To What Extent Can Managed Aquifer Recharge Contributes To Augmentation Of Water Resources In Arid Areas : Sharing Experience From The Sultanate Of Oman

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Outline

- Case study – Alkoud aquifer
- Case study of Salalah MAR field project

Case 1: Aquifer Storage and Recovery of excess desalinated water (Optimization with multi-objective functions)

- Oman (and other GCC countries) depends heavily desalination technology for urban water supply.
- Different techniques are used for desalination and heavy investments in developing desalination plants under different **contractual models** (e.g., **take-or-pay** or **pay-on demand**) are in use.
- Since **urban water supply is often uncertain**, a common type of long-term water purchase agreement **in both developing and developed countries is the "take-or pay" contract** in which the buyer agrees to pay for a fixed volume of water from the seller, even if the buyer's network does not need that water for the whole year.

Case 1: Aquifer Storage and Recovery of excess desalinated water (Optimization with multi-objective functions)

- **Muscat City**: all the water produced by the ad-hoc desalination plant is consumed all during hot months.
- However, during winter months (Nov to Feb) there is an excess of production capacity due to low demand. **Currently, the Authority has no choice other than discharging excess production to the sea (10 Mm^3). The authority pays 85% of the cost even when the production is stopped)**

- **The main objective of the study is**: to explore the possibility to bank the excess desalinated water rather than discharging it to the sea along which the aquifer storage will be enhanced and thus ensure more water availability during stressed periods.
- This conjunctive use of storing water in aquifers during excess supply periods for recovery when demand exceeds supply.

Case 1: Aquifer Storage and Recovery of excess desalinated water (Optimization with multi-objective functions)

- Work estimates the benefits of optimal conjunctive use of groundwater and desalinated water by recharging seasonal surplus desalinated water to Al-Khoud aquifer.
- **The methodology consisted of coupling a numerical groundwater flow simulation model with a dynamic multi-objective optimization model.**
- We counted on the 45 existing wells and maximum number of new potential wells for injection and recovery.
- Each of these wells can assume the status of being **inactive, active for dual abstraction/injection** or **active for only injection or only abstraction**.
- We also considered the annual natural recharge for the selected 12 years simulation (**an average value of 33,769 m^3/day)**

Case 1: Aquifer Storage and Recovery of excess desalinated water (Optimization with multi-objective functions)

Objective functions:

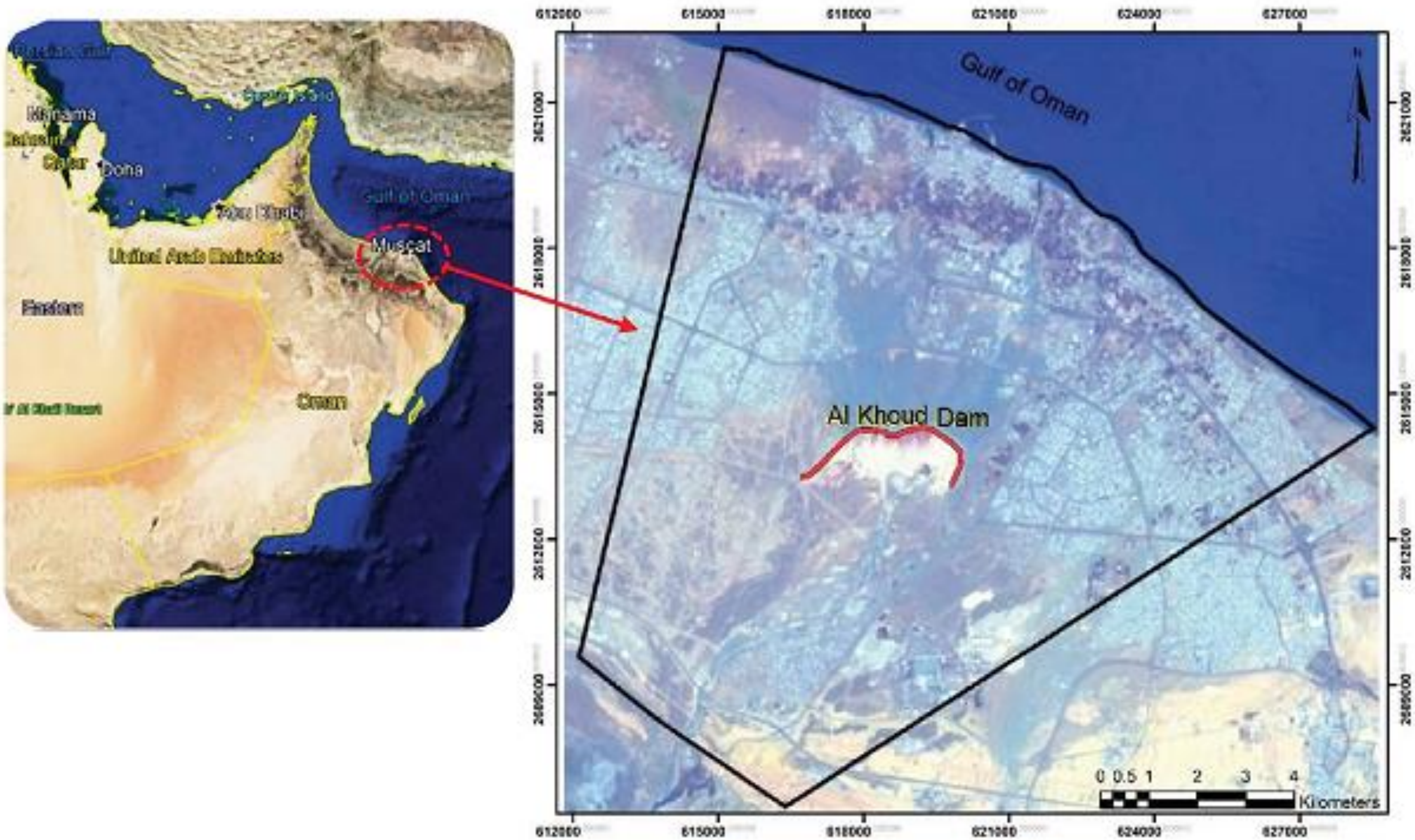
- the value of groundwater abstracted from the aquifer.
- minimizing the freshwater loss to the sea.
- the desalinated water cost and, finally,
- the last term expresses the annualized cost of drilling new wells, that will be counted only if that specific well is activated (drilling and maintenance cost US$ 3237/well/year)

