# Aquifer Storage and Recovery and Managed Aquifer Recharge of Reclaimed Water for Management of Coastal Aquifers


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# Water Scarcity: Management Is A Must

- In arid climate region (e.g., Oman), water resources are limited and threatens the development of different sectors.
- The use of groundwater in densely populated coastal areas becomes practically intense, (seawater intrusion + depleting the storage)→ the farming community and other uses.
- Therefore, augmenting and managing stressed aquifers is a **MUST**.
- **Managed Aquifer Recharge (MAR, ASR, ASTR, etc) is one of the effective measures in managing groundwater.**
    - **Recharge Dams: irregular rainfall patterns.**
    - **Desalinated water: expensive, limited uses – however, excess desalinated water**
    - **Reclaimed wastewater: only source that increases with time,**

# Reuse of Reclaimed water and role of groundwater Modeling

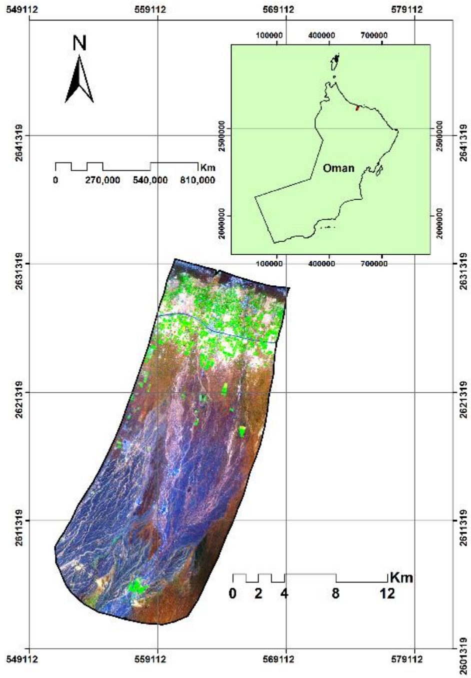
- Hydraulic barrier against seawater intrusion (major problem in developed coastal aquifers)
- Augment the depleted aquifer storage along with dilute saline groundwater

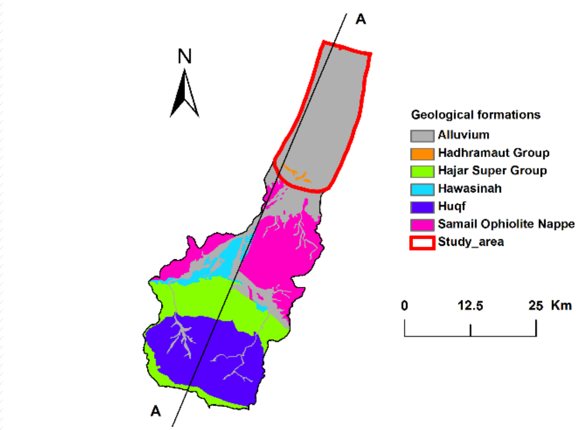
**Challenges of reclaimed water reuse:**

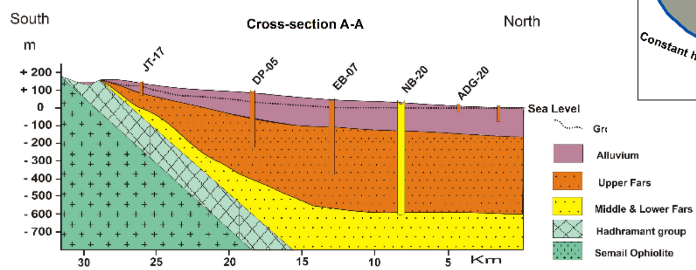
MAR using reclaimed water faces **several challenges and risks**, **both technical and economical**: include understanding the development of the groundwater mound, the dynamics of its development and dissipation, the storage period of the injected water, the water recovery rate, cost of installation of MAR system, operation and maintenance, and hence the net benefit value. **This can be achieved by improved aquifer characterization and modelling groundwater mounds generated by MAR practices**

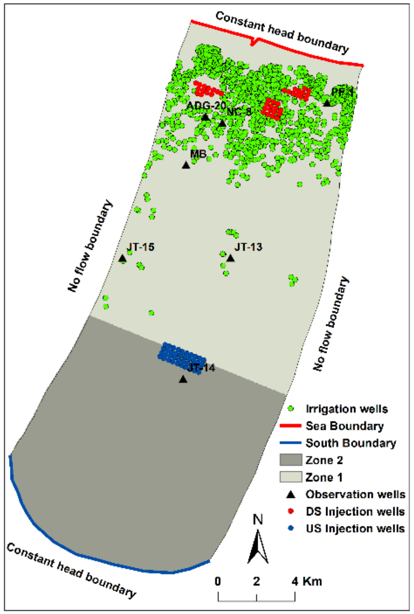
- **Presented Case studies:**
  - explore the feasibility of Managed Aquifer Recharge (MAR) in mitigating a deteriorated coastal aquifer – North of Oman using numerical modeling. Jamma and Al-Khoud Aquifers
  - ASR of excess desalinated water and ASR in saline aquifer

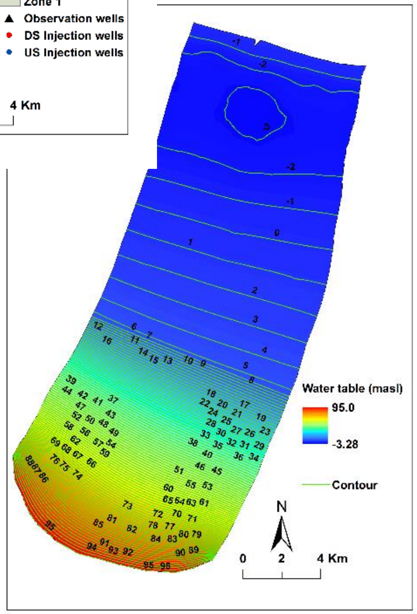
# Case study 1: The Study Area: Jamma Site




