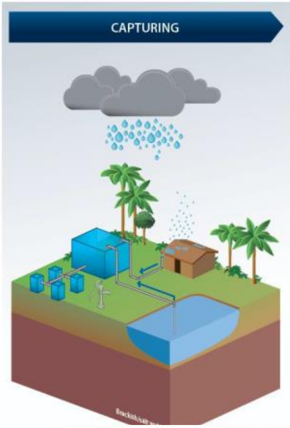

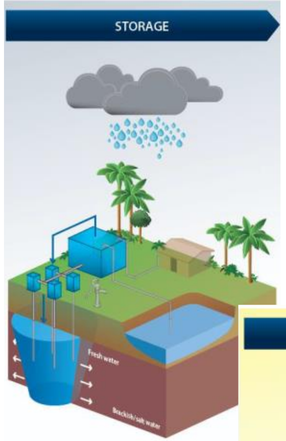

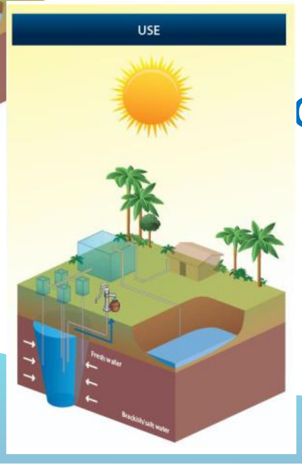

Feasibility And Site Investigation Study For Artificial Aquifer Storage And Recovery Applications For Water Supply In Arid Areas: Case Study From Oman

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Overview

- Introduction about the ASR Project
- Project Scope and Objectives
- Methodology
- Results
- Main conclusions

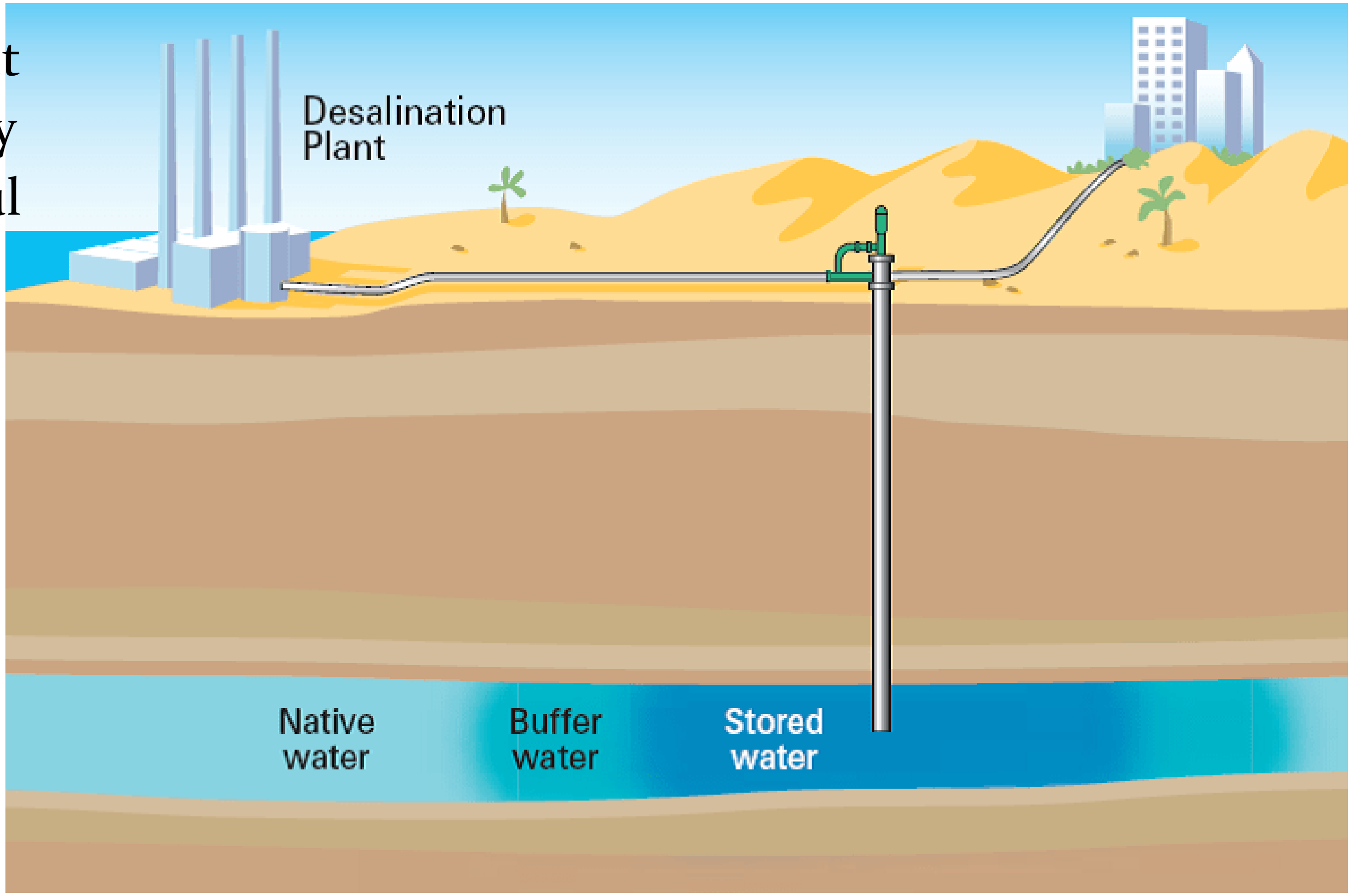
Introduction

- Sultanate of Oman – ASR as a strategic project
- Desalination of seawater for freshwater supply
- Episodic problems with seawater (e.g. harmful algae, oil spills) affect intake
- Extreme weather events (e.g. cyclones) affect energy supply
- Peak demand vs peak supply causes overproduction

Need to store (bank) desalinated water in aquifers for use during emergency and peak demand time

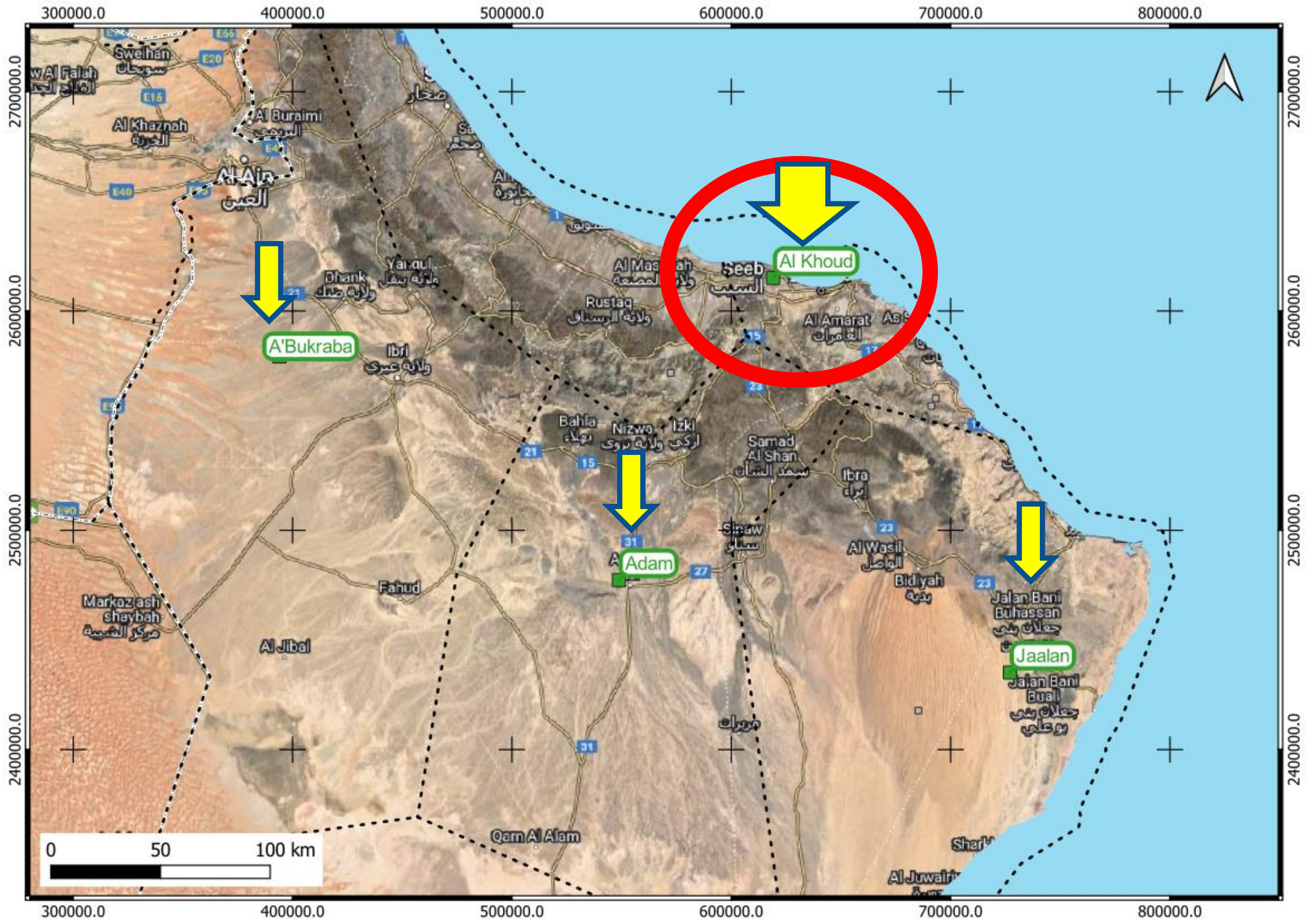
→ enhance drinking water supply security