Case 1: Aquifer Storage and Recovery of excess desalinated water (Optimization with multi-objective functions)

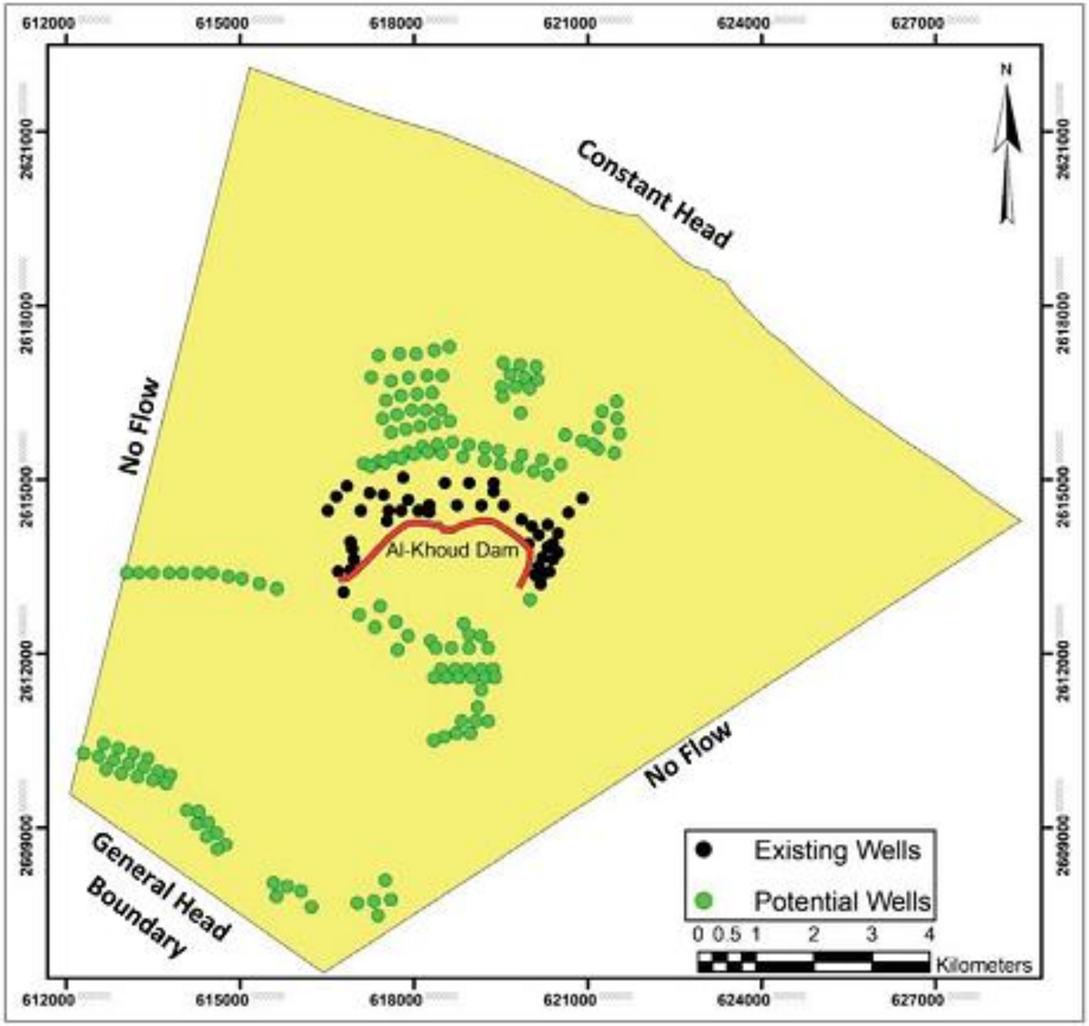
Constraints:

- Total groundwater abstraction volume
- Total volume of water lost to the sea
- Total volume of injection of desalinated water
- Total cost of injection of desalinated water
- Depth of rising water table must be below 7 m
- Total number of activated wells –based on minimization process
- restrict the maximum annual mean drawdown and the maximum seasonal mean drawdown near the sea over the simulation period
- forcing the **total groundwater abstraction volume** along the simulation years **not to exceed** the **total amount of natural recharge plus the desalinated water injected**

