination water during non-peak hours for recovery during emergency or peak hours. In an attempt to capture, store and redistribute desalinated water and to regulate the quality, quantity, timing and distribution of water flows, Abu Dhabi Emirate started in 2002 to study and evaluate the construction of ASR pilot project in western region. The initial target injection of pilot ASR facilities is to store 2.5 MIGD using five injection wells and one infiltration basin. Desalinated water is infiltrated into a desert dune sand aquifer using "sand-covered gravel-bed" recharge basins. In this study, we evaluate the hydrogeological and hydrogeochemical stratification of the (sub)oxic target aquifer, and water quality changes of DSW during trial infiltration runs. A three dimensional model was developed to assess the impact of hydrologic and operational parameters and factors on the recovery efficiency of the pilot ASR experiment. The model was integrated with geodatabase tool to produce an easily updateable model. Results from this study demonstrate the interaction between hydrologic and operational parameters on the predictions of recovery efficiency. The pilot observations and modeling results demonstrate that in scenario A recovered water quality still complies with Abu Dhabi's drinking water standards (even up to 85% recovery).

Keywords: Three-dimensional modeling; Geodatabase; Visualization; Artificial recharge; Water supply; Abu Dhabi

1. General background

Aquifer storage and recovery (ASR) involves the injection of freshwater in an aquifer through wells or infiltration basins for the purpose of creating a subsurface water supply that is recovered at a later time, to meet seasonal, long-term, emergency, natural crises or other demands (Pyne, 2007). United Arab Emirates (UAE) as well as other Gulf Cooperation Council (GCC) Countries mainly relay on desalinated water as the main source of fresh water for domestic, sustainable development and security of their communities. Moreover, desalination is still considered as very expensive source of water compared with other natural resources. Research and development, new ideas, and improved technologies are all needed to explore new approaches that are more cost-effective to desalinate water. It has been argued that the best long-term solution for the water crises in the domestic sector is to build a network of large-scale desalination plants. The problem faced by the GCC countries, however, is the vulnerability of desalination plants to pollution, natural crises, and emergency conditions. The possible alternatives for reserving fresh water sources for emergency and peak demand conditions are: (1) to increase ground reservoirs and distribution network storage capacity or (2) using a groundwater ASR system. It has been proved that increasing the capacity of the ground reservoirs and network is very expensive and not environmentally friendly. One solution is to store this

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water in groundwater aquifers using aquifer storage and recovery technique. For example, the maximum stored water in the ground reservoirs and distribution network is enough only for 24 h, except in Saudi Arabia and Kuwait, where it is 3 and 5 d, respectively (Fig. 1; Dawoud 2008). Thus, in any crisis or emergency, the stored water will not be enough to cover the demand. ASR has been explored in diverse settings worldwide (Bichara 1974; Khanal 1980; Bouwer et al. 1990; Calleguas 2004; Artimo et al. 2008).

Aquifer storage and recovery is used to overcome the groundwater depletion and unavailability of strategic fresh water reserve (Heilweil 2005), store and recover groundwater (Lowe 2005), provide seasonal and long-term storage, and regulate and improve water quality (Topper et al. 2004). It is particularly useful as a purification method for surface and wastewaters (Rüetschi and Wülser 1999; Brissaud 2003; Al-Katheeri 2007). Artificially recharged water can be introduced into aquifers in various geological settings, such as river basins (Lowe et al. 2003), fractured sandstone bedrock (Heilweil 2005), and esker aquifers (Artimo et al. 2003).

In an arid country such as the Emirate of Abu Dhabi with no permanently existing natural surface water and limited groundwater resources, artificial recharge and storage of surplus desalinated water in aquifers can play a major role in the management of water resources. Due to the absence of large storage reservoirs, desalination plants producing fresh water for urban supply are forced to operate at sub-optimal conditions. Thus, artificial recharge of groundwater and storage of freshwater is deemed necessary and promising technology for meeting seasonal peak demand and offset periods of water deficit due to long-term emergency and natural crisis conditions. Also, it will help to manage the daily and seasonal fluctuations in desalination water production and consumption as the production of desalination plants is constant and the demand is not constant. The excess amount of produced desalinated water during the non-peak hours could be stored in aquifers.

The success of the ASR scheme is normally measured in terms of recovery efficiency, which is defined as the percentage of water injected into a system in an ASR site that fulfills the targeted water quality when recovered. The recovery efficiency is controlled by a wide variety of factors including ambient hydraulic gradient; aquifer permeability, porosity, heterogeneity, thickness, and confinement; ambient groundwater density and quality; injected water density and quality; ASR operation (Bear, 1979; Merritt, 1985; Missimer et al., 2002; Reese, 2002). For example, aquifer transmissivity, the product of permeability and aquifer thickness, must be high enough to permit injection under reasonable pressures and to allow for high flow recoveries. However, if the transmissivity is too high, injected water can migrate excessively (sometimes beyond the capture zone of the ASR well) and in turn reduce recovery efficiencies.