→ reduce energy costs



Introduction

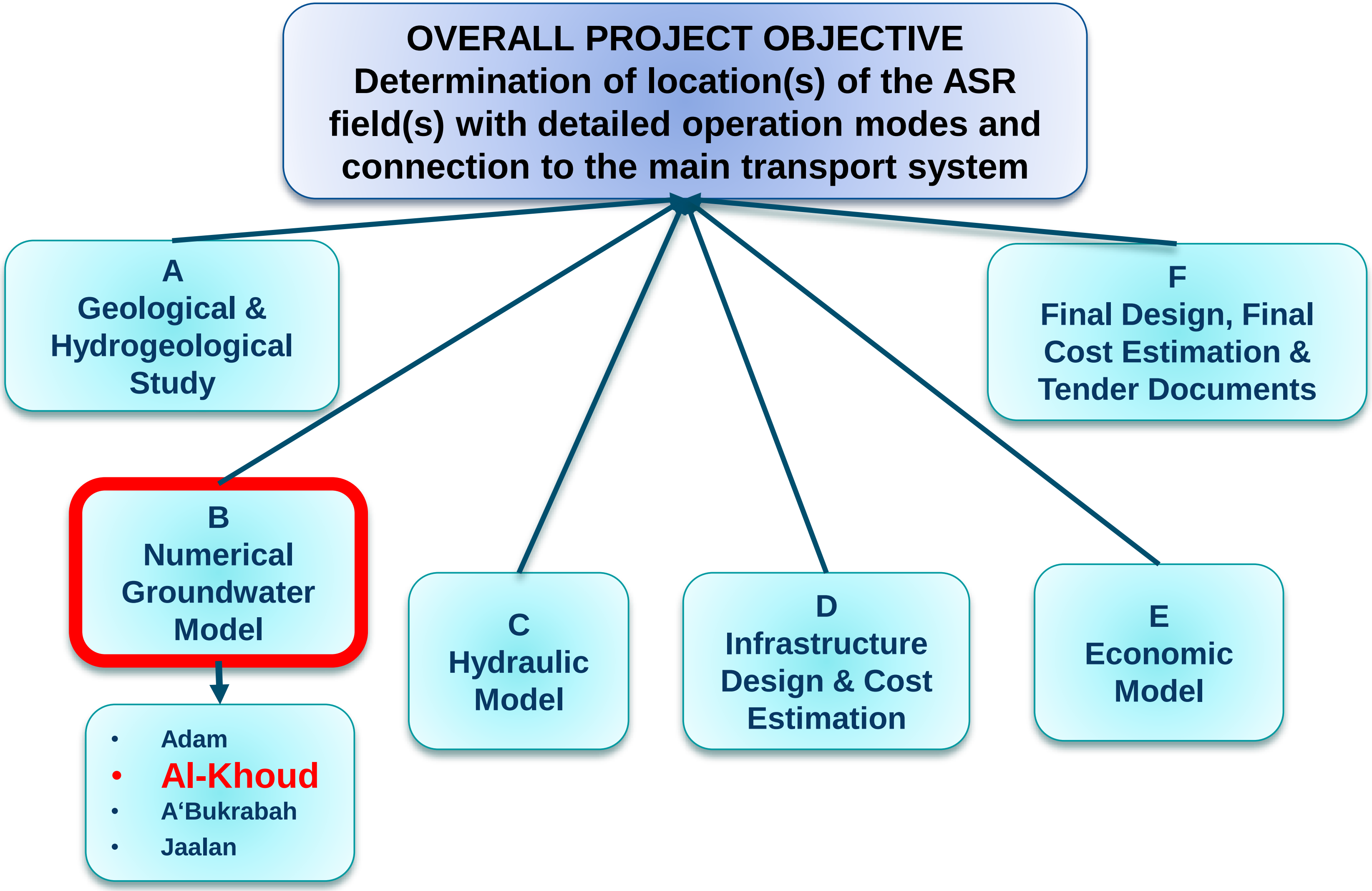
- **Feasibility study of ASR operation in Oman**
- **4 potential ASR sites selected in pre-feasibility study**
- **Hydrogeological analysis of ASR sites**
- **Hydraulic analysis of transportation system**
- **Wellfield design of potential ASR sites**



- **Investment cost estimation and economic analysis → *Technical and economic analysis of feasibility of ASR sites***

PROJECT SCOPE AND OBJECTIVES

- The goals of the Groundwater modelling phase are:
- to test suitability of the selected ASR sites;
- to analyze operational scenarios and optimize well field design of implementing ASR schemes;
- to predict the hydrochemical and hydraulic impacts of ASR operation on the aquifer system;
- to provide inputs for the hydraulic model and economic model to assess technical and economical feasibility of ASR operation at each site.



IMPORTANCE OF GROUNDWATER MODELING FOR ASR PROJECTS

- The groundwater model will provide insights in the amount of fresh water (% of the available surplus of the desalination plant) that can be injected and stored at the selected ASR site and the amount of water that can be recovered during a calamity (emergency scenario) or during a period of high demand (normal operational scenario), within the given conditions and criteria.

ASR Scenarios and Criteria

1. **ASR operational scenarios**

The **design horizon for the groundwater modelling is 2045** under the following operational scenarios for ASR :

- **Emergency scenario: 13 weeks injection – 6 weeks rest – 6 weeks recovery (same volume of water as injection) – 27 weeks rest**
- **Normal operational scenario: 13 weeks injection – 26 weeks rest – 13 weeks recovery (same volume of water as injection)**

2. **Available amount of water to be injected**
3. **Available areas for ASR**

ASR locations and available area.

ASR location	ASR area (km²)	ASR perimeter	Wellfield Protection Zones
Al Khoud	3.0	1.8 x 0.9 + 2.0 x 0.7 km	Within highly protected zone
Adam	6.0	2.5 x 2.4 km	Partly within highly restricted zone, partly within restricted zone
A'Bukrabah	6.0	3.5 x 1.7 km	Within highly protected zone
Jaalan	5.0	5.0 x 1.0 km	To be defined

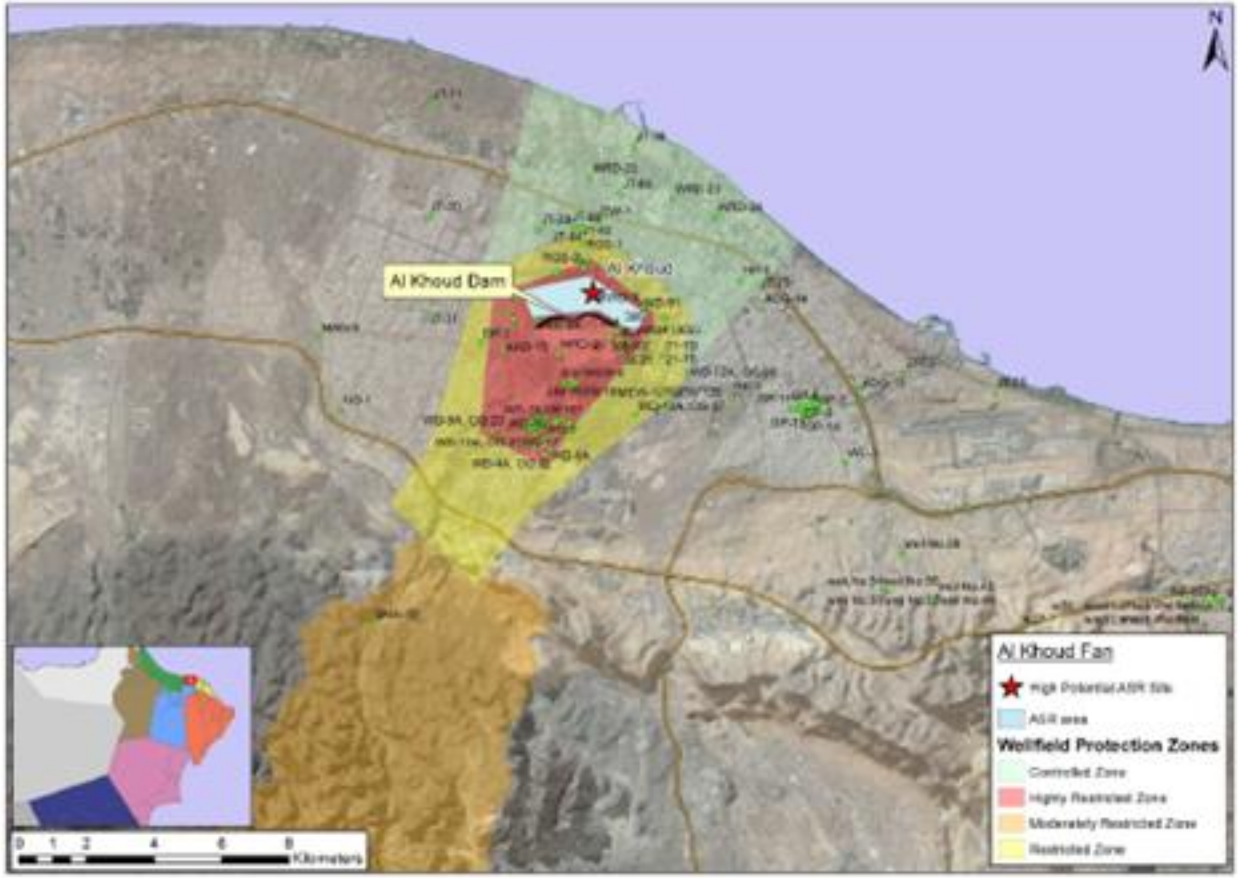
Maximum available amount of surplus water in 2045 (low peak time)