**The Purpose:** augment storage, barrier to seawater intrusion, and hence improve farming community

# Description of Simulated Scenarios

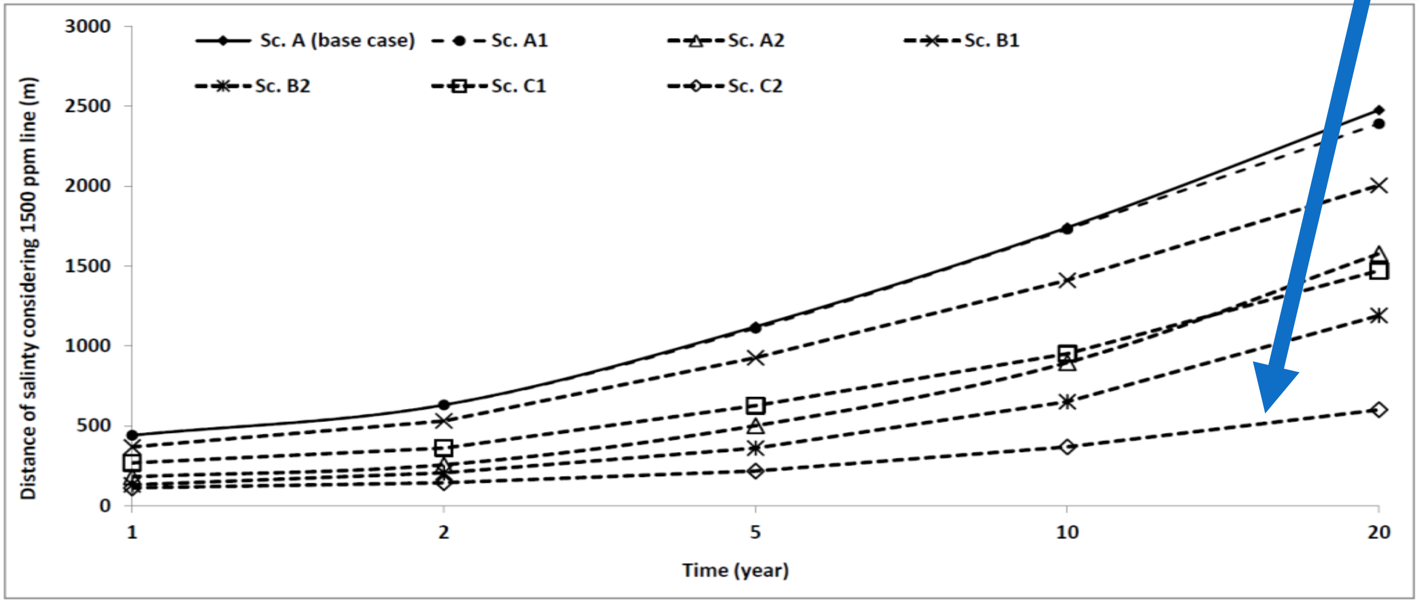
| The Scenario | Location of the injection | Description | Injection rate and number of wells | Period of injection | Total abstraction |
|---|---|---|---|---|---|
| **Sc. base** | No injection | Represents the current condition | non | non | 243,695 $m^3$/day |
| **Sc. A1** | Upstream, 16.5 km upstream the coastal line. | This scenario aims to restore the declined water table through increasing the storage term. | 40 wells with 240 m spacing, with 1500 $m^3$/day as recommended by Pyne (1995).<br>In total 60,000 $m^3$/day | 4 months followed by 8 months without MAR. | 243,695 $m^3$/day |
| **Sc. A2** | Downstream, in the vicinity of the farming area. Shown as red dots represent the injection well in Fig. 1c. | The aim of this scenario is to act as hydraulic barrier to seawater intrusion along with reducing the stress caused by intense abstraction by irrigation wells. | Same as Sc. 1a and Sc. 1b | 4 months followed by 8 months without MAR. | |
| **Sc. B1, B2** | The MAR of this scenario was applied for both Sc.1a and Sc. 1b. | This scenario suggests that improvement in irrigation water use efficiency will take place by regulating abstraction rate. This is expected to reduce abstraction volume by 25 %. | Same as Sc. 1a and Sc. 1b | Same as Sc. 1a and Sc. 1b | 194,956 $m^3$/day |
| **Sc. C1, C2** | The MAR of this scenario was applied for both Sc. 1a and Sc. 1b. | This scenario suggests that using modern irrigation system will increase irrigation efficiency. This reduces the total abstraction by 50% as per (Abdel-Rahman and Abdel-Magid, 1993). About 80% of the agricultural area of Jamma area is irrigating by flood irrigation system. | Same as Sc. 1a and Sc. 1b | Same as Sc. 1a and Sc. 1b | 128,888 $m^3$/day |

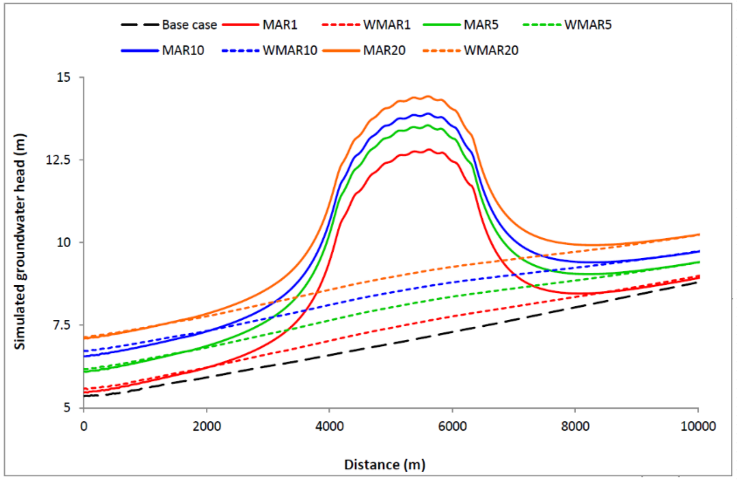
# Results of Simulated Scenarios (water balance)