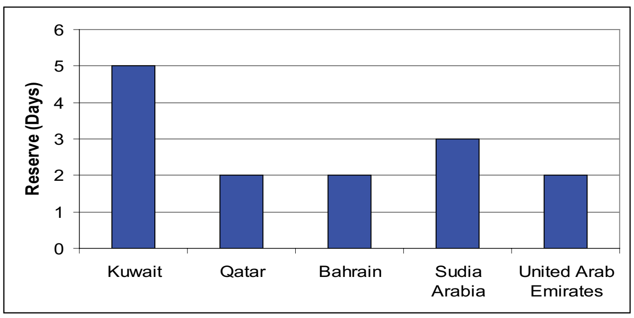

Fig. 1. Storage capacity for emergency water in GCC countries (Dawoud, 2008).

In Abu Dhabi, the pumping test evaluations revealed a range of the transmissivity from some 100 to 3,000 m²/d, with an average of 1,065 m²/d and a median of 950 m²/d. The lower values mostly refer to wells, in which the deeper section of the aquifer was tested. The calculated geohydraulic conductivity varies between 2 and 106 m/d with an average of 27 m/d and a median of 28 m/d as shown in Table 1. Therefore, the optimum transmissivity is within a limited range depending on desired pumping rates and recovery efficiencies (Missimer et al., 2002). In most hydrologic settings, the simplistic "underground storage tank" conceptual model applied to ASR system may have limited utility. Multiple processes including physical, chemical and biological, which can degrade water quality and quantity, control the ASR efficiency. Groundwater models can play an important role in the assessment of ASR scheme. Development of good calibrated modeling tool enables a variety of approaches concerning characterization of aquifer that will host artificially recharged groundwater. Collection and management of primary hydrologic data are key factors to successful characterization of any ASR system. Optimum injection and recovery rates are a function of site-specific conditions. The applications of developing geodatabases combined with geographic information systems (GIS) and three dimensional (3-D) modeling tools have been applied in models of regional scale (Kolm 1996; Russell et al. 1996; Kassenaar et al. 2004; Ross et al. 2005; Thorleifson et al. 2005; Cools et al. 2006) and at local scale (Shah 2004). Three-dimensional modeling tool is needed to build consistent conceptual model for groundwater flow (Shafer et al. 2006)

Table 1
Values of transmissivity and geohydraulic conductivity for the study area (derived from pumping test evaluation)

Well No.	Transmissivity (T)		Geohydraulic conductivity (kf)	
	(m²/d)	(m²/s)	(m/d)	(m/s)
GWA-141	1,050	1.2E-02	19	2.2E-04
GWA-144	250	2.9E-03	6	7.1E-05
GWA-148B	500	5.8E-03	13	1.5E-04
GWA-151	900	1.0E-02	22	2.6E-04
GWA-153	830	9.6E-03	16	1.8E-04
GWA-156	800	9.3E-03	28	3.3E-04
GWA-164	245	2.8E-03	6	6.5E-05
GWA-172	140	1.6E-03	5	5.9E-05
GWA-177	1,200	1.4E-02	45	5.2E-04
GWA-178	1,500	1.7E-02	38	4.4E-04
GWA-215B	2,500	2.9E-02	51	5.9E-04
GWA-240	950	1.1E-02	28	3.2E-04

to simulate the movement of artificially recharged water through the unsaturated zone building the fresh water bubble and the interaction of native water in the aquifer system with fresh injected water. In Abu Dhabi Feflow package was used for simulating the groundwater flow in the study area.

2. Sit selection

The success of the pilot project is mainly dependent on the selection of the most suitable site. To select the most suitable location for the ASR pilot experiment, Abu Dhabi Emirate (Fig. 2) was divided into 10 × 10 km squares. A site selection suitability index was developed including all factors affecting the success of the ASR. GIS was used to overlay various layers and calculate the site suitability index and evaluate and propose an initial array of potential ASR site locations. The suitability index was based on the premise of maximizing ASR effectiveness while minimizing any attendant impacts (Fig. 3). Multiple planning factors were used for the evaluation of ASR feasibility in Abu Dhabi Emirate including the availability of recharge water in terms of quantity and quality, topography, cost of required surface facilities and infrastructures, aquifer native groundwater quality, unsaturated aquifer thickness, aquifer extent and boundary conditions, and aquifer hydraulic parameters. From this analysis, it was found that northern Liwa area is the most suitable site for the pilot ASR project (Fig. 4).