ASR location	Supply system	Supply zone	Surplus m^3/month	Surplus m^3/hour
Al Khoud		Muscat	4,704,000	7,000
Adam	Main Interconnected System	Barka	10,052,000	14,958
A'Bukraba	Main Interconnected System	Sohar	5,152,000	7,667
Jaalan	Ash-Sharqiyah System	Sharqiyah	2,632,000	3,917

ASR operational design criteria- Al Khoud Site

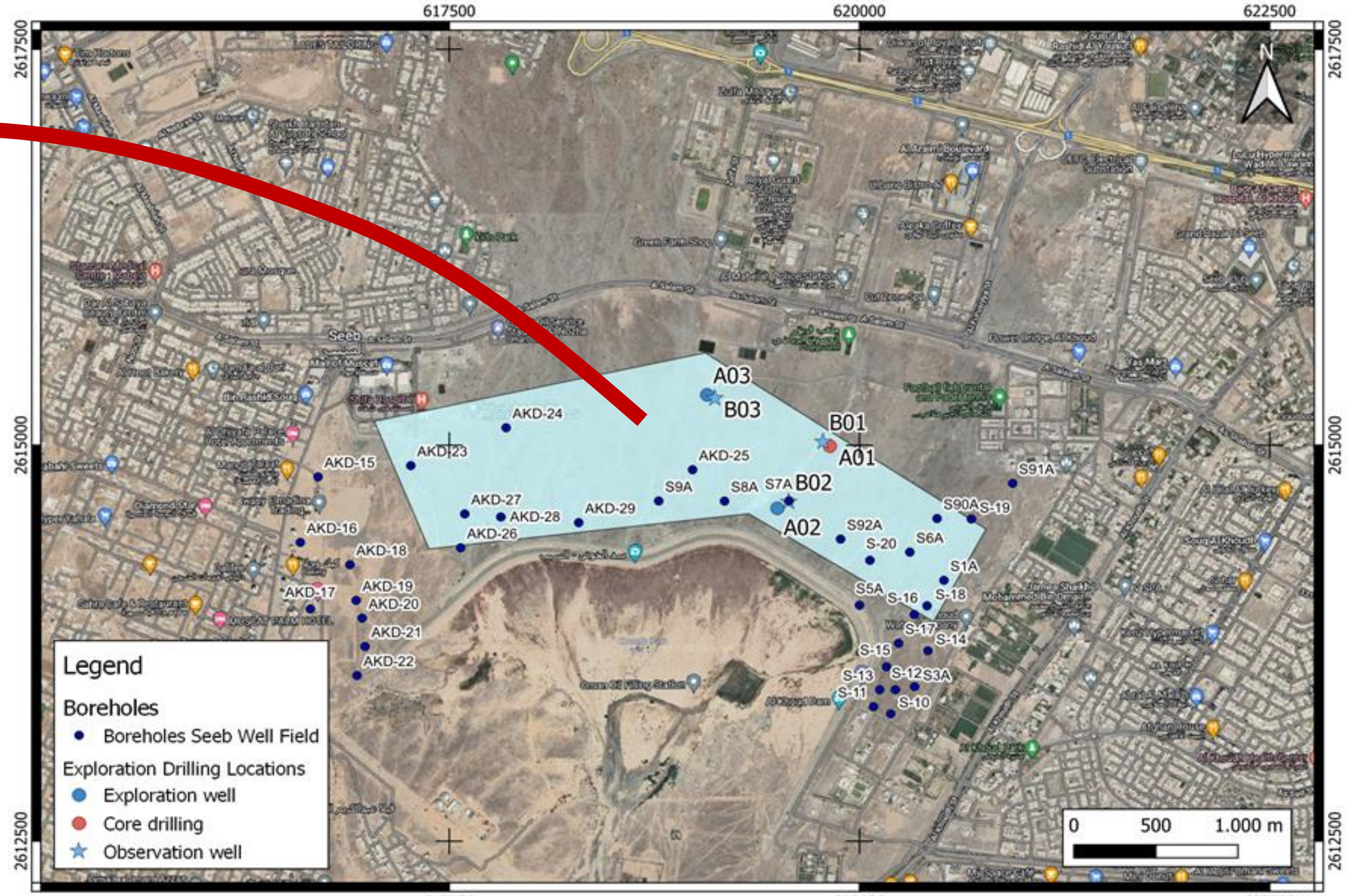
Constraints for sustainable ASR system:

1. **The ASR wells should be located within the ‘highly protected zones’ (right Figure) and within the available ASR area (previous slide) as defined during the pre-feasibility study.**
2. **During the injection phase (storage) of ASR operation, the groundwater level in a phreatic aquifer should never rise above 5 meter below ground level.**
3. **During the abstraction phase (recovery) of ASR operation, the groundwater level (or head) in the aquifer should never fall below:**
   - **half of the saturated aquifer thickness; and**
   - **5 meter above the top of the (upper) well screen.**



ASR Al-Khoud Site

- Recharge Dam [total storage capacity of 11.6 Mm^3, designed recharge rate is about 4 Mm^3 but studies showed for first 10 years 2 Mm^3/year]
- Public water supply wells [70 public water supply wells with an average well depth of 90 m with a total abstraction of 14 Mm^3 in 2020, OWWSC]
- Private wells [15 Mm^3/ year and 1.3 Mm^3 farms]



Map of ASR site Al Khoud, with the project wells (test wells A01, A02, A03 and monitoring wells B01, B02/S-7A, B03) and the Seeb well field (S-##) and Al Khoud Dam well field (AKD-##).

Project test wells at Al Khoud

- Short-term step-drawdown pumping test and long-term pumping test and recovery tests were conducted at project wells A01, A02 and A03.

- All pumping wells showed good yields.

Project test wells

Well ID*	Type	Easting	Northing	Ground level (masl)	Drilled depth (mbgl)	Water strikes (mbgl)	Well depth (mbgl)	Screened depth (mbgl)	Internal diameter (uPVC)	Drilled diameter
A01	Test well	619819	2614994	24.4	85	41, 52, 71	83	50.5 - 80.0	254 mm (10”)	444.5 mm (17.5”)
	+ core drilling	619819	2614994	24.4	100					101.6 mm (4”)
B01	Obs. well	619776	2615022	24.7	85	34, 45, 51	83	50.5 - 80.0	101.6 mm (4”)	215.9 mm (8 ½”)
A02	Test well	619499	2614602	28.3	85	44, 51, 73	83	50.5 - 80.0	254 mm (10”)	444.5 mm (17.5”)
S-7A / B02	Obs. well **	619568	2614643	28.1	85		81			
A03	Test well	619071	2615319	24.3		37, 53, 72	83	50.5 - 80.0	254 mm (10”)	444.5 mm (17.5”)
B03	Obs. well	619118	2615297	24.5	85	35, 43, 51	83	50.5 - 80.0	101.6 mm (4”)	215.9 mm (8 ½”)

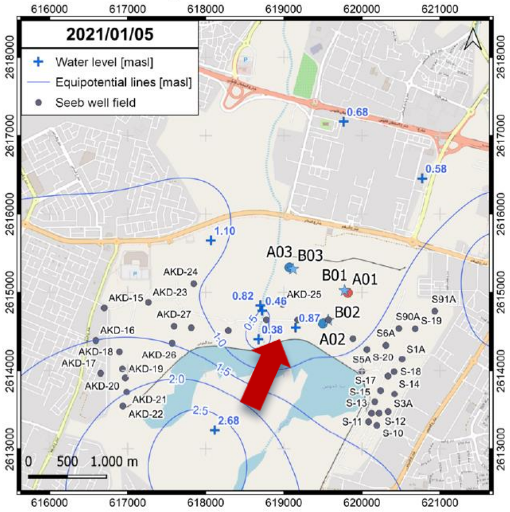
Pumping Test data by the Project

Well ID	EC * [µS/cm]	SWL [mbgl / masl]	Q [m^3/h]	DD [m]	T [m^2/d]	S	L [1/d]	Remarks
A01	802 / (970)	23.13 / 1.27	104.4	0.63	5832	1.4 E-03	0.0182	Leaky aquifer, no well losses observed
B01	(800)	23.16 / 1.44		0.26				Observation well located 51 m northwest of A01
A02	729 / (732)	27.42 / 0.78	117.2	2.42	3698	1.0 E-04	0.0025	Leaky aquifer, moderate well losses observed
S-7A / B02		27.08 / 1.02		0.34				Well S-7A is located 80 m northeast of A02
A03	1180 / (1287)	22.74 / 1.46	108.7	4.84	4121	1.0 E-04	0.0004	Leaky aquifer, moderate well losses observed
B03	(785)	22.79 / 1.71		0.46				Observation well located 52 m east of A03

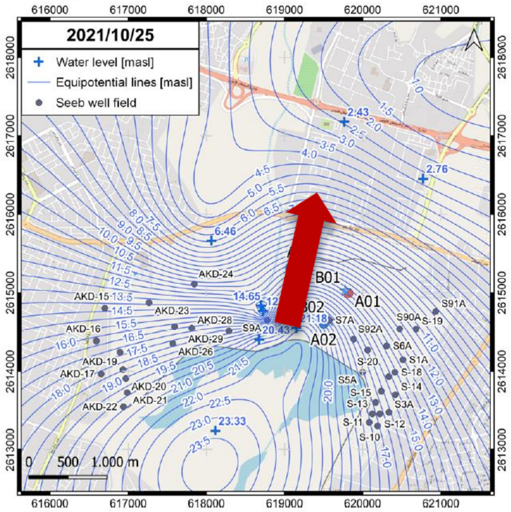
Groundwater Level and Flow

Equipotential lines of groundwater level (in masl) at Al Khoud.