| Scenario | Abstraction from Agric. wells | Injection rate | Change in Inflow from the sea | | Change in Evapo-traspiration | Change in Average of groundwater level |
|---|---|---|---|---|---|---|
| | ($m^3/d$) | | | | | (m) |
| **Sc. A (base)** | **243,695** | **0** | **171,000** | | - | - |
| **Sc. A1** | 243,695 | 60,000 | 12,012 | | 351 | 0.85 |
| **Sc. A2** | 243,695 | 60,000 | 11,608 | | 318 | 0.20 |
| **Sc. B (base)** | 194,956 | 0 | 46,235 | | 1,560 | 0.82 |
| **Sc. B1a** | **194,956** | 60,000 | 58,344 | | 2,106 | 1.66 |
| **Sc. B2** | 194,956 | 60,000 | 57,628 | | 2,029 | 1.01 |
| **Sc. C (base)** | 128,888 | 0 | **107,881** | | 4,701 | 1.91 |
| **Sc. C1** | 128,888 | 60,000 | **119,704** | | 5,608 | 2.75 |

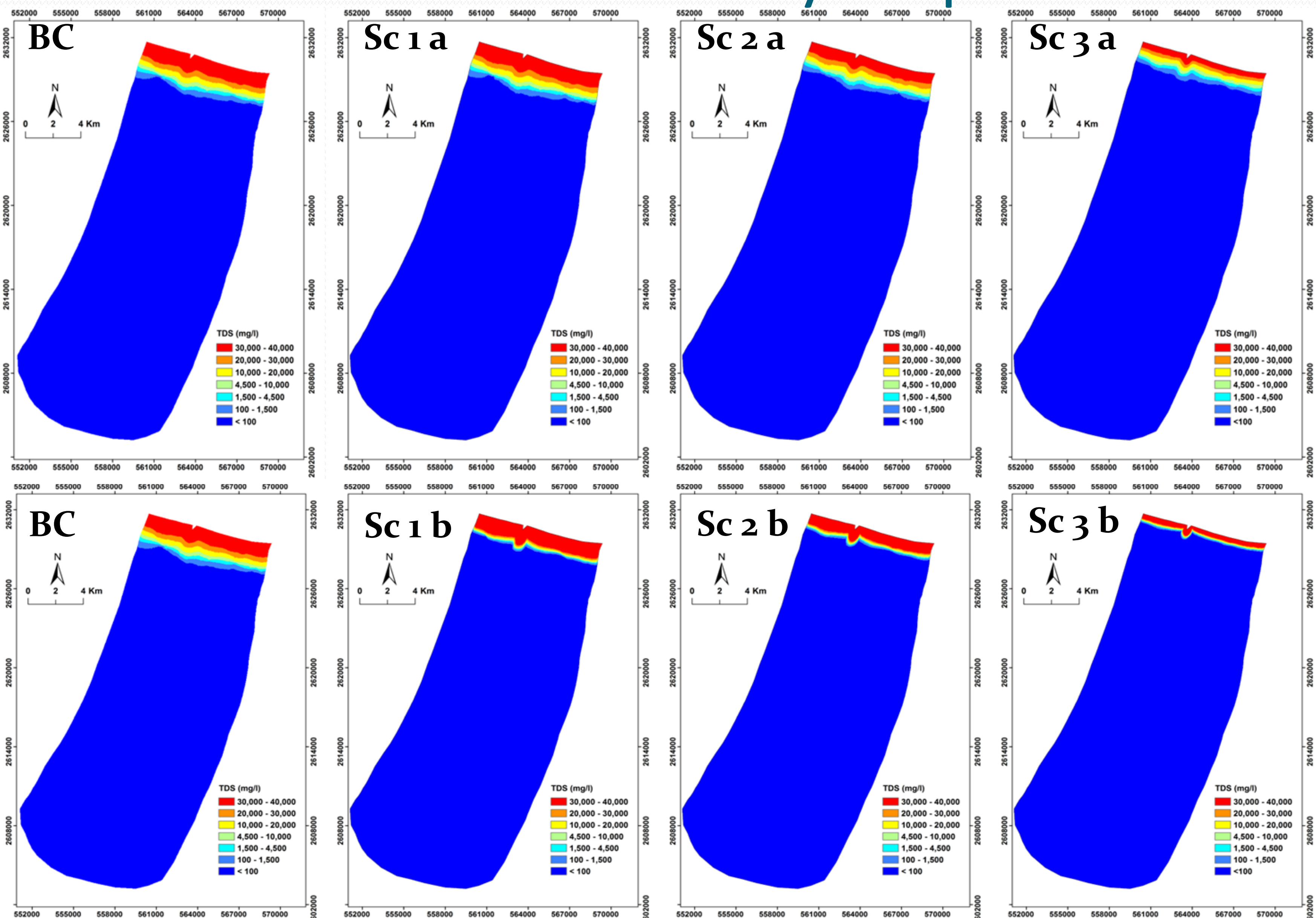
# Results: Jamma Site

**C2: the iso-concentric line recedes by 2 km**



# Results: Salinity Maps



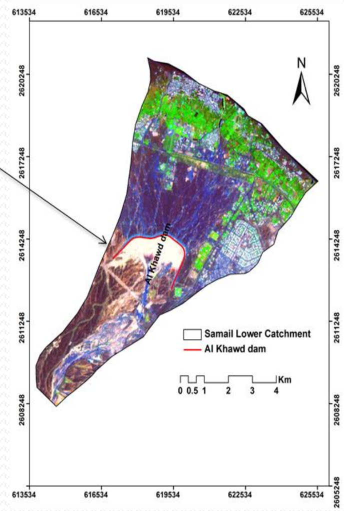
# Economic analysis of the modeled scenarios