Map of the study area



Boundary conditions and locations of existing and potential wells

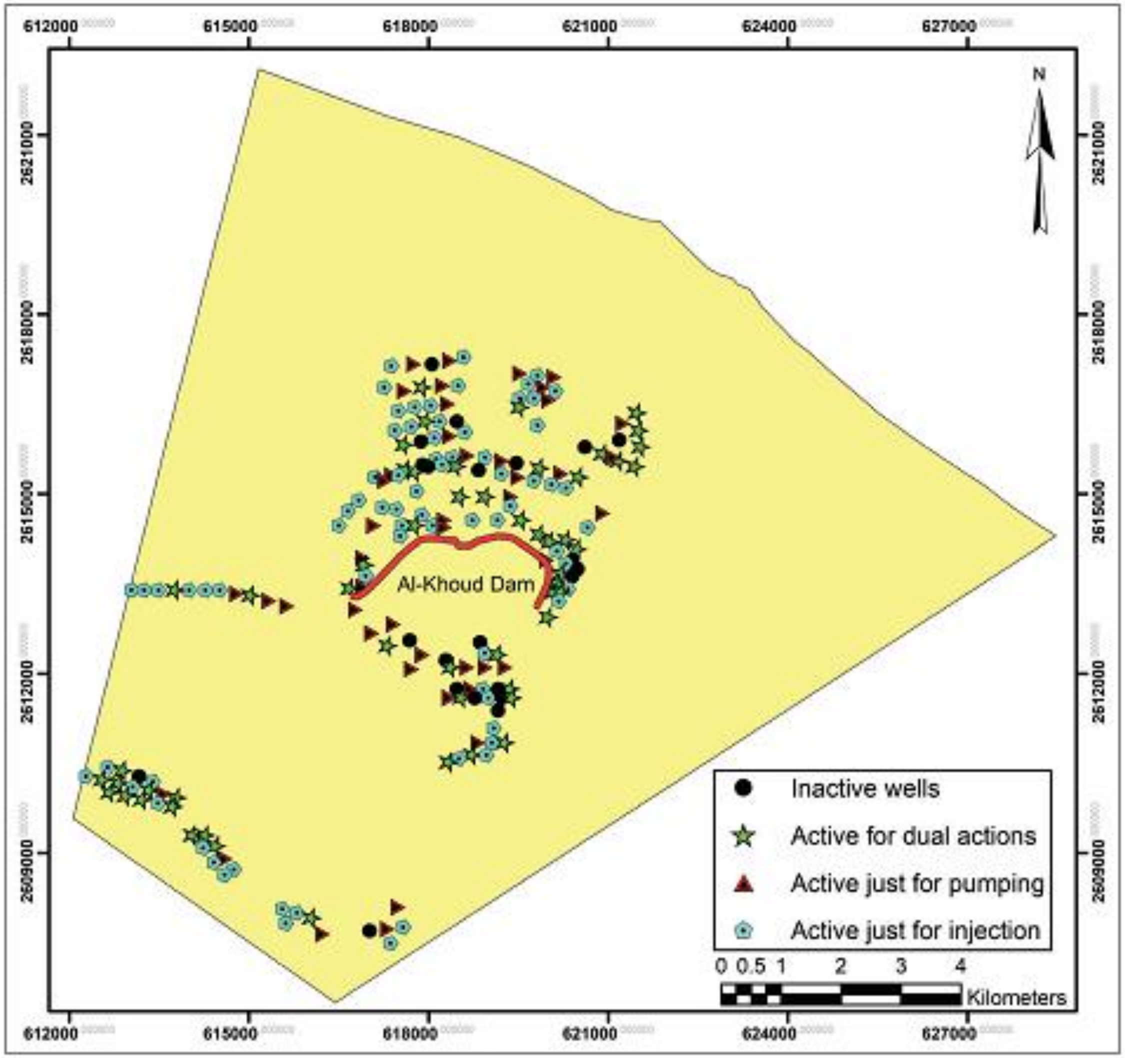


Unite Price of Water in the Study Area

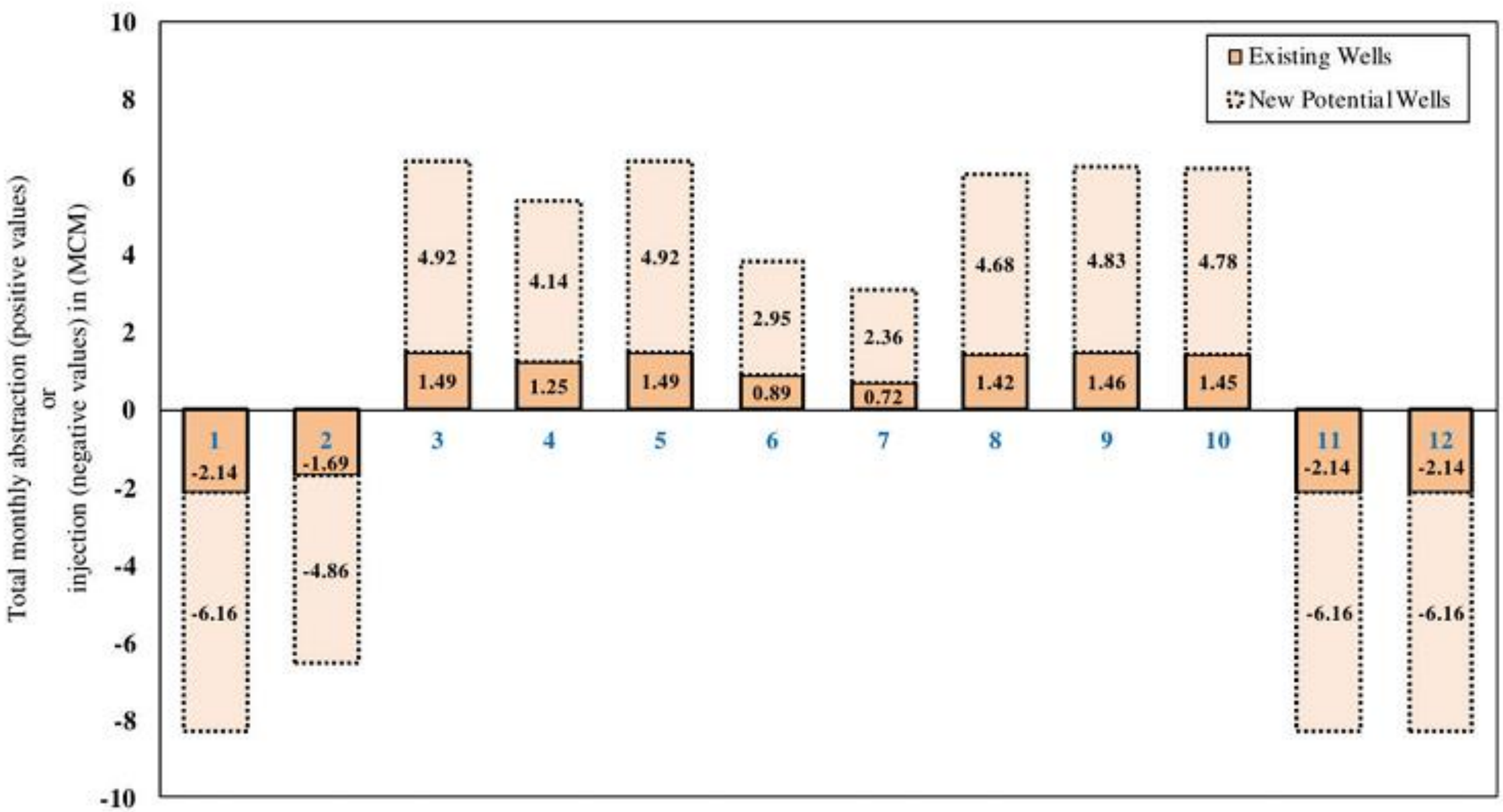
Unit Price of Water in the Study Area

Item	Source of the Information	Unit Price (US$/m^3)
Total cost of water (desalination, transportation and loss)	PAEW (2015)	3.18
The losses (leakages and nonpaid water)	PAEW (2015)	0.82
Desalination cost	PAEW (2015)	1.04
Cost of water transportation and delivery		1.32
Operation cost of injection of the water into the aquifer	Zekri et al. (2014)	0.042
Total operational cost of injection (injection costs) for volumes below 10 Mm^3		1.36
Total cost of injection for volumes above 10 Mm^3		1.51
Value of the desalinated water used for injection is considered zero as it is currently lost to the sea		0
The value of water in Muscat		2.36
The value of groundwater naturally lost to the sea		1.04

The Obtained optimal status of existing wells and potential wells for combined aquifer storage, transfer, and recovery.



Total monthly abstraction/injection from/to the new activated wells and existing wells



Main outcomes of study

1. The results of this study show that increasing the number of wells from the existing 45 wells to 173 **would allow storing 31.4 Mm3/year of excess desalinated water into the aquifer** that can be used later during summer months.
2. The net benefit would reach **US$ 55 million/year** while the cost of drilling the new wells is **US$ 5.11 million**.
3. Our findings suggest that, besides the **10 Mm^3 currently lost to the sea**, **it is advantageous to produce 21.45 Mm^3 additional desalinated water** to be injected into the aquifer. Even though there is a considerable volume of water to be lost to the sea, our approach will ensure **a net benefit of US$660 million over the 12 years** considered in our simulation.

Case 2: Salalah MAR Project

Salalah STP capacity is **20,000 m^3/day**.

- The MAR system designed to inject **18,000 m^3/day**.

Main purpose:

1. The main objective was to create a hydraulic barrier to decelerate seawater intrusion along Salalah coastal area [due to over extraction of groundwater]
2. To augment aquifer water storage and decelerate deterioration of its quality
3. Storing TWW and maximize its use.