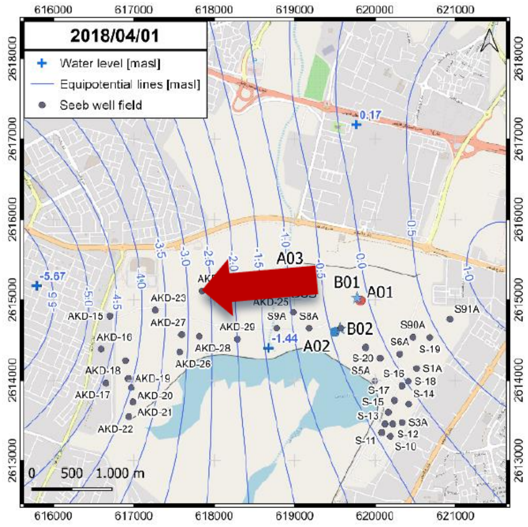
No water stored in dam: 0.2 ‰
(05/01/2021)



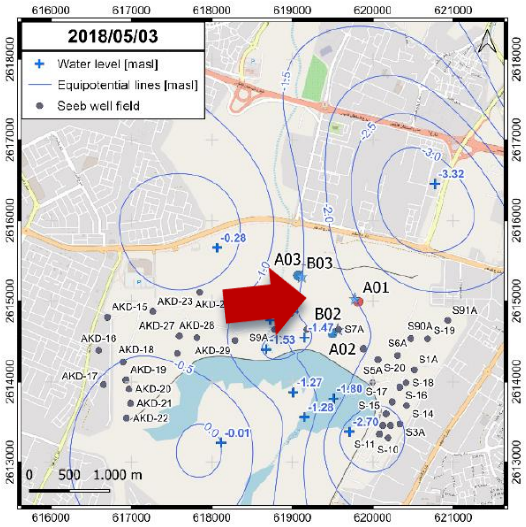
Water stored in dam: 9.0 ‰
(25/10/2021)



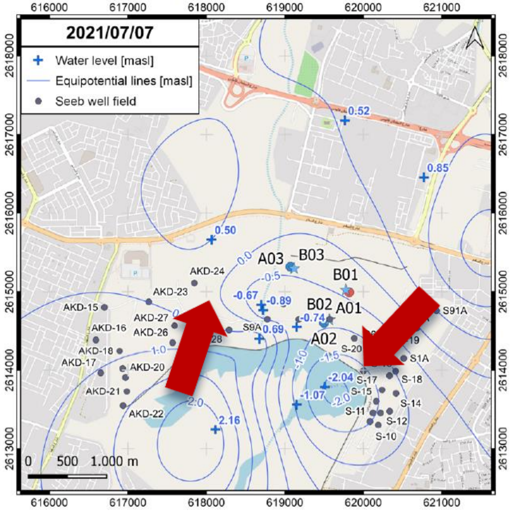
Groundwater flow towards the West



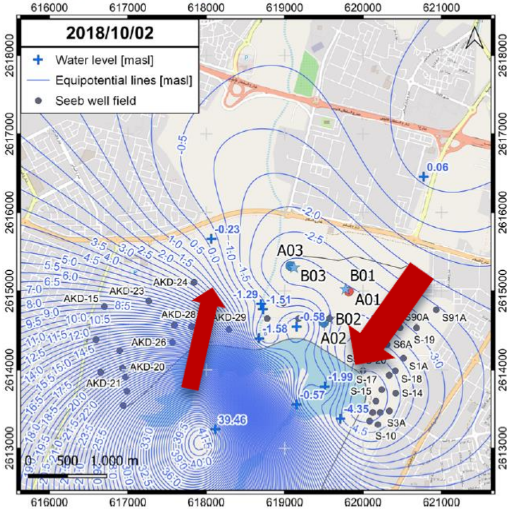
Groundwater flow towards the East



No water stored in dam: -1.2 ‰
(07/07/2021)

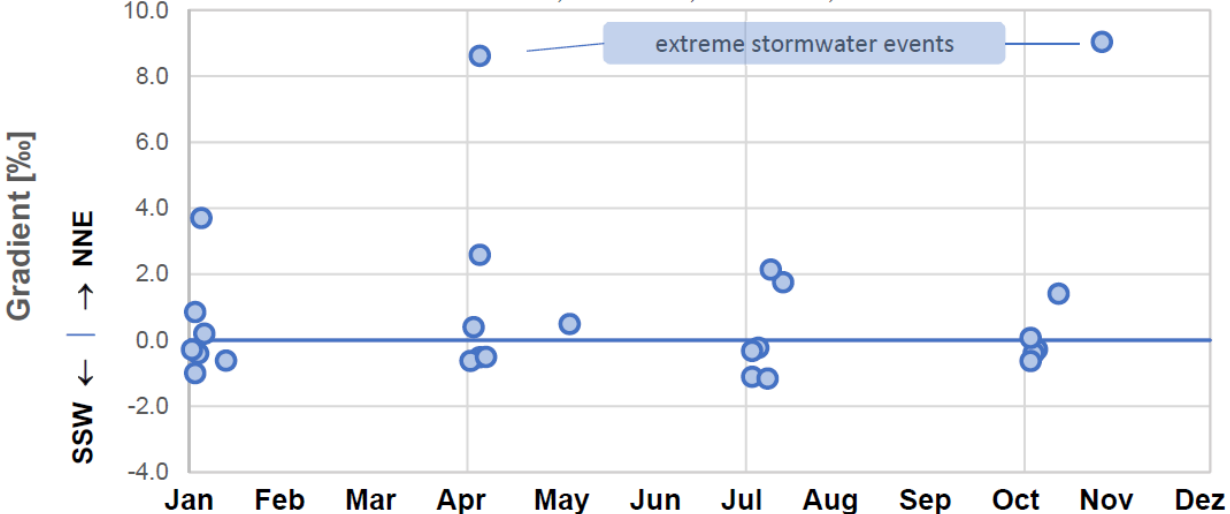


Water stored in dam: 0.1 ‰
(02/10/2018)