| Scenario | | Investment cost in $ | Operation and Maintenance cost in $/year | Net Present Value $ | Net Benefit Investment Ratio |
|---|---|---|---|---|---|
| A1 | Investment in pipelines to transfer water from the wastewater treatment plant up to the recharging wells upstream at a distance of 16.5 km from source | 20,592,000 | 748,800 | -12,122,585 | 0.57 |
| A2 | Investment in pipelines to transfer water from the wastewater treatment plant up to the recharging wells downstream at a distance of 1 km from source | 1,248,000 | 374,400 | 11,973,877 | 3.18 |
| B | Investment in smart water meters & online control of pumping from the wells | 1,555,500 | 64,709 | 7,585,026 | 4.41 |
| B1 | investment in A1 + Investment in smart water meters to control pumping | 22,147,500 | 813,509 | -19,489,484 | 0.36 |
| B2 | investment in A2 + Investment in smart water meters to control pumping | 2,803,500 | 439,109 | 11,442,837 | 2.48 |
| C | Investment in drip and sprinkler irrigation systems renewable every 7 years | 12,653,125 | - | -8,344,547 | 0.68 |
| C1 | Investment in A1 + Investment in drip and sprinkler irrigation systems | 33,245,125 | 748,800 | -36,263,495 | 0.34 |
| C2 | Investment in A2 + Investment in drip and sprinkler irrigation systems | 13,901,125 | 374,400 | -12,519,153 | 0.61 |

# Conclusions of Jamma case Study

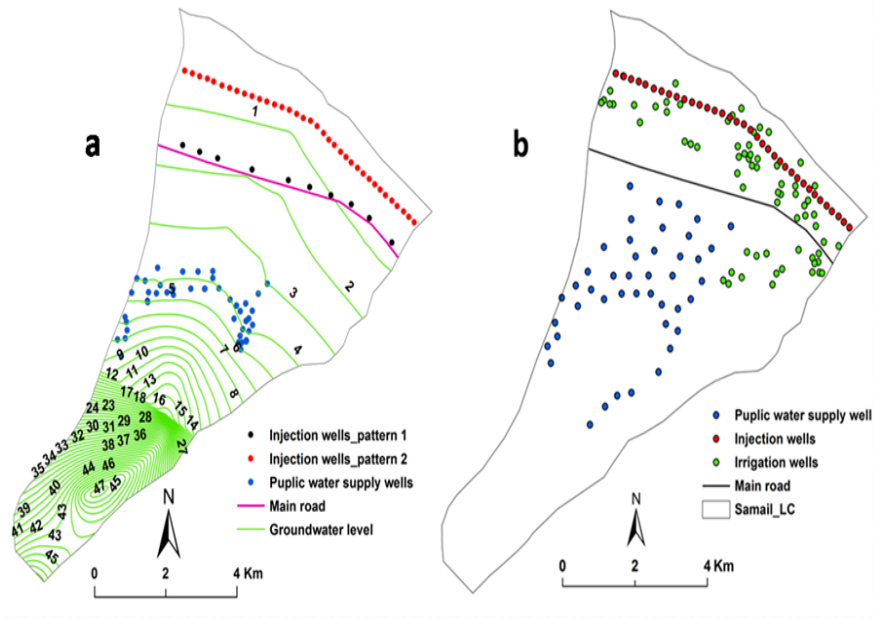
- Continuing with the current practices without management for the next 20 years would further drop the water table by 3 m in average. Without MAR, saline water interface will advance up to 3 km.
- **The best managerial results can be achieved when the management of groundwater abstraction (e.g., using modern irrigation systems) is integrated with MAR using TWW.**
- MAR is a feasible management practice to augment water resources in salinized coastal aquifers in arid areas and to help improve farming profitability and sustainability in the country.
- Recharge in the upstream area is not economically feasible because of the very high investment cost of the installation of pipes to transport the TWW over large distance.
- Because the financial resources for investments are limited, **scenario B shows a Net Benefit Investment Ratio of 4.41 (i.e., investment of a $1 yields $ 4.41)**.
- **The second-best option is scenario A2,** with a ratio of 3.38. Although the profitability of scenario B2 is lower, it is very attractive from a social perspective because it involves two measures at a time. Thus, farmers are requested to cut pumping and the government will invest in recharge to improve the quality of the groundwater and protect the aquifer from seawater intrusion in the long run. **Integrated efforts of the ministry and farmers' community will have higher chances for success than acting from a single side only.**
- *Optimization modeling is needed to achieve the best practices* ***(ongoing research).***

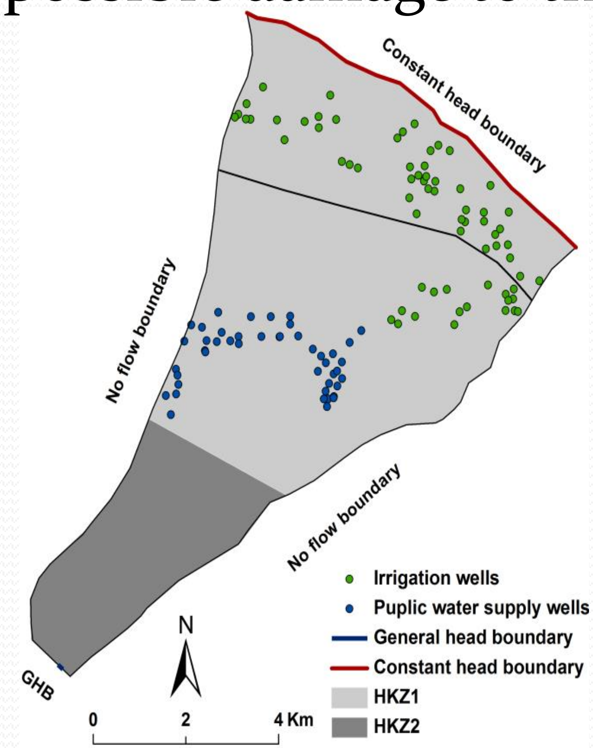
# Case 2: Al-Khoud Coastal Aquifer


Projected coordinate System:
WGS 1984 UMT Zone 40N
Projection: Transverse Mercator
Centeral Meridian: 57.00
Latitude of Orgin = 0.0
Source: Landsat

**Purpose**: Our primary objective is to increase the urban water supply and to sustain the aquifer service with the lowest possible damage to the aquifer.

