جمعية علوم وتقنية المياه
Water Sciences and Technology Association

جامعة الخليج العربي
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Bahrain's Experience in using Stochastic Modeling to Assess the Sustainability of a Brackish, Non-renewable Aquifer to Feed a Desalination Plant

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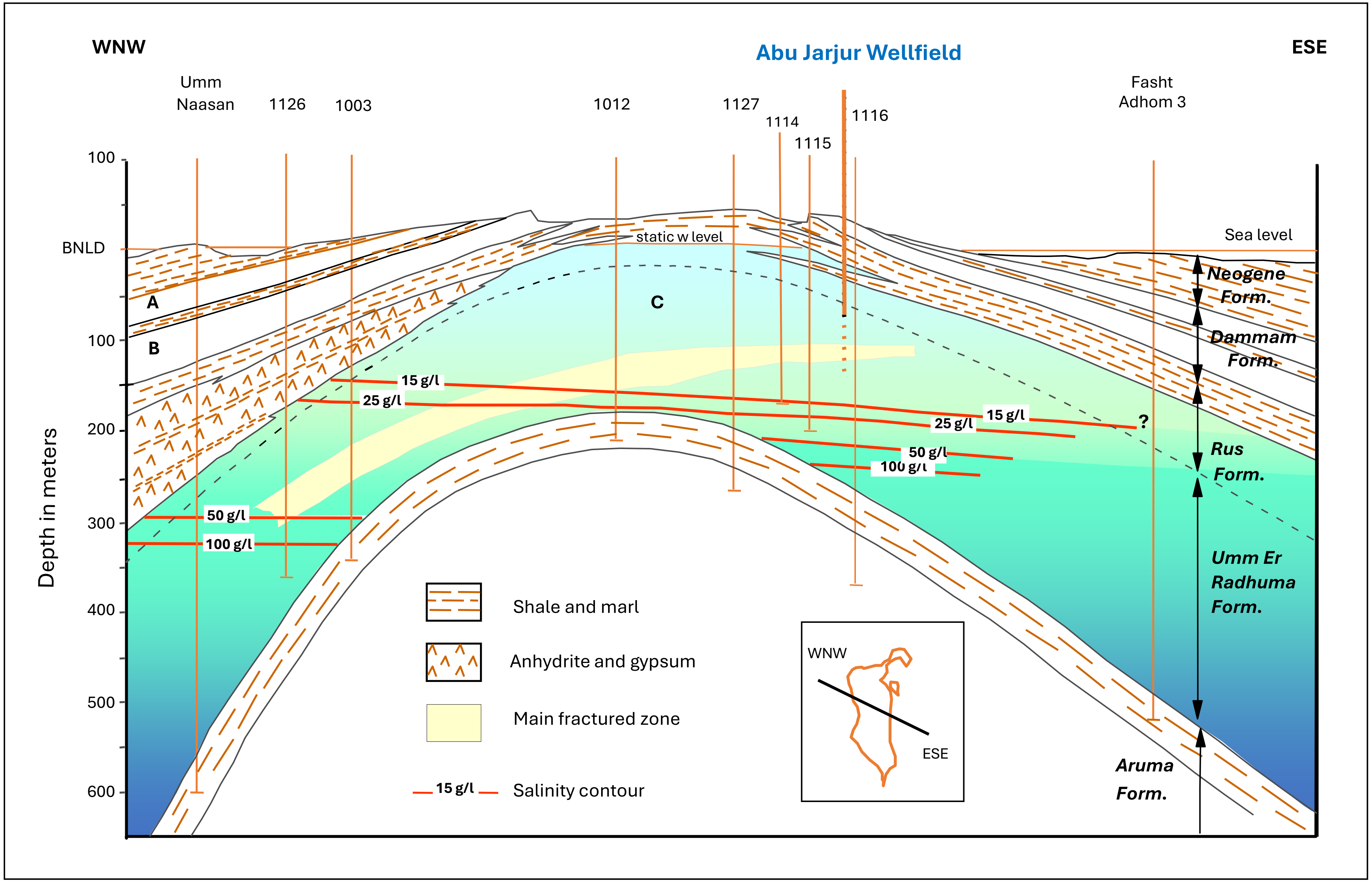
Introduction

- The Rus-Umm Er Radhuma Aquifer (C Aquifer) occurs in the form of a lens of finite lateral extent (underlying the main freshwater Dammam aquifer)
- Contains brackish waters (8-15 g/L) underlain everywhere by brines (50-100 g/L)
- Industrial sector utilization started in 1982 (Amiri Decree 12/1980)
- Major utilization started at the 1984 at a rate of 24 Mm^3/y to feed the Abu Jarjur RO desalination plant (AJROP), designed feedwater <20 g/L

Aquifer C Extension and Location of Abu Jarjur Wellfield and RO Plant

Hydrogeological cross section showing Aquifer C System geometry and boundaries



- As a non-renewable aquifer, its management is based on mining a one-time brackish water reserve stored in the aquifer
- Main management objective is to sustain the aquifer future availability in feeding the RO desalination plant with a specified salinity limit (20 g/L) over the economic age of the desalination plant/and plant rehabilitation period
- i.e., the economics of the process and its continuation (i.e., brackish water RO membranes) depends primarily on the increase in the salinity(not to exceed 20 g/L) of the water produced by the wellfield to feed the desalination plant
- After 40 years of production, rehabilitation of the RO plant is planned (a major investment); the decision will be dependent on the future salinity of the wellfield