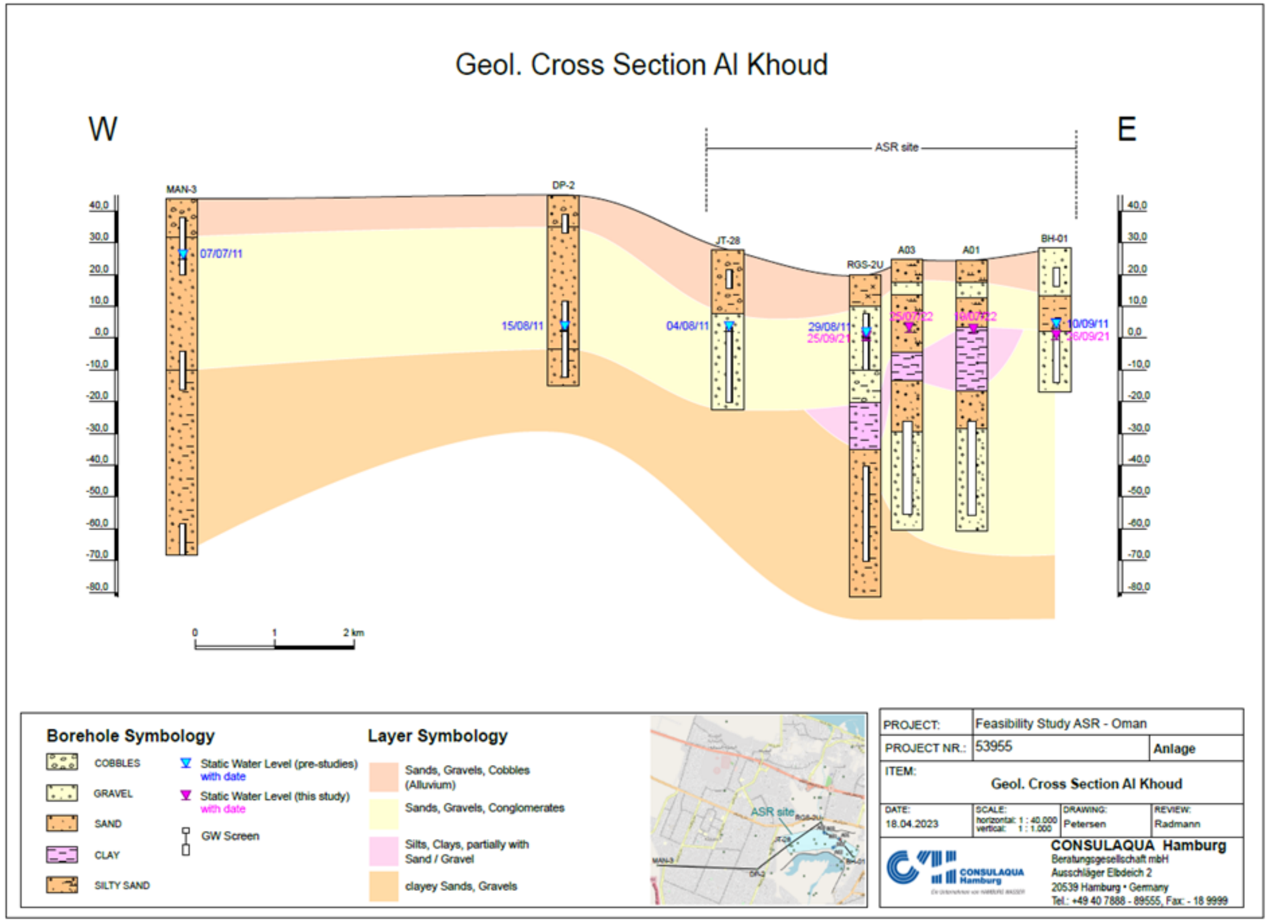
Hydraulic gradients 2016 - 2022

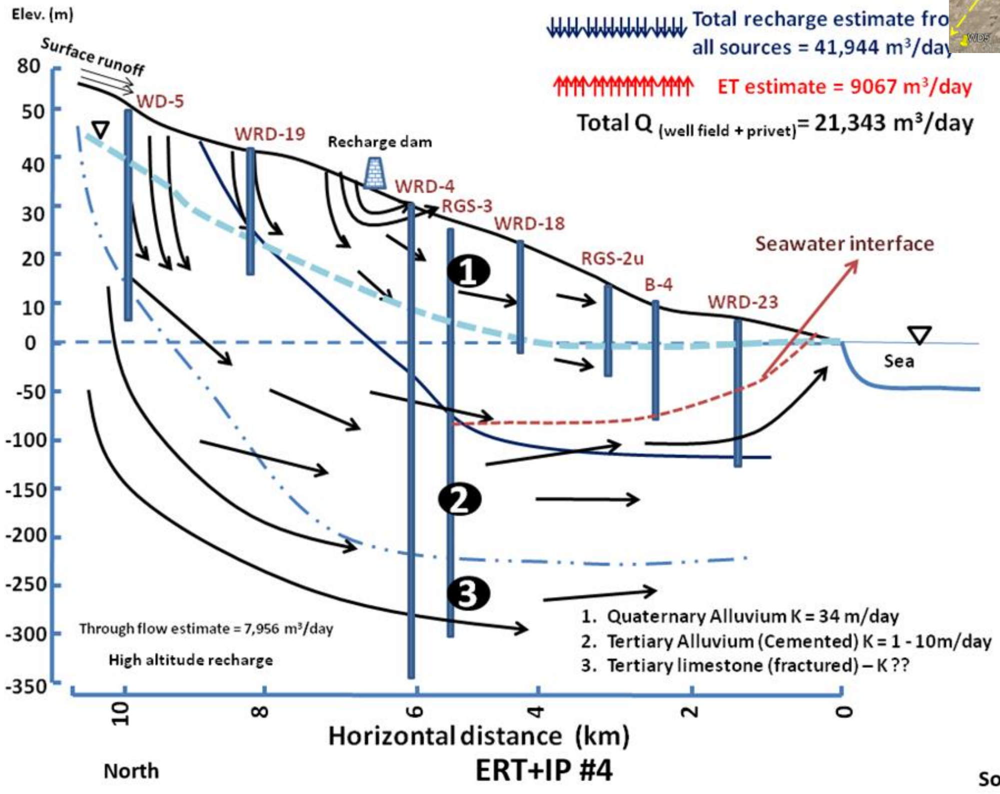
Mean: 0,89 ‰ NNE, median: -0,25 SSW

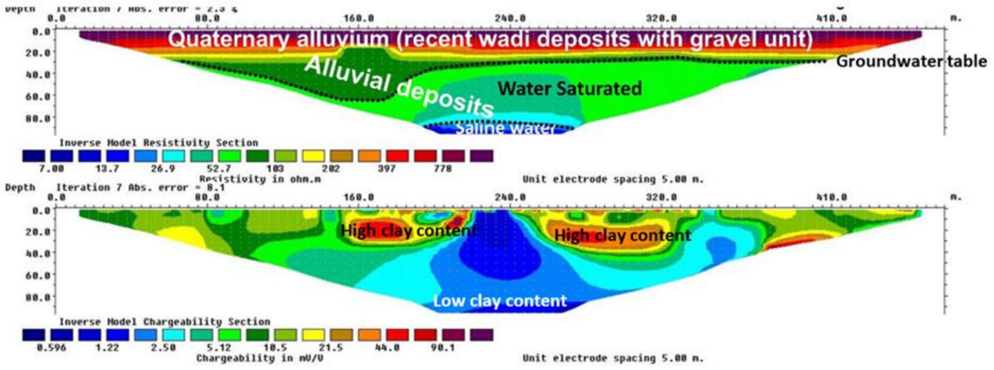


Conceptualization of the Groundwater System based on the hydrological and geophysical investigations

Hydrogeological cross section (W-E) at ASR site Al Khoud and project test wells







Operational Design Criteria

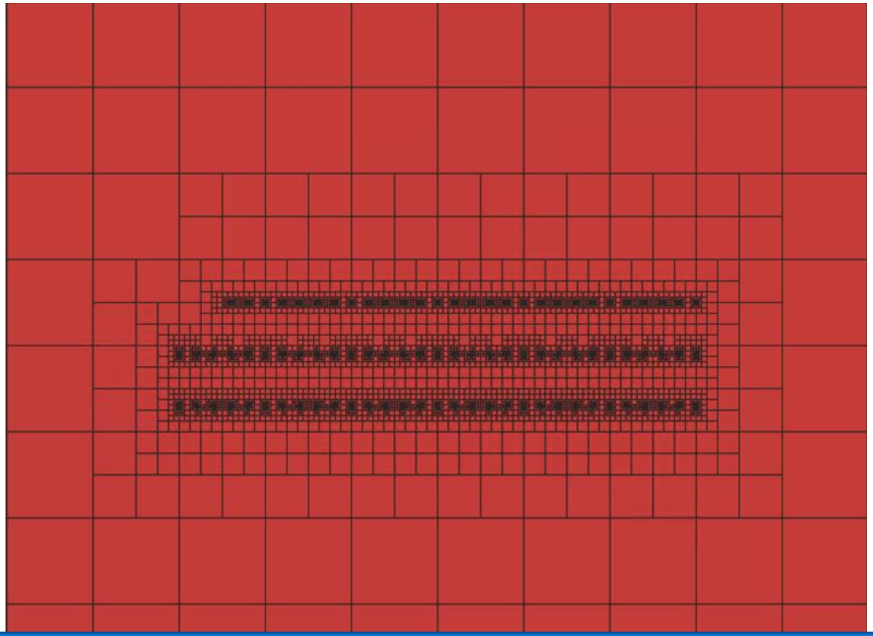
Considering the three well-field constraints, the ASR operational design criteria for Al Khoud are:

1. The wells should be located within the available ASR area of 3.0 km2 measuring approximately 1.8 x 0.9 km plus 2.0 x 0.7 km.
2. During the injection phase (storage) of ASR operation, the head/groundwater level (SWL = 24 mbgl) in aquifer 1 should not rise more than 19 m, in order to stay below 5 mbgl.
3. During the abstraction phase (recovery) of ASR operation, the head/groundwater level in Aquifer 1 should
   - **not fall more than 88 m (from 24 mbgl to 200 mbgl) in order to remain >50% of the aquifer thickness (176 m) saturated; and**
   - **not fall more than 21 m (from 24 mbgl to 45 mbgl) in order to stay 5 meters above the top of the (upper) well screen (at 50 mbgl).**

The most critical situation under standard operating conditions is the injection, during which the maximum drop in head should be less than 21 m. In the emergency scenario, the abstraction of the same volume of water during 6 weeks would be critical, as the fall in head should not exceed 21 m.

Well field design option investigated with the regional groundwater model

Grid regional groundwater model around Al-Khoud well field, refining from 500m to 0.25m



Design option	# of wells	Duration	Volume	Well placement	Comments
Evenly distributed wells					
Ia	90	13 weeks	Injection 14.1 Mm^3 (100%)	2 rows of 31 wells, 1 row of 28 wells	Normal operational scenario: 72 m^3/hr injection
Ib	90	6 weeks	Abstraction 14.1 Mm^3 (100%)	2 rows of 31 wells, 1 row of 28 wells	Emergency scenario: 155 m^3/hr abstraction

Model-layer	Type layer	Bottom layer [mbgl]	Thickness [m]	kh [m/d]	kv [m/d]	Storativity [-]
	top	-24				
1	aquifer 1a	-30	6	50	10	0.20
2	clay layer	-31	1	0.001	0.001	2.82E-06
3	aquifer 1b	-50	19	50	10	4.51E-05
4	aquifer 1c (screened)	-80	30	50	10	5.28E-05
5	aquifer 1d	-200	120	20	5	1.00E-05

Volumes and required rates during ASR operational scenarios for Al Khoud

ASR Al Khoud during a year	Total volume	Duration of period	Average rate
General use of ASR (normal operational scenario)			
injection	14,112,000 m^3	13 weeks	+6,462 m^3/h
rest	0 m^3	26 weeks	
abstraction	14,112,000 m^3	13 weeks	-6,462 m^3/h
rest	0 m^3	0 weeks	
ASR during calamity (emergency scenario)			
injection	14,112,000 m^3	13 weeks	+6,462 m^3/h
rest	0 m^3	6 weeks	
abstraction	14,112,000 m^3	6 weeks	-14,000 m^3/h
rest	0 m^3	27 weeks	

Density Flow Model Alkhoud – Low Gradient

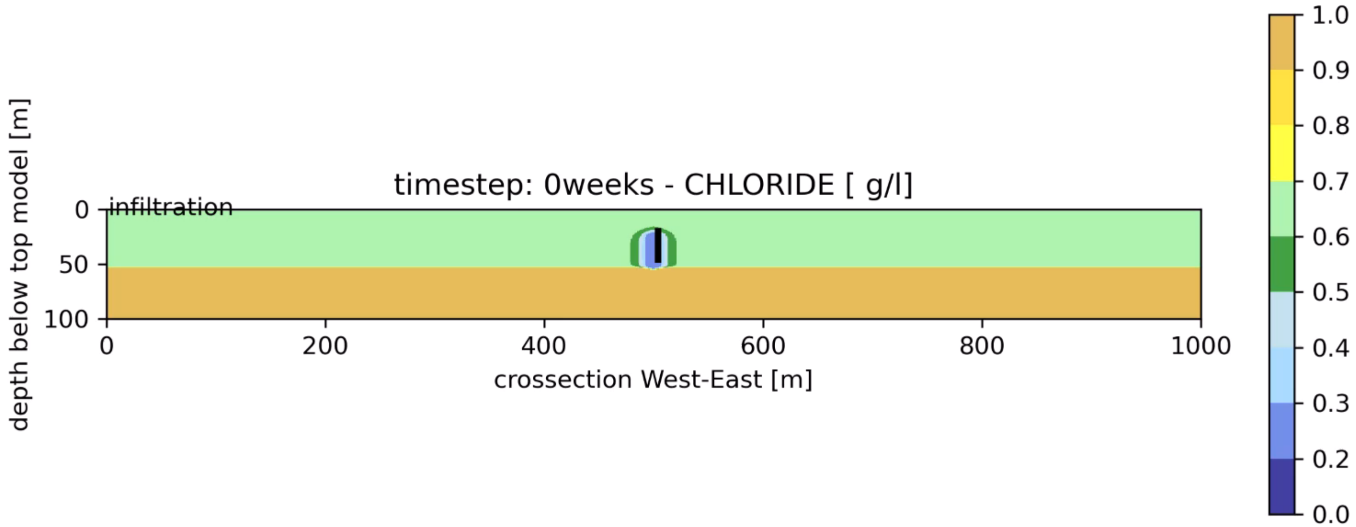
Density flow model one well: normal operational scenario:

1 well with 70 m^3/hour injection (152,900 m^3 in 13 weeks)

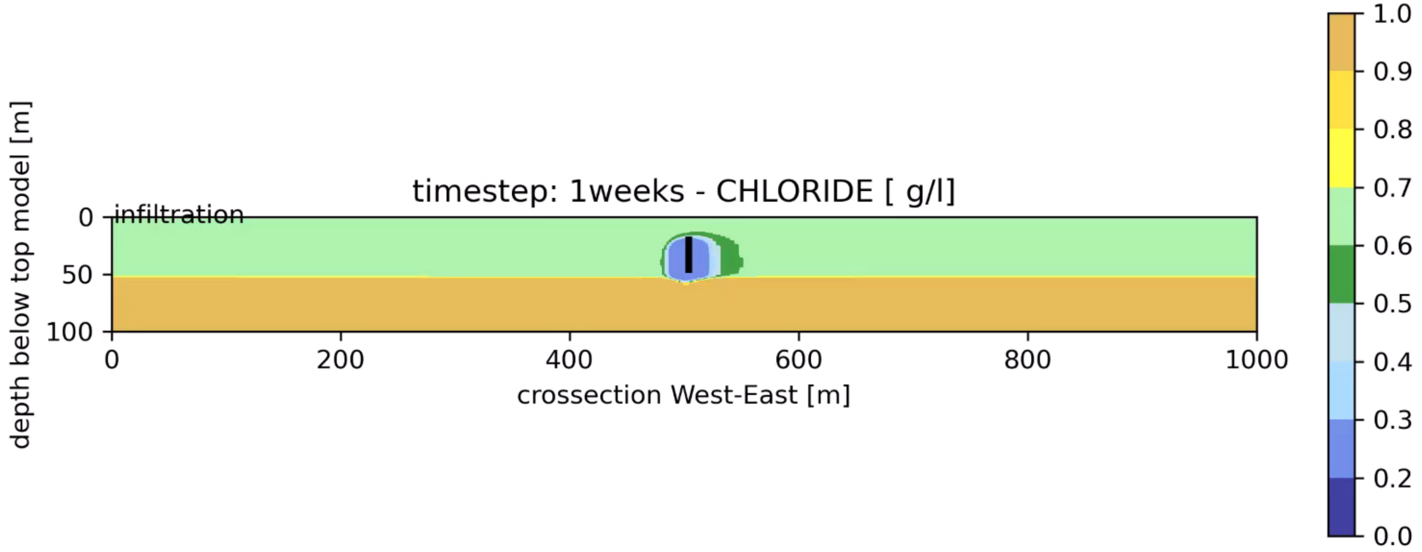
Two scenarios:

Low gradient, gw flow towards the sea - One well - Hydraulic gradient = 0.0002 (no water stored in Al Khoud recharge dam)

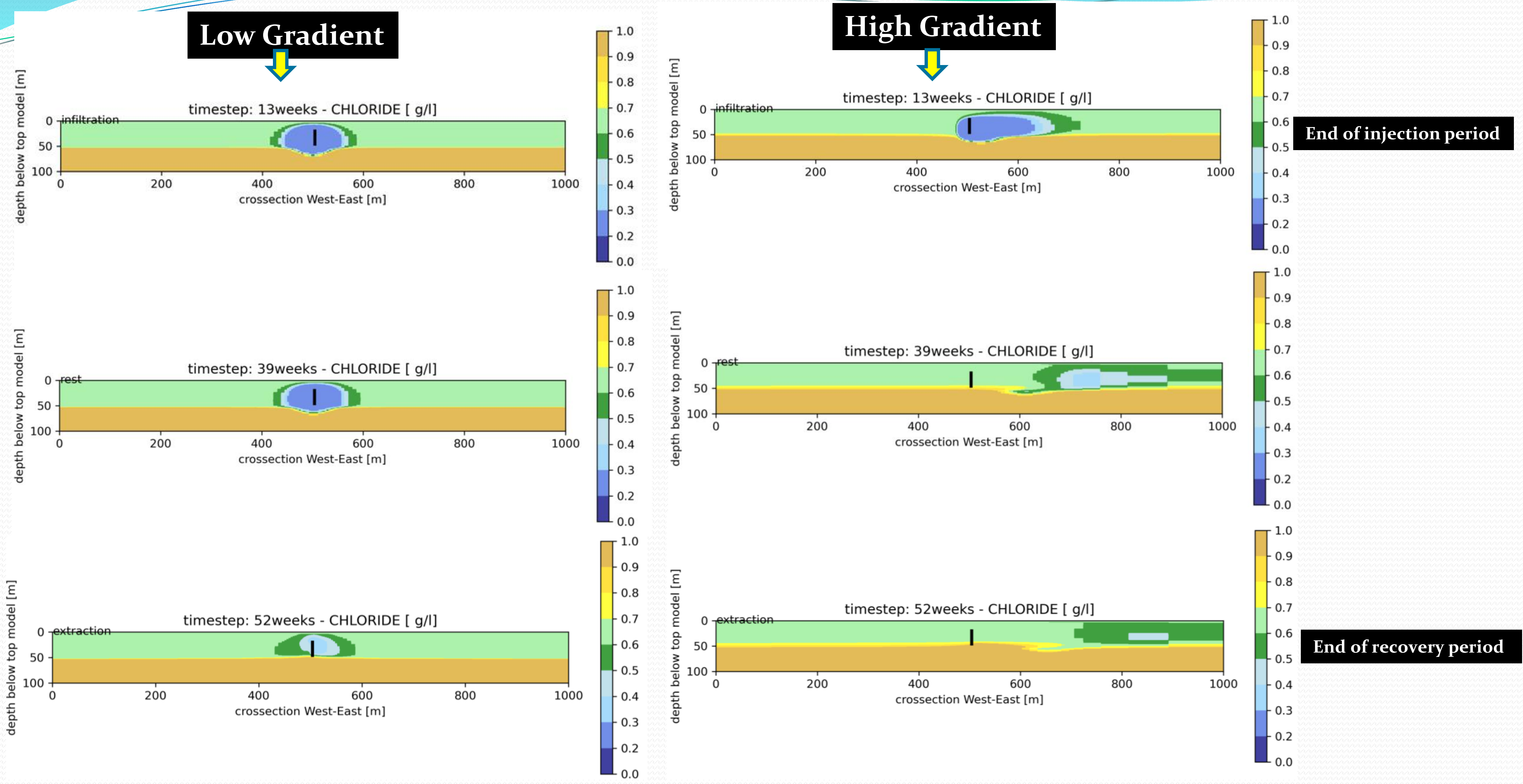
High gradient, gw flow towards the sea, One well - Hyraulic gradient = 0.01 (Al Khoud recharge dam is full)