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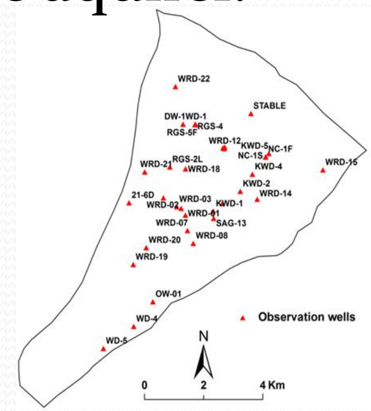
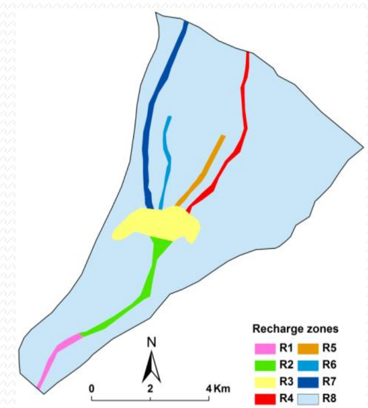



b

# Description of The Simulated Scenarios.

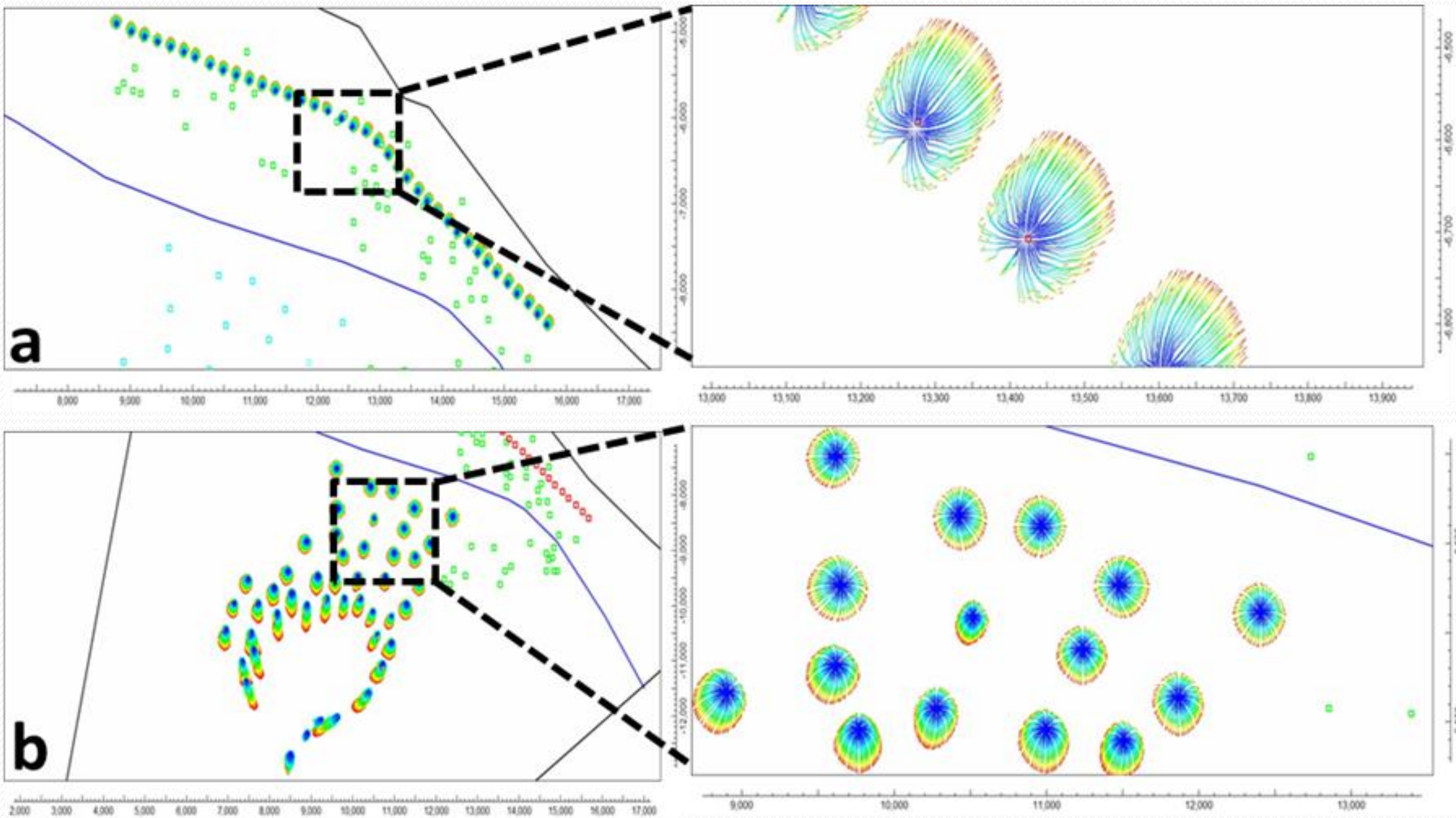
| Scenario | Description |
|---|---|
| **Base case (BCS)** | This case represents the current condition. |
| **S1** | This scenario illustrates the case when the abstraction rate from the public wells is increased as recommended by (Zekri et al., 2015a) with no MAR. |
| **S2** | This scenario is similar to S1 with MAR injecting TWW for farmer's use. |
| **S3** | In this scenario, a volume of 3,536 $m^3$/day of TWW is provided free of charge to farmers through direct pipelines in exchange for shutting down their agricultural wells. |
| **S4** | This scenario is similar to S2 except that the injection wells are located near the coast (Pattern 2-Fig. 3) using 38 injection wells with an injection rate of 121 $m^3$/day per well. |
| **S5** | This scenario is similar to S4 with reduced pumping from public wells. |
| **S6** | This scenario is similar to S5 with relocated public wells. |
| **S7** | This scenario is similar to S6 with a 25% reduced abstracted volume. |
| **S8** | This scenario is similar to S7 but without injection of TWW. |