The following advantages for the water supply system of the Emirate of Abu Dhabi are obvious in case of the northern Liwa area would be developed and utilized in the way described above:

- The geological settings and relative remoteness of the northern Liwa area offer a vast natural storage capacity and an excellent protection of naturally and artificially recharged water resources from environmental influences at the surface. In comparison, man-made storage facilities with a comparable capacity would be almost impossible to build and to maintain;
- A deep-seated underground reservoir utilizing natural sand formations as storage with a possible extension of up to 400 km^2 and with sufficient aquifer thickness and unsaturated depth to groundwater table is hardly vulnerable as a whole against environmental hazards and vandalism.
- The mixture of the artificially recharged desalinated seawater and the native existing fresh groundwater will improve quality of the resource and presumably favorable hydrochemical conditions. Huge volumes of the existing fresh groundwater (salinity of up to 1,000 ppm) could then meet the international WHO-Drinking Water Standard.
- Such a groundwater enhancement project in the northern Liwa area would be an essential back-up water supply for the Emirate of Abu Dhabi. The proposed system can cope with seasonal consumption peaks as well as emergency situations easily

The current investigations mainly focus on the water supply of the City of Abu Dhabi. Yet, any provision scheme for other urban or agricultural areas is possible, depending on the water balance the supplier wants to achieve through abstraction and injection. The artificially recharged groundwater

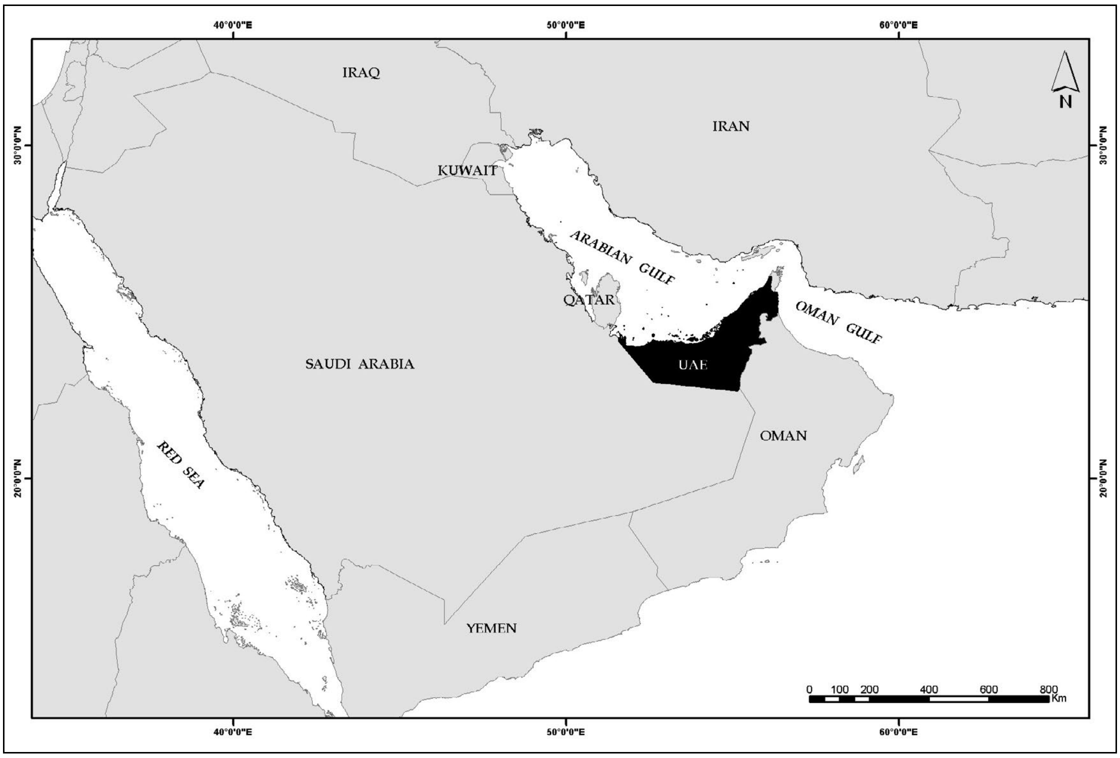

Fig. 2. General location map for Abu Dhabi Emirate.