Density Flow Model Alkhoud – High Gradient

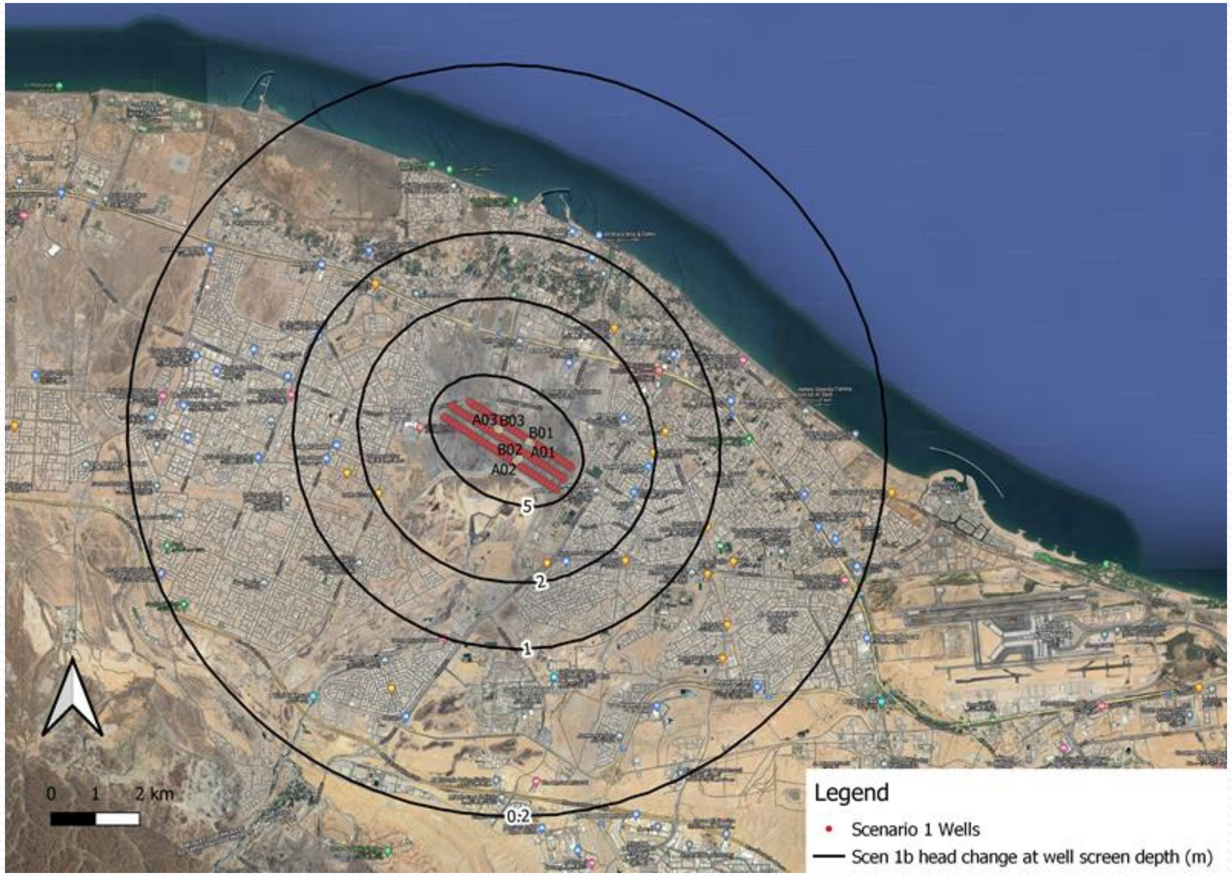


Density Flow and Transport Model

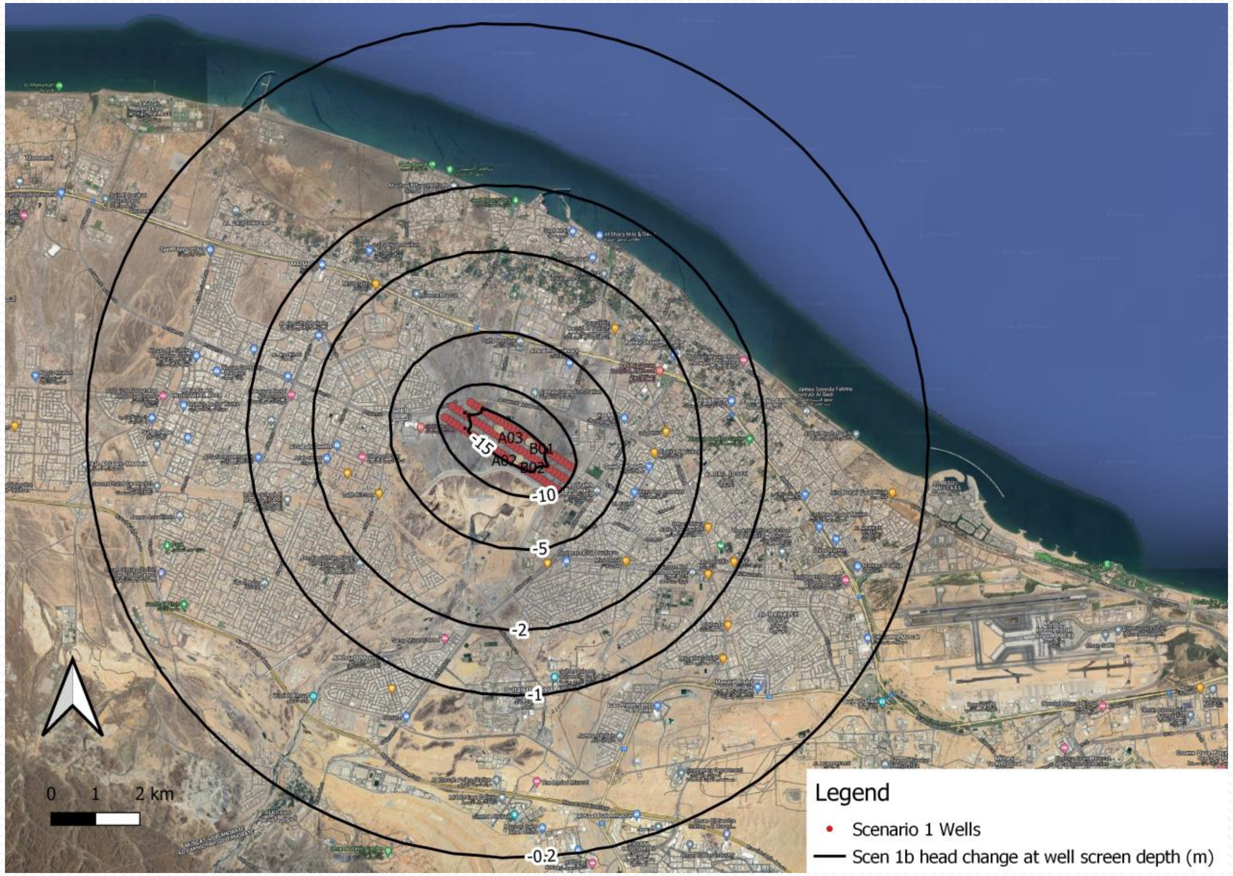


Contour Lines of Change in Head

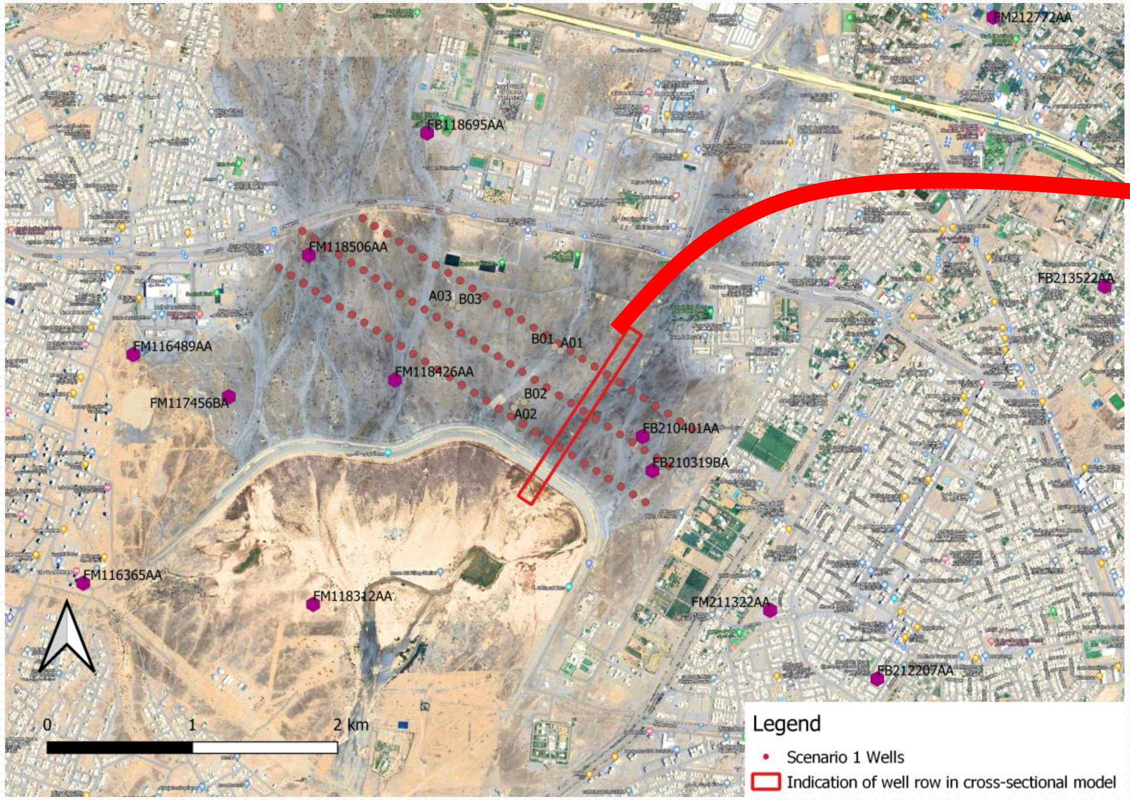
90 wells evenly distributed along 2 rows of 31 wells, and 1 row of 28 wells. Change in head (in m) at the well screen depth (model layer 4) at the end of 13 weeks injection (72 m3/hr per well) of in total 14.1 Mm3.