# Water Balance and The Average Groundwater Level for the Simulated Scenarios

| Scenario | Abstraction from public wells | Abstraction from Agric. wells | Injection rate | Inflow from the sea | Outflow to the sea | Evapo-transpiration | Average groundwater level | Average of GW level 500 m from the sea |
|---|---|---|---|---|---|---|---|---|
| | (m³/day ) | | | | | | (m) | |
| Base case (BCS) | 17,808 | 3536 | 0 | 418 | 12,837 | 9,067 | 8.95 | **0.318** |
| S1 | 51,488 | 3,536 | 0 | 9,515 | 220 | 5,995 | 5.45 | -0.13 |
| S2 | 51,488 | 3,536 | 4,596 | 5,930 | 647 | 6,172 | 5.85 | -0.029 |
| S3 | 51,488 | 0 | 0 | 6,636 | 555 | 6,086 | 5.75 | -0.046 |
| S4 | 51,488 | 3,536 | 4,596 | 5,884 | 863 | 6,147 | 5.75 | -0.002 |
| S5 | 45,604 | 3,536 | 4,596 | 3,627 | 2,494 | 6,536 | 6.35 | 0.077 |
| S6* relocating the wells | 45,604 | 3,536 | 4,596 | 4,174 | 1,750 | 6,551 | 6.55 | 0.017 |
| S7* | 34,180 | 3,536 | 4,596 | 1,582 | 6,896 | 7,507 | 7.65 | **0.184** |
| S8* | 34,180 | 3,536 | 0 | 2.325 | 3.465 | 7.237 | 7.4 | **0.058** |

# Particle tracking of the injected water

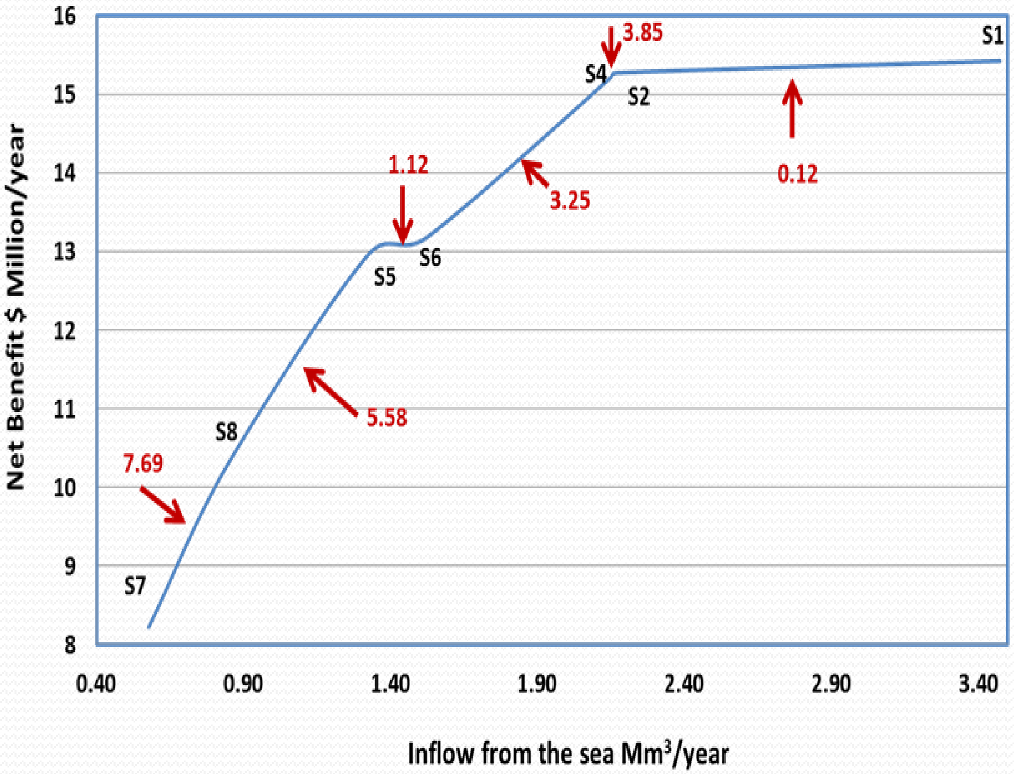
The **forward particle tracking** for the injection wells (Fig. a) and the **backward particle tracking for the public wells** (Fig. b) suggests that the slowly injected TWW primarily flowed in the seaward direction (Fig. a) and the public wells received only pristine water from the aquifer (Fig. b). This result was obtained for all scenarios.



# Economic analysis of the modeled scenarios

An economic analysis using a multi-criteria approach was conducted to gain insight into **the trade-offs between the benefits of MAR and seawater inflow to the aquifer** under the increased abstraction of groundwater for urban use.

**Trade-off between the net benefit from MAR and inflow from the sea.**




| | Criteria 1 | Criteria 2 | Criteria 3 | Criteria 4 |
|---|---|---|---|---|
| | Net Benefit | Inflow from the sea | Decline in water Table | GW level in sea-boundary |
| | $ Million/year | $Mm^3$/year | m | m |
| Base case (BCS) | 1.57 | 0.15 | - | 0.32 |
| S1 | 15.42 | 3.47 | 3.50 | -0.13 |
| S2 | 15.27 | 2.16 | 3.10 | -0.03 |
| S3 | 15.24 | 2.42 | 3.20 | -0.05 |
| S4 | 15.21 | 2.15 | 3.20 | 0.00 |
| S5 | 12.96 | 1.32 | 2.60 | 0.08 |
| S6 | 13.18 | 1.52 | 2.40 | 0.02 |
| S7 | 8.22 | 0.58 | 1.30 | 0.18 |
| S8 | 10 | 0.85 | 2 | 0.058 |