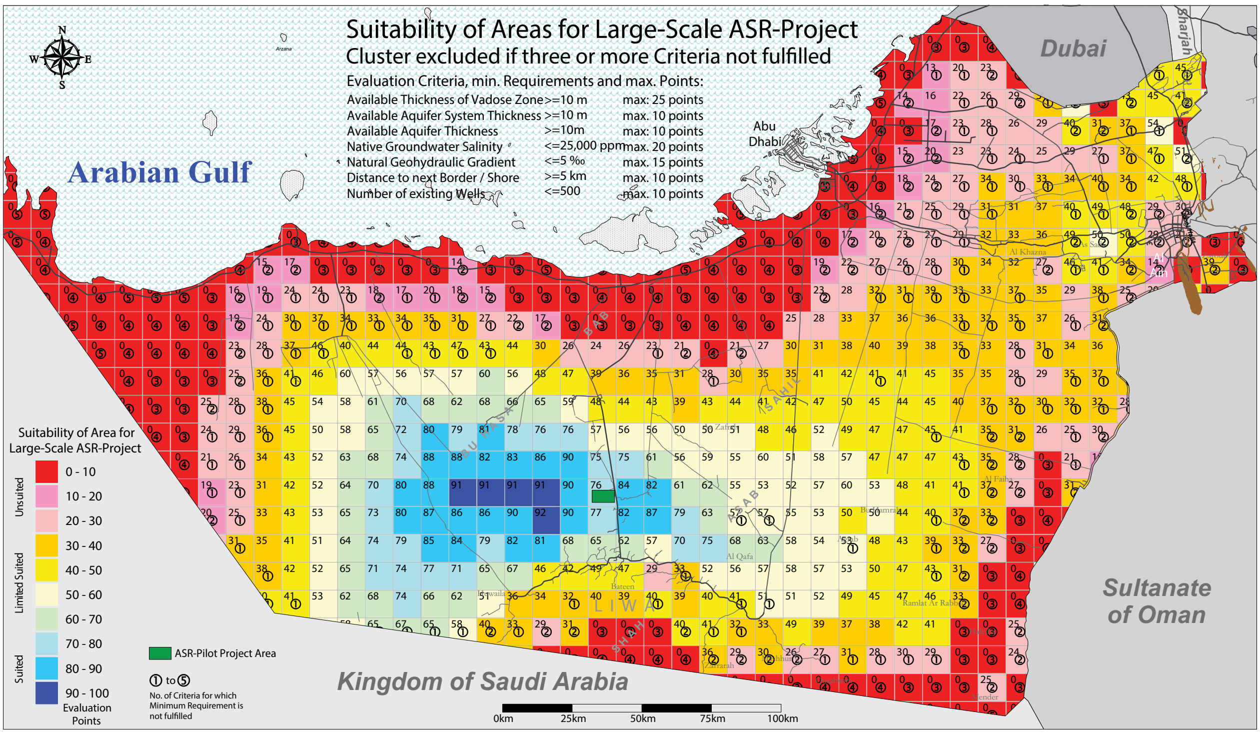

Fig. 3. Development of site suitability index.