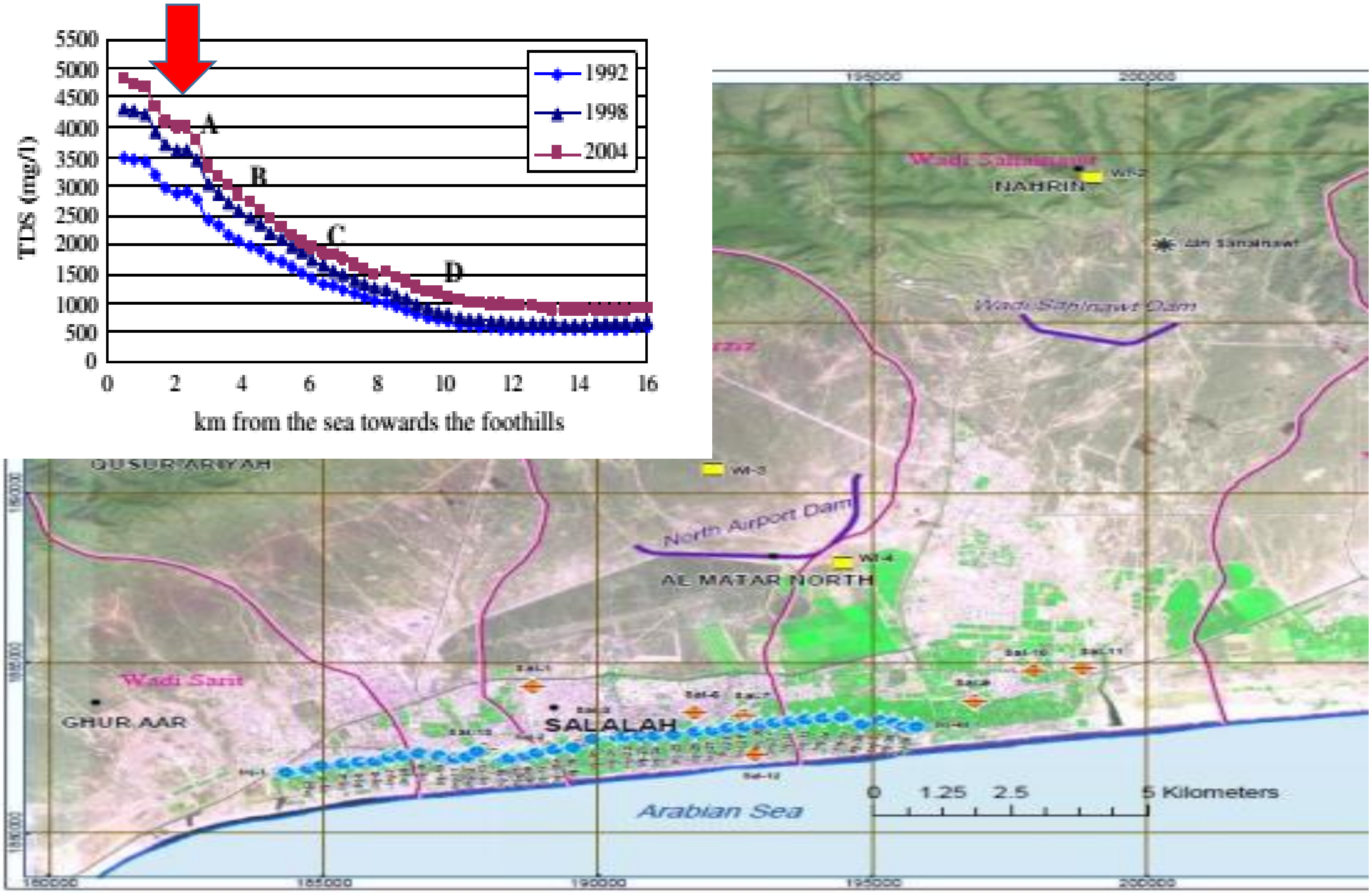
Location of the study area

Salalah MAR Project

- The injection started in April 2003 **through 40 injection wells equipped with 40 observation wells. The injection wells along the agricultural strip are situated approximately 1.0 to 2.0 km from the Arabian Sea shore [?]**
- The layout of the **injection wells** is designed so that they are **not less than 300 m** distant from each other, whilst the **observation wells are located such that they are within 5 m from the injection wells**.
- **The wells are constructed to a depth of 48 m below ground level** along the agricultural strip. Groundwater quantity and quality monitoring wells are located along the water supply well field zones (monthly).

Salalah injection project

- **The quality of the groundwater in the agricultural strip does not meet drinking-water standards (Shammas, 1998) pre to injection.**