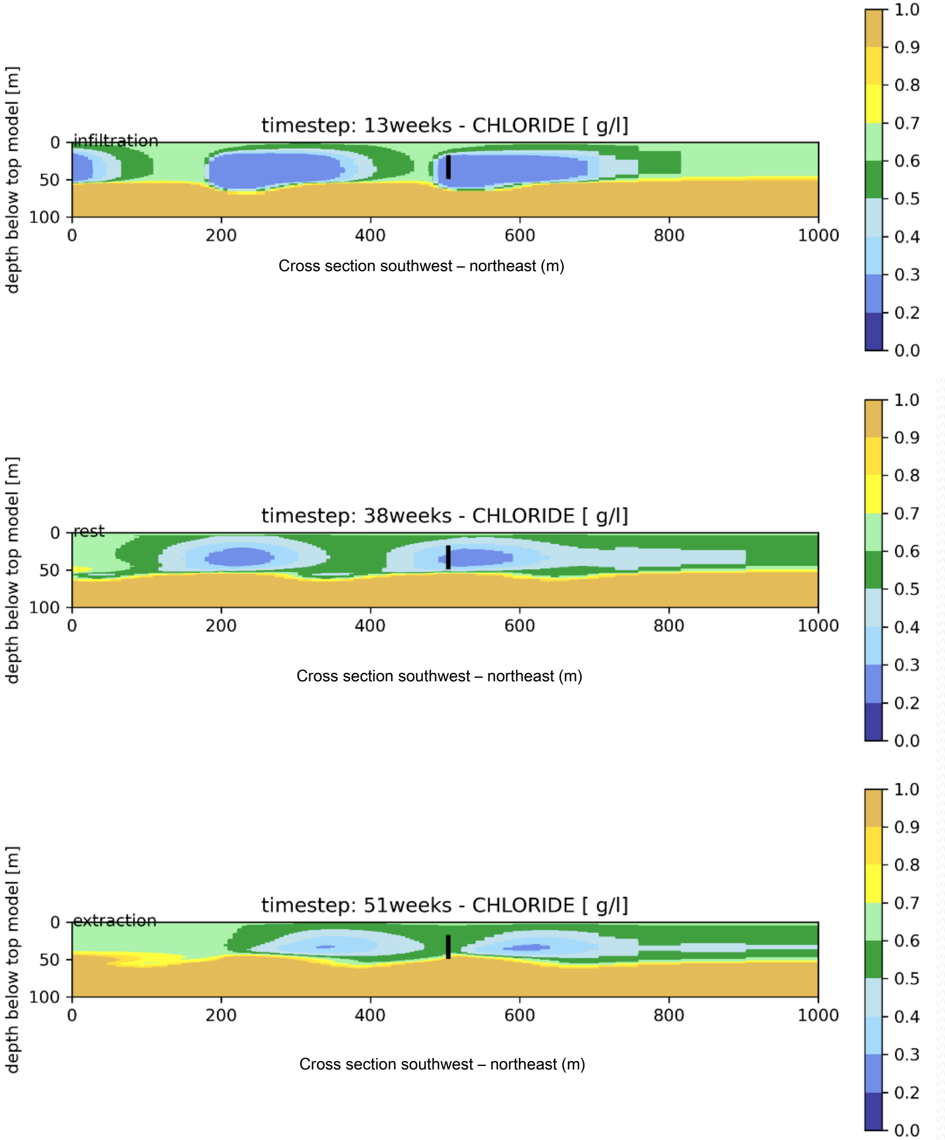


90 wells evenly distributed along 2 rows of 31 wells, and 1 row of 28 wells. Change in head (in m) at the well screen depth (model layer 4) at the end of 6 weeks abstraction (155 m3/hr per well) of in total 14.1 Mm3 in the emergency scenario



Visualization of 3-well row used in cross-sectional model run

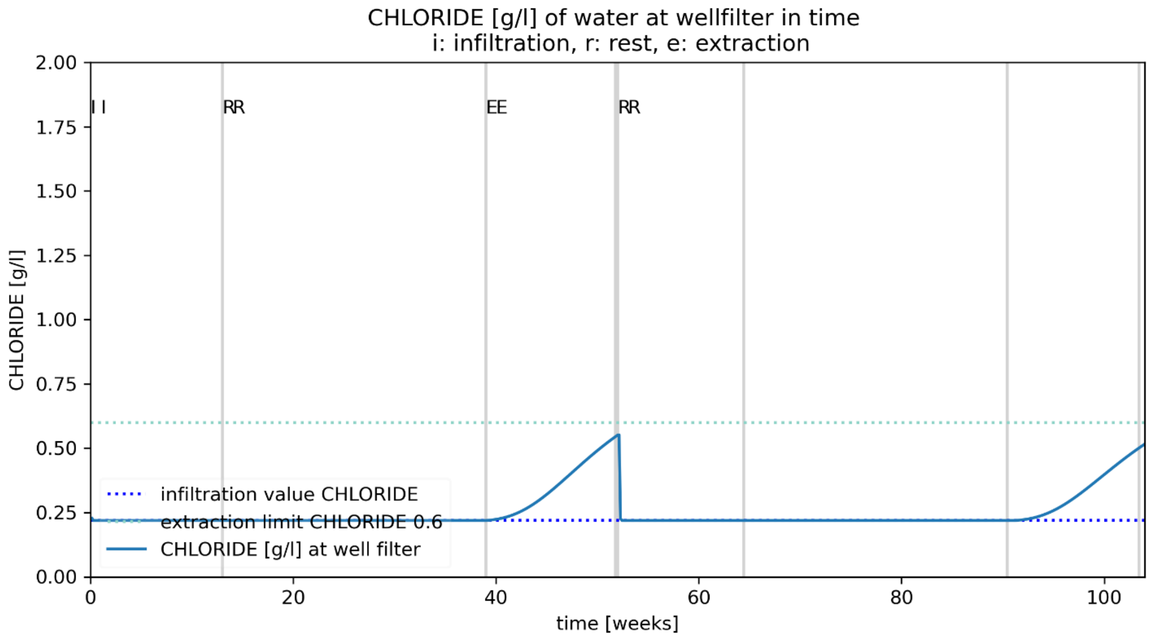




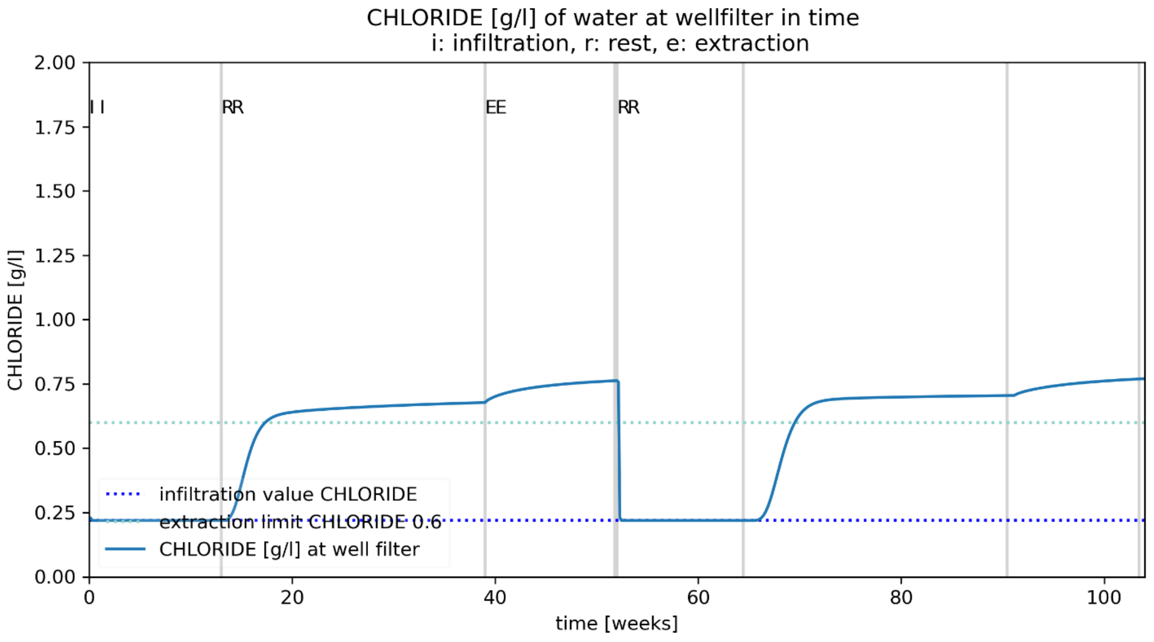
Cross section of aquifers 1 and 2 in the most down-gradient well showing the chloride concentrations after 13 weeks of injection (upper), at the end of the rest period after 39 weeks (middle) and concentrations at the end of the abstraction period (lower).

Density Flow Model Alkhoud – Chloride Concentration Extracted Water

Scenario low gradient



Scenario high gradient



Risks of ASR Operation at AlKhoud

- **Uncontrolled bubble drift due to changing groundwater gradients and directions**
- **High hydraulic gradient towards the sea when the dam is full after rain events**
- **Abstraction of stored water by private wells nearby (so Loss of stored water)**
- **Upconing of saline groundwater from deeper groundwater layers in case of increased abstraction due to high ASR well density and highly permeable aquifer until a depth where brackish and saline water occurs (Salinization of wellfield)**
- **There is no space for separate injection and abstraction wells (due to growth of urbanization) & without knowing if and when the hydraulic gradient might change.**

Conclusions and Recommendations

- The groundwater modelling shows **that the injected bubble of desalinated water can drift away from the ASR site uncontrollably and at unpredictable moments, due to changing groundwater flow conditions.**
- **Private and public groundwater abstractions: are taking place all around Al Khoud recharge, highly affecting groundwater flow at the ASR site**.
- **In addition, sporadic heavy rain events cause floodwater to be stored at the Al Khoud recharge dam, creating a strong groundwater gradient at the ASR site. Such a floodwater event can push away the injected bubble of desalinated water at any time and at high velocity. This interference of natural recharge and ASR would make it impossible to recover part or most of that injected water.**
- **An additional risk for successful ASR operation is the salinity of the ambient groundwater. Upconing of brackish and saline groundwater from deeper groundwater layers and lateral movement of intruded seawater by the concentrated abstraction of multiple ASR wells during the recovery phase is a serious risk that could jeopardize ASR operation in Al Khoud. Even after an injection phase, in which brackish and saline water is pushed back by infiltration of desalinated water, during the recovery phase (some of) the wells will encounter salinization problems.**

Conclusion and Recommendations

- **It is only under ideal and controlled conditions, in which during a full yearly ASR-cycle no groundwater abstractions in the surrounding area would take place and no floodwater event filling the recharge dam would occur, that all the available surplus water could be stored and recovered within the given 3.0 km^2 ASR site.**

> - **Feasible ASR site must be protected**
> - **Feasible and unfeasible site – operation-based feasibility**

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  - [2]ACACIA WATER, The Netherlands
  - [3]AZD, Oman
  - [4]CONSULAQUA, Germany
  - [5]Oman Water & Wastewater Services Company, Nama Water Services, Oman
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