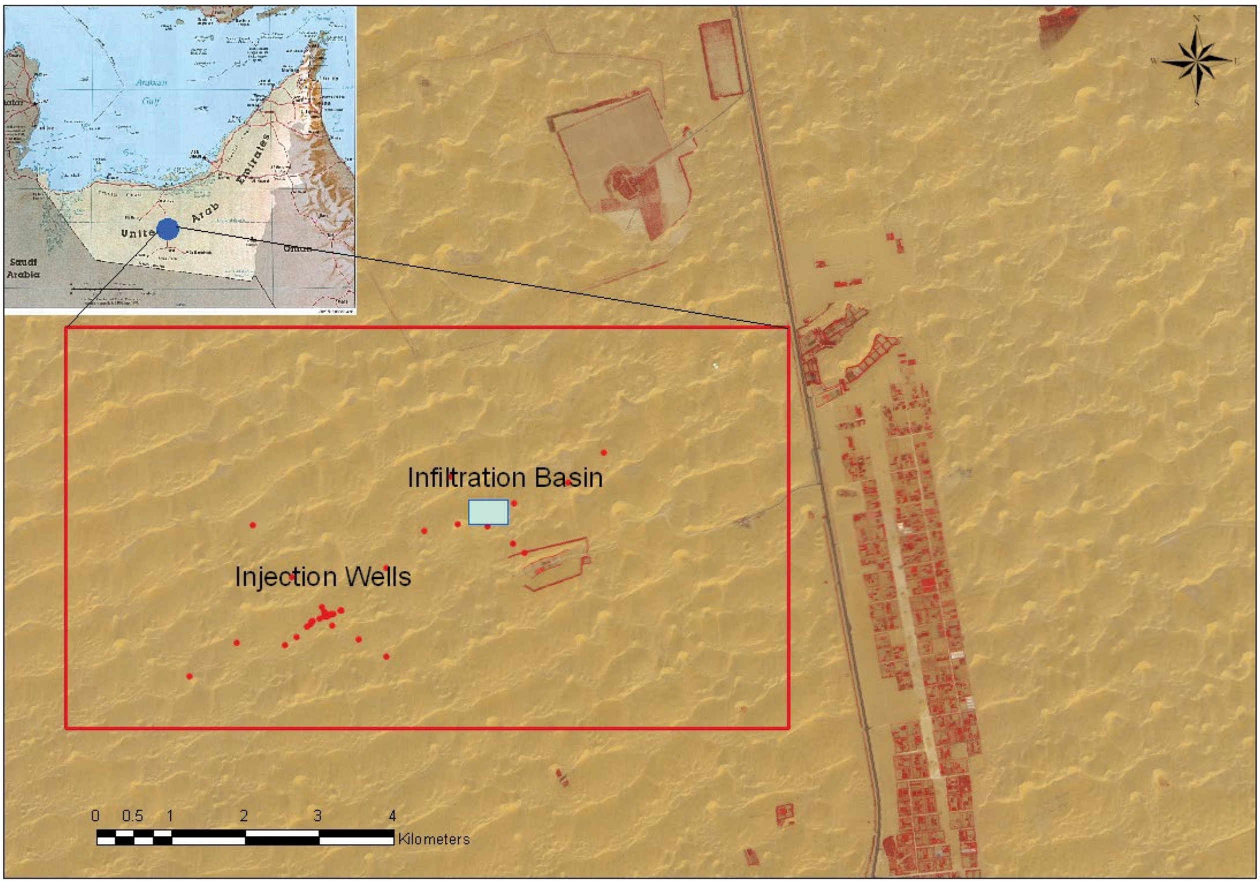

Fig. 4. Selected site for ASR pilot project (Northern Liwa).

resource in the northern Liwa area could be considered as the strategic drinking water reserve of the Emirate of Abu Dhabi for future generations.

3. Hydrogeological assessment

3.1. Lithology and aquifer system geometry

To assess the aquifer geometry and the stratifications, geodatabase populated with the information collected from 43 wells drilled within the study area and 140 existing wells around it. As the injection of fresh water will be in shallow groundwater, the depth of most selected wells is less than 150 m and is not penetrating the deep aquifer. However, four boreholes were drilled deeper than 490 m. In consequence, more detailed lithologic information is available for the uppermost layers of the stratigraphic sequence of the region. Two main stratigraphic units have been encountered:

- *Quarternary unit:* Holocene and Pleistocene eolian fine to medium sands and interdunal deposits. The thickness of this unit varies between 100 and 150 m, depending on the topographic height of the respective location within the study area.
- *Tertiary unit:* mudstones, evaporites and clastics of Miocene age. This unit has a thickness of over 350 m and has not been completely penetrated by any project well.

The Quarternary unit may be divided into two subunits. The upper unit is characterised by the predominance of well-sorted, fairly loose eolian dune sands with occasional intercalations of fine-grained, slightly cemented interdunal deposits. In the lower subunit of the Quarternary, these interdunal deposits prevail. They consist of caliche horizons with traces of organic matter, siltstones and even marls that may be interpreted as playa lake sediments and give evidence of more frequent pluvial periods in the Pleistocene. The Tertiary unit can also be subdivided into an upper unit, consisting of mudston layers and evaporites (gypsum, anhydrite, dolomite) of the Lower Fars Formation, and a lower subunit that is marked by the predominance of clastic sediments (sandstones, siltstones), that are intercalated with layers of mudstones and anhydrite. Table 2 summarizes the upper stratigraphic sequence in the study area as revealed by the project boreholes. The approximate spatial distribution of the stratigraphic units is shown in the hydrogeological cross-sections (Fig. 5).

The boundary between the Quarternary upper unit (aquifer) and the Quarternary lower unit (aquitard) is not clearly defined and cannot be easily correlated between boreholes. However, a significant increase of slightly cemented interdunal deposits is generally noticed around 60 m + MSL. Below this depth, the formation is still fully saturated, but does not contribute significant amounts of groundwater to wells, due to its relatively low permeability. This part of the formation is thus considered as an aquitard. A very significant lithological and hydrogeological boundary is the one between the Quarternary lower unit (aquitard) and the Tertiary upper unit (aquiclude). This boundary is defined by the first occurrences of evaporites of the Lower Fars Formation and marks the bottom of the aquifer/aquitard system. As shown in the hydrogeological cross-sections, in the study area, this interface is encountered at a depth of around 30 m-MSL. The static groundwater level is encountered between 104 m + MSL and 107 m + MSL. Hence, the average thickness of the main aquifer is about 40 to 50 m.