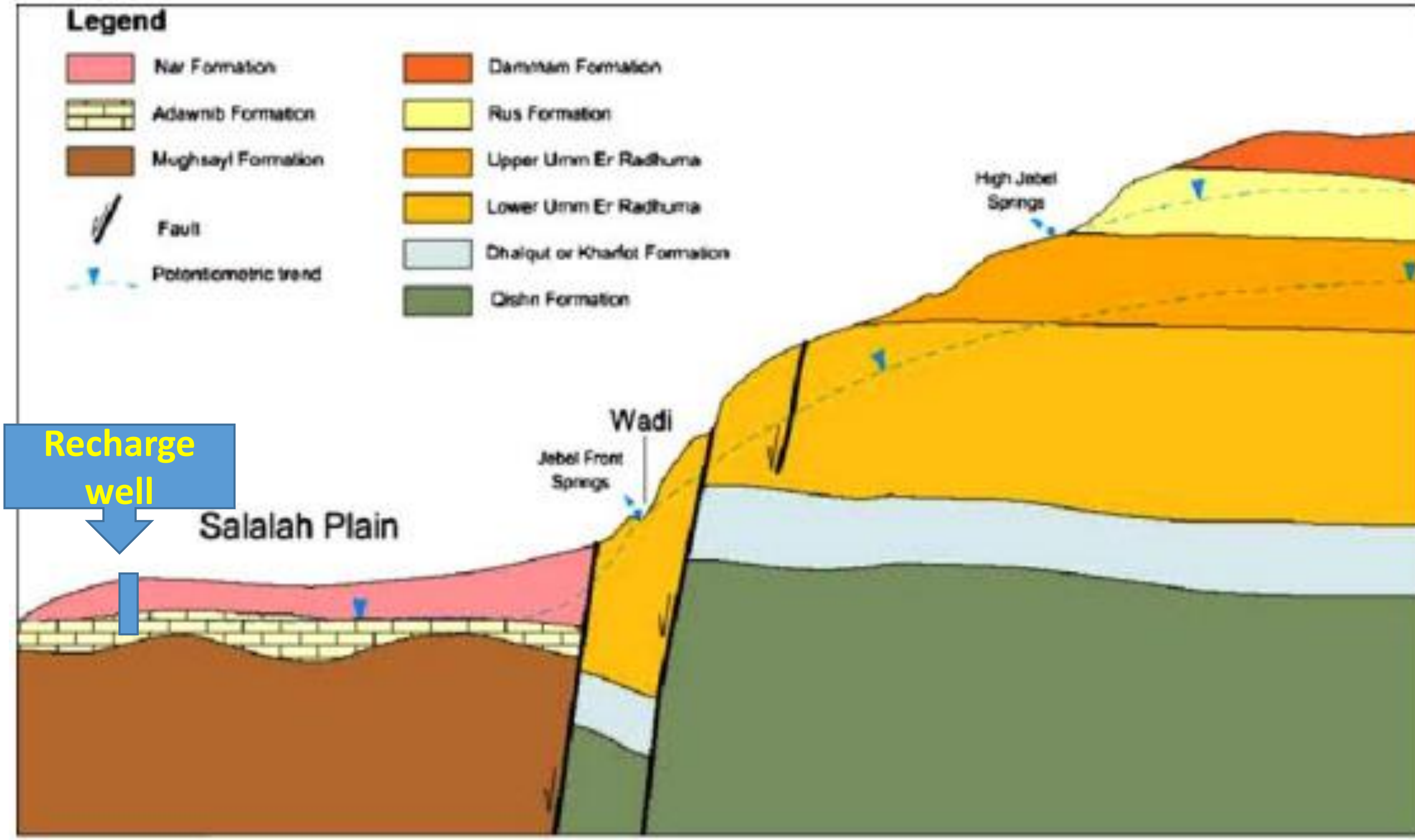


Salalah injection project

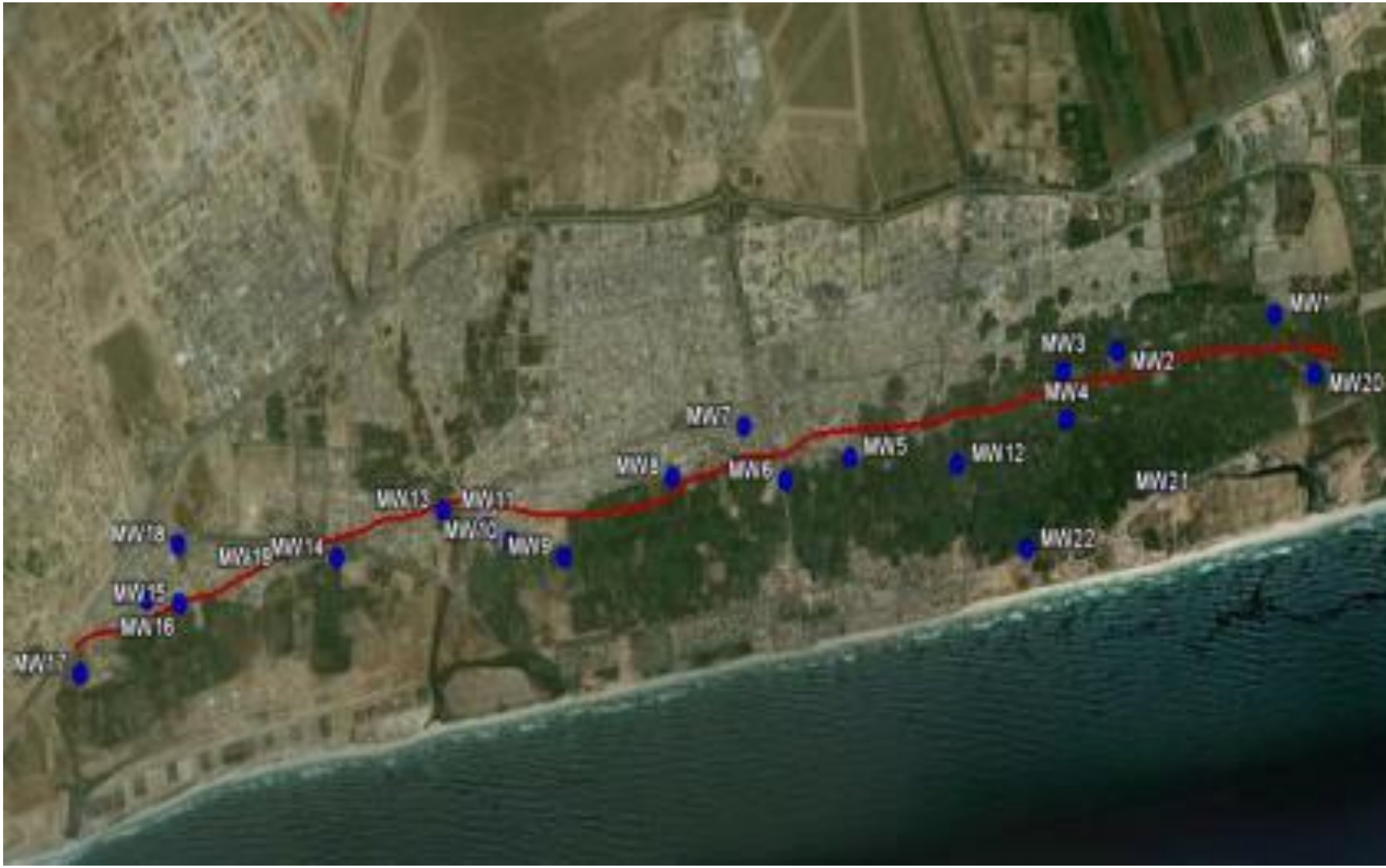
- The targeted formations is the quaternary and the Adawnib formations (**30 to 45 m thick** and fully penetrated by the recharge wells. **The water table is within 2.5 to 7.5 m in the injection line**)
- The most permeable horizons are encountered in the Baleed member, which consists of weakly cemented limestone with abundant solution channels. **A high degree of porosity to (35%).**
- **Aquifer Transmissivity is 2110 to 2725 m^2/day**
- 18,000 m^3 (**6.57 million m^3 a year**) of treated effluent is available for injection only. **(Is this volume is enough to achieve the planned objectives?) – below drinking water standards**
- **Total annual natural recharge is 32.4 Mm^3, and abstracted volume is 40 Mm^3, resulting in a deficit of 7.6 Mm^3 predicted to be around 20.7 Mm^3/year by 2020 if as usual business remains and no action took place [that is why MAR using TWW is one of the efforts to augment water resources in Salalah].**
- **No recharge if water quality does not meet the standards.**