**Scenarios and the criteria for selection**

# Conclusions of Al-Khoud case Study

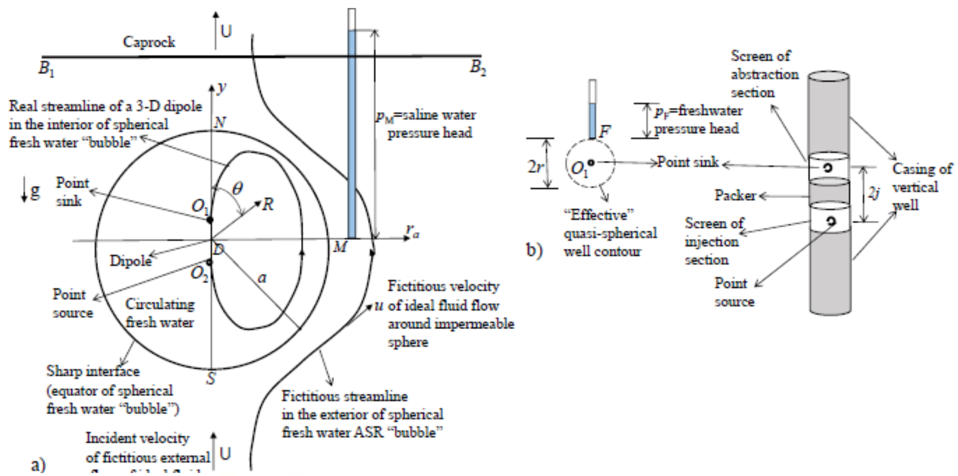
- The results show that by managing irrigation wells and relocating public wells in conjunction with MAR practices, the abstracted volume for drinking purposes can be increased by 2 times.
- With the help of MAR, the hydraulic gradient was maintained in the seaward direction (1.2E-4) regardless of the increased stress on the aquifer (for the base case, the gradient is 6.4E-4).
- Even though the cost of TWW injection is high, it is found to result in large benefits. The results show that managing the aquifer **would produce a net benefit ranging from $8.22 million (Scenario 7) to $15.21 million (Scenario 4) compared to the current practice**. Opting for higher benefits entails accepting higher volumes of seawater inflow. This necessitates exploring the associated risk to the aquifer over the long term.
- MAR using TWW is a feasible solution to develop water resources in arid regions and the best scenario depends on the decision maker's preference when weighing the benefits from MAR and the level of damage to the aquifer. **MAR was found to help manage stressed aquifer systems in arid zones to maximize the benefits of using the groundwater for urban supply (instead of costly desalinated water) with minimal damage to the aquifer.**

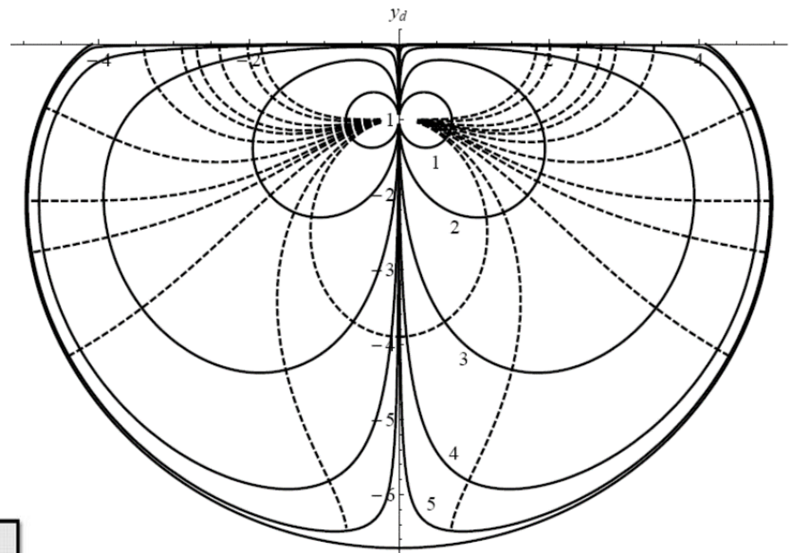
# Case 3: Aquifer Storage and Recovery of excess desalinated water (Optimization with multi-objective functions)

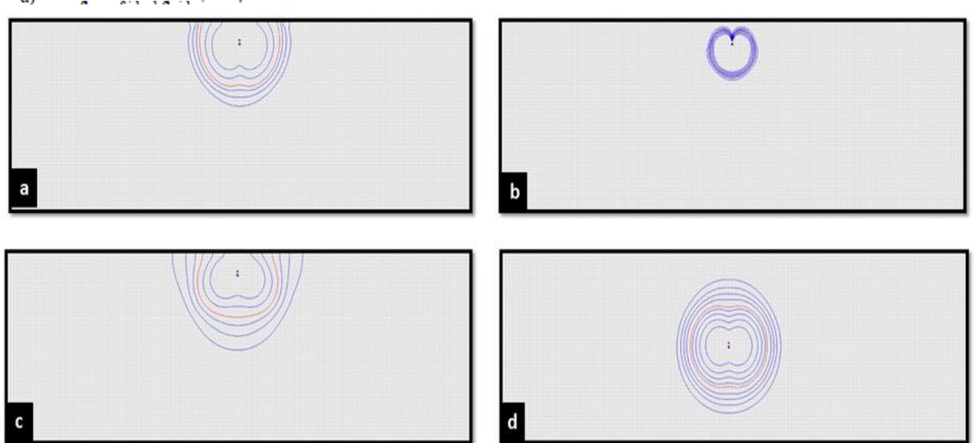
- The work estimates the benefits of optimal conjunctive use of groundwater and desalinated water by recharging seasonal surplus desalinated water to Al-Khoud aquifer.
- The methodology consisted of coupling a numerical groundwater flow simulation model with a dynamic multi-objective optimization model.
- The results show that the suggested conjunctive management of the aquifer using **dual recharge/abstraction wells** plays an important role in reducing the wasteful disposal of the excess desalinated water.
- The potential net benefit of injection and recovery of the desalinated water in the aquifer might **reach up to $ 17.80 million/year.**
- The maximum profitable volume that can be recharged in the aquifer, given the limited number of wells and their location, is estimated **at 8.40 Mm³/year,** lower than the current excess estimated at 10 Mm³/year.