Table 2
Upper stratigraphic sequences in the study area

Unit	Subunit	Description
Quaternary Unit	Upper subunit	Eolian, loose fine to medium sand
Holocene + Pleistocene)	Lower subunit	Interdunal deposits (caliche, silt, marl and sand
Tertiary Unit	Upper subunit	Mudstone and evaporites of the Lower Fars Formation
Miocene	Lower subunit	Miocene clastics (sandstones, mudstones, anhydrite)

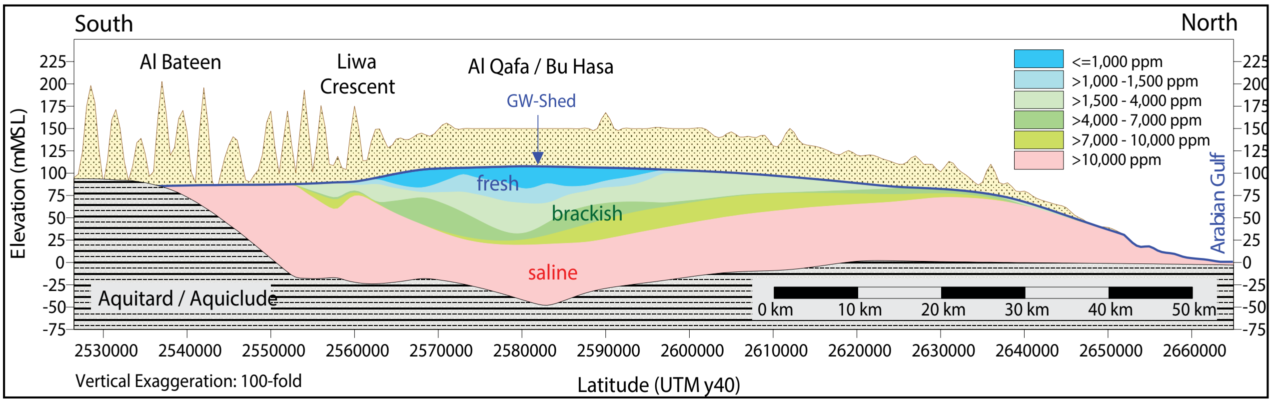

Fig. 5. Hydrogeological cross-section for the selected area.

The entire aquifer/aquiclude system exhibits a total thickness of around 130 m.

3.2. Groundwater flow

Generally, in geohydraulic terms, the Western Region of the Emirate of Abu Dhabi is separated by a major groundwater divide, running approximately from east to west. It passes the greater Liwa area some 20 to 30 km north of the Liwa Crescent. All shallow to medium deep-seated groundwater north of it flows to the north, towards the Arabian Gulf as the receiving body, while all groundwater south of it flows southerly to Saudi Arabia. There, huge Sabkha areas, much lower in elevation than the central part of the Western Region, function as a discharge area, where tremendous groundwater volumes constantly evaporate. The study area is located exactly along this major groundwater divide. The measured groundwater level in December 2001 was between 103.6 m + MSL and 107.2 m + MSL, with an aerial average of 106 m + MSL (Fig. 6). From the highest geohydraulic head in the central part of the eastern half of the study area, groundwater flows naturally radial to the adjacent areas under a maximum geohydraulic gradient of 0.5‰. The calculated natural velocity of groundwater movement ranges from 1 to 10 m/a. Although the geohydraulic gradient is comparatively low, the groundwater flow system is a dynamic one, which cannot be maintained without a driving force. Groundwater abstraction by discharging wells modifies the current flow pattern only locally; its effect on the large-scale groundwater flow is still negligible.

3.3. Aquifer hydraulic parameters

To calculate the aquifer hydraulic properties within the study area, 23 pumping tests were carried out between October 2001 and February 2002. Analyzing the results of these pumping tests gave more detailed information regarding:

- *Geohydraulic parameters* (such as transmissivity, geohydraulic conductivity and storage coefficient of the aquifer)
- *Well performance characteristics* (well capacity, well efficiency)
- *Groundwater quality* (general hydrochemical composition, vertical salinity profile and possible dependency of the quality on the discharge rate).