Salalah injection project

- Hydrological cross section of Salalah plain and adjacent Jabal Al-Qara



Salalah injection project



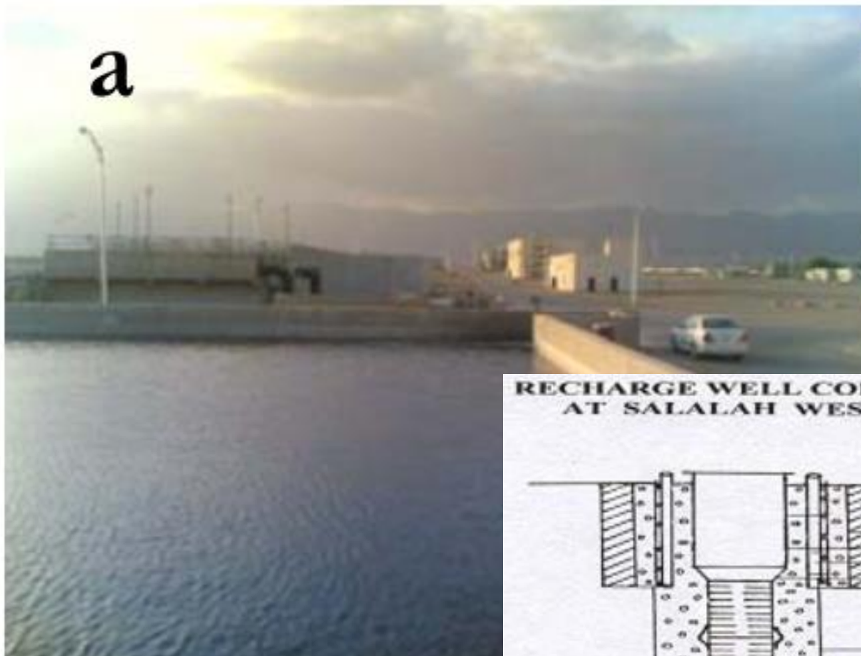
Salalah injection project

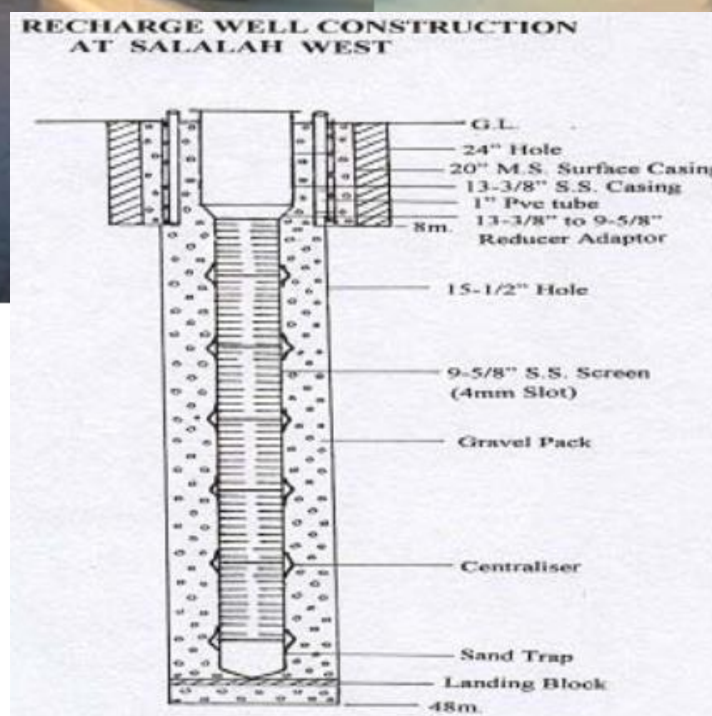
- Field Sampling from monitoring wells

Salalah injection project

Collection tank of treated wastewater

On e of the injection wells and observation well (yellow)in Salalah coastal plain





Effectiveness of MAR on water quality

- The water-collected samples for feacal coliforms and T.E-Coli were higher in the observation bores than in the STP final disposal storage tank.

Parameter	STP collection tank	observation bores
Faecal coliforms bacteria	5-7 (per 100 ml)	1-201 (per 100 ml)
T.E-Coli	0-1 (per 100 ml)	10-25[a] and 1-200[b] (per 100 ml)

[a] Note: on 19th May 2003 and [b] on 6th Feb. 2007

The aquifer is contaminated with E-coil from the septic tank before injection

Effectiveness of recharge on water level

Figure 5-3: Water level Contour map for CY April 1999

Effectiveness of recharge on water level

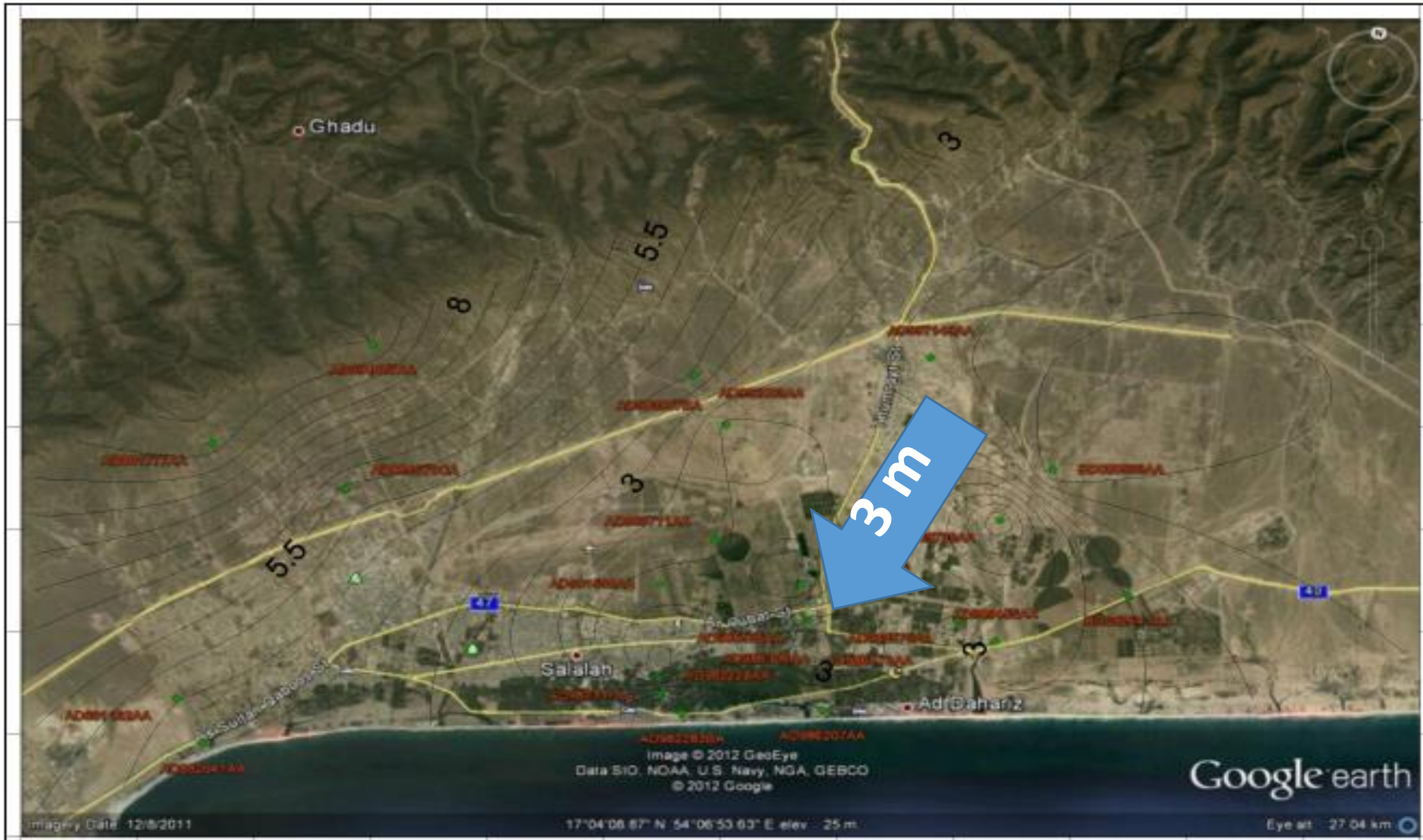


Figure 5-4: Water level Contour map for CY April 2010

Effectiveness of recharge on water level

1. In and around the injection strip, groundwater TDS value is ≤ 2000 mg/L, whereas the outside of the injection strip the groundwater TDS value is > 2000 mg/L.
2. The Nitrogen Nitrate concentrations on downstream of the injection line ranged between **5 to 15 mg/L**. The range was found from **10 to 20 mg/L** upstream the injection line.

Main messages from the project

1. MAR effectiveness is a site specific and must be tailored according the specifications and characteristics of the sites and water availability
2. For MAR projects to be effective, management of water post to injection is crucial, otherwise it is a failure.
3. Salalah MAR project contributed to improvement of the deteriorated coastal aquifer, **however uncontrolled abstraction affected its effectiveness.**
4. **Excellent understanding of the hydrogeology of the targeted aquifer, optimum location of injection and abstraction wells is needed to achieve the objectives are extremely necessary**.
5. The 6.5Mm^3 of injected water was to enough to control seawater intrusion but to some extent retarded further seawater intrusion. The location of injection might not be optimal.

Acknowledgment

Co-authors (case 1):

1. **Prof. Slim Zekri**, Natural Resources Economy, Sultan Qaboos University
2. **Dr. Chefi Triki**, Associate Professor, College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar
3. **Mohammad R. Bazargan-Lari**, Department of Civil Engineering, Islamic Azad University, Tehran, Iran

References for Salalah MAR project (Case 2):

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Thank You

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Sustainable water development is a responsibility of all