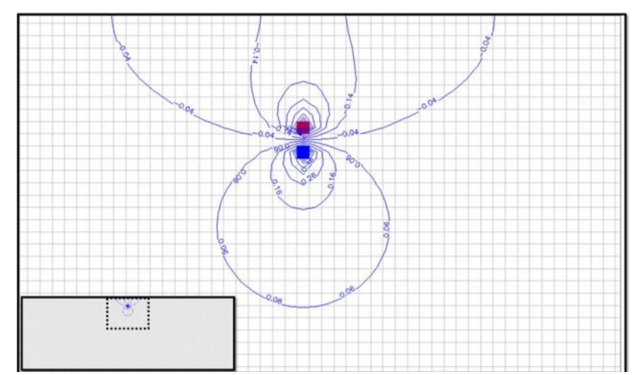
# Case 4:Dipolic Flows: ASR in Saline Aquifer

**In this case study, we utilized analytical and numerical solutions for steady-state flows generated by a fresh water dipole making a fresh water lens in saline water. The problems solved are of theoretical interest because we assumed a close proximity of the inlet and outlet of the injection and abstraction wells and a continuous steady flow with equal rates. Real ASR systems have a cyclic operation, i.e., periods of storing (excess) fresh water alternate with periods in which the stored water is abstracted for use**



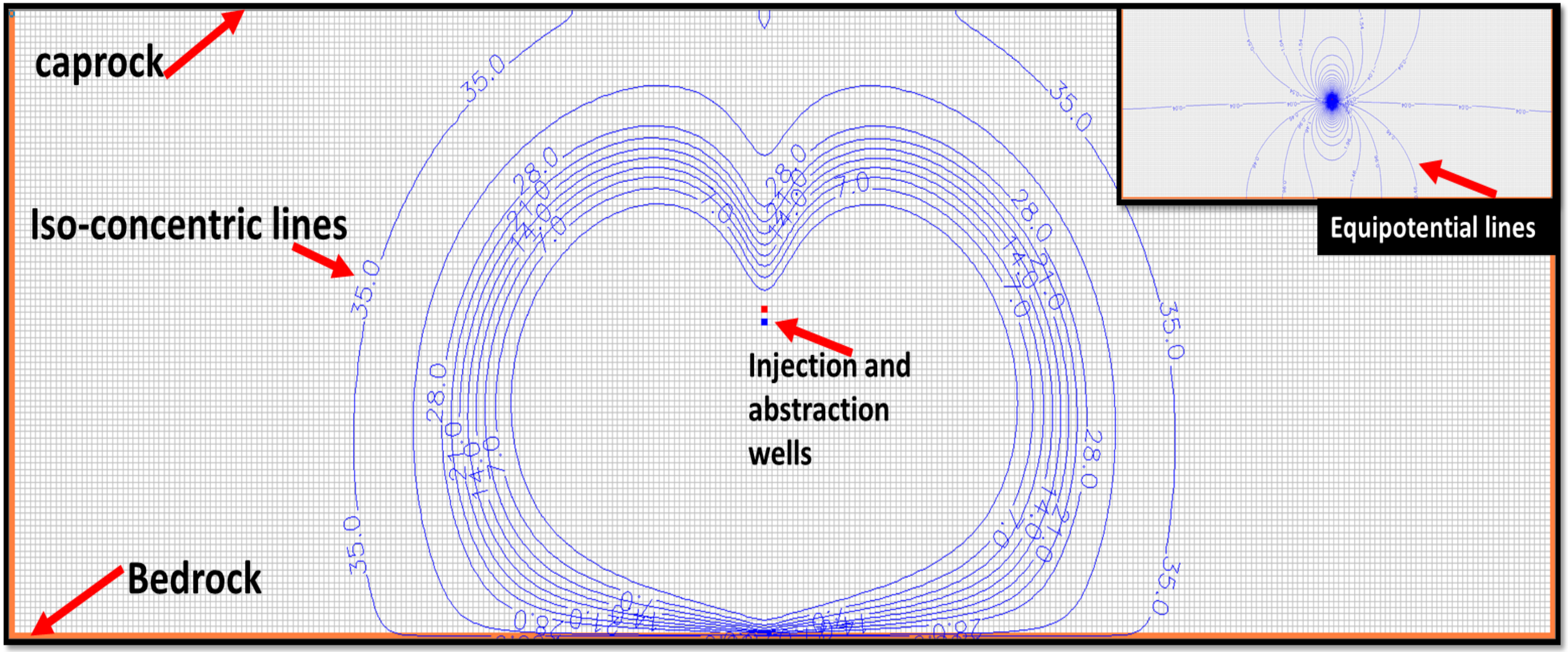



# Dipolic Flows: ASR in Saline Aquifer cont.

**Ongoing research:**

Aquifer with small thickness: freshwater bubble between the confining beds



# Acknowledgement

- **This study was supported by a grant from USAID-FABRI, project contract: AID-OAA-TO-11-00049 (project code: 1001626 – 104). The authors also acknowledge the support of the Sultan Qaboos University, Oman. Acknowledgement is also extended to:**
- **Ministry of Regional Municipalities and Water Resources, Oman**
- **Public Authority for Water, Oman**
- **Oman Water Society - Oman**
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- **Slim Zekri, SQU, Oman**
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- **Mustafa El-Rawy, Minia University, Egypt**
- **Osman Abdalla, SQU, Oman**
- **Rashid Al-Abri, Oman Water Society and MRMWR, Oman**
- **Chefi Triki, SQU, Oman**
- **Mohammad Reza Bazargan--Lari, Islamic Azad University, Iran**

# Thanks