The calculated geohydraulic conductivity varies between 2 and 60 m/d with an average of 27 m/d and a median of 28 m/d and the calculated transmissivity ranges from 100 to 3,000 m²/d, with an average of 1,065 m²/d and a median of 950 m²/d. The lower values mostly refer to wells, in which the deeper section of the aquifer was tested. The storage coefficient was obtained only for those pumping tests, where additional piezometers in the vicinity of the tested well could be monitored. However, the determined values strongly depend on the test duration. For the 2-d lasting test, an

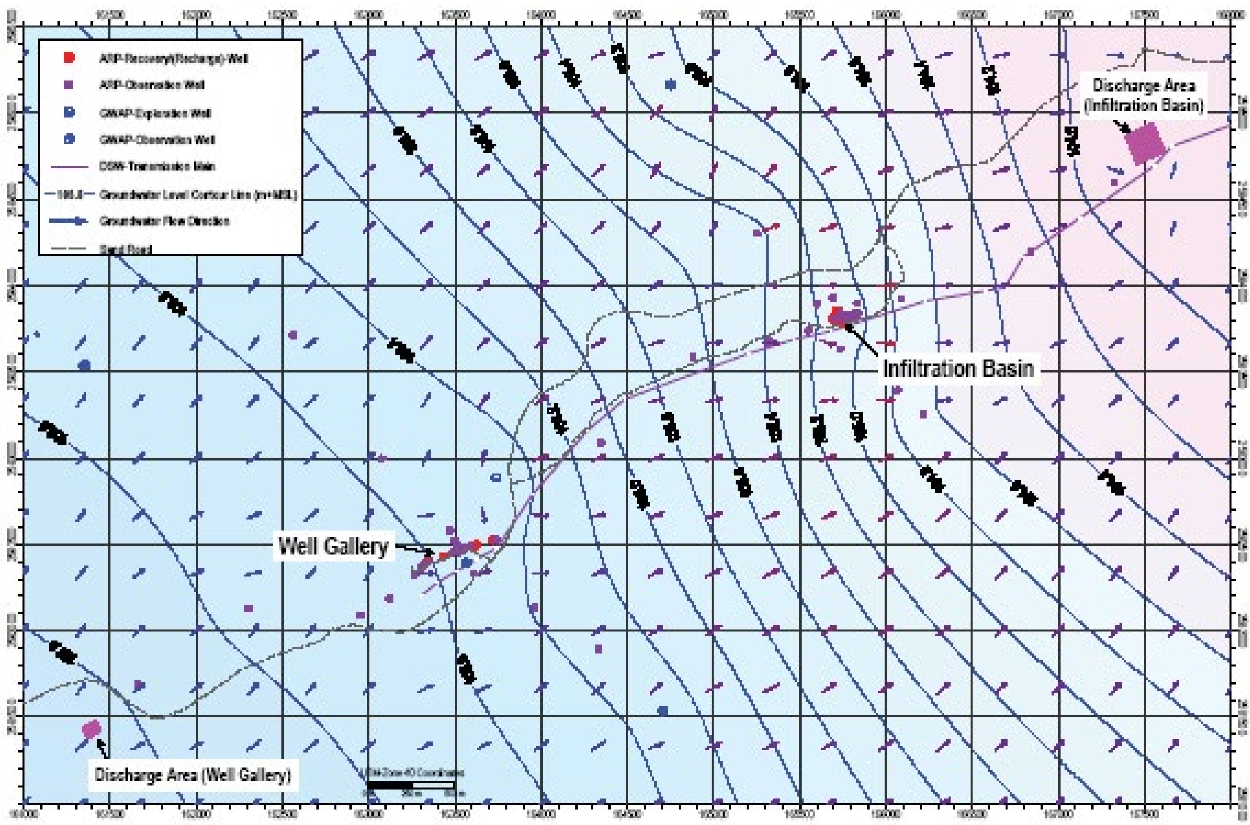

Fig. 6. Groundwater levels contour map (before injection, 2001).

average storage coefficient of $S = 0.16$ was calculated, while the 10-d lasting test finally gave the higher value of $S = 0.32$. The projected short to medium-term yield of the tested wells is comparatively high and ranging from 40 to 250 m^3/h with an average of about 130 m^3/h (GTZ/DCO 2002).

3.4. Field infiltration tests

In order to obtain information on infiltration rates and vertical geohydraulic conductivity, one well infiltration test and four tank infiltration tests were conducted. The results of the infiltration test indicated that the infiltration rate per m^2 ranges from 0.77 to 0.49 m^3/h. The evaluated vertical hydraulic conductivity in the vadose zone ranged from 1.6 10^{-4} to 2.5 10^{-4} m/s, indicating an approximately 40% lower conductivity value than that of the horizontal hydraulic conductivity.

3.5. Evaporation column tests

Evaporation has to be considered as an essential part in the artificial recharge project and needs to be surveyed precisely. Evaporation from bare soils occurs by capillary rise of soil water up to the evaporation front, at certain soil depth, followed by molecular diffusive water vapour transport through the dry soil layer above. For bare soil conditions and certain depths of groundwater table, the following evaporation rates are reported (Table 3).

This indicated that direct evaporation from the groundwater body is negligible beyond a depth to the groundwater table of about 5 m. Here, less than one mm/a of evaporation has to be considered. If the capillary fringe does not reach the ground surface, evaporation occurs mostly as transport of water vapour. In order to obtain long-term groundwater evaporation data, two holes have been drilled with a diameter of 26″ down to 50′, and a bottom sealed 21½″ steel conductor pipe was installed. An impermeability test of the 21½″ steel casing was conducted followed by the installation of a 2ʺ pipe inside the monitoring well. The steel casing was filled up with sand and afterwards water was pumped from a tank through the 2″ pipe into the well until the sand was saturated and the water level reached the top of the 21½″ casing. The impact of temperature, humidity and wind speed was correlated with the evaporation and possible recharge in the capillary zone. The test results and obtained data indicated that significant evaporation from the Liwa Aquifer could only occur in zones of very shallow groundwater table (<1 m). Literature evaporation data support these preliminary results and observations.

3.6. Groundwater quality

Complete hydrochemical analyses were carried out for 400 wells. The evaluation of the hydrochemical and hydroisotopical composition of the groundwater within the study area is based on 40 groundwater samples, 37 samples of which have been collected from wells, mostly at the end of the long-term constant discharge pumping test. Furthermore, three samples of the very shallow groundwater were taken from excavations. The analyzed total dissolved

Table 3
Evaporation rates of sands (after Kontny 1993)

Depth of groundwater table (m bgl)*	Mean depth of groundwater table (m bgl)*	Groundwater evaporation (mm/a)	
		Coarse sand	Fine sand
0–5	2.5	2.18	6.91
5–10	7.5	0.53	0.79
10–15	12.5	0.28	0.38
15–20	17.5	0.20	0.24

*m bgl = Meter below ground level.

Table 3
Salinity-related classification of groundwater samples

TDS (ppm)	Classification	Samples
≤1,000	Freshwater (World Health Organization WHO)	28
>1,000–1,500	Freshwater	7
≤1,500	Freshwater (Local UAE-Standard	35
>1,500–4,000	Slightly brackish	3
>4,000–7,000	Medium brackish	1
>7,000–10,000	Strongly brackish	0
>10,000–25,000	Slightly saline	1
>25,000–50,000	Medium saline	0
>50,000–100,000	Strongly saline	0
>100,000	Brine	0

solids (TDS) of the 40 groundwater samples ranged from 348 to 12,314 ppm. The number of samples according to the applied groundwater salinity classification is shown in Table 3.

In terms of mineralization, as much as 70% of the analyzed samples meet the limit of the WHO-Drinking Water Standard and almost 90% of the analyzed samples are fresh, according to the local standard (TDS: ≤1,500 ppm). Deeper screened wells produce groundwater of higher salinity: three samples are slightly brackish (>1,500 to 4,000 ppm), one is medium brackish (>4,000 to 7,000 ppm) and another one is slightly saline (>10,000 to 25,000 ppm). As sodium is the dominant cation, and chloride is the prevailing anion, hydrochemically, the tapped groundwater can be characterised as "alkaline water, predominantly chloridic". The calculated content of sodiumchloride (salt) as the major dissolved mineral phase ranges from 77 to 7,169 ppm with a median value of 431 ppm.

4. Conclusions

In Abu Dhabi emirate, two recharge schemes using injection wells and infiltration basins were used for injecting the desalinated water into the shallow groundwater aquifer system. Recovery cycles results indicated that under the given conditions the recovery ratios ranged between 85% and 90% were physically recovered. At the end of 250 d lasting period of constant recharge, the lateral migration of the outer injected freshwater body was only 0.2 m/d. For 75% recovery ratio, the recovered water salinity will be up to 430 ppm, and for 85% recovery ratio, the recovered water salinity will be up to 485 ppm. Both schemes proved to function perfectly. However, in contrast to the infiltration basin scheme, for the dual-purpose wells of the well gallery scheme there are indications of reducing injection and abstraction capacity over time due to clogging effects. Moreover, considering the local hydrogeological conditions, the infiltration basin conception is advantageous as it is easier to operate and maintain. It was recommended to use recharge basin in the full scheme project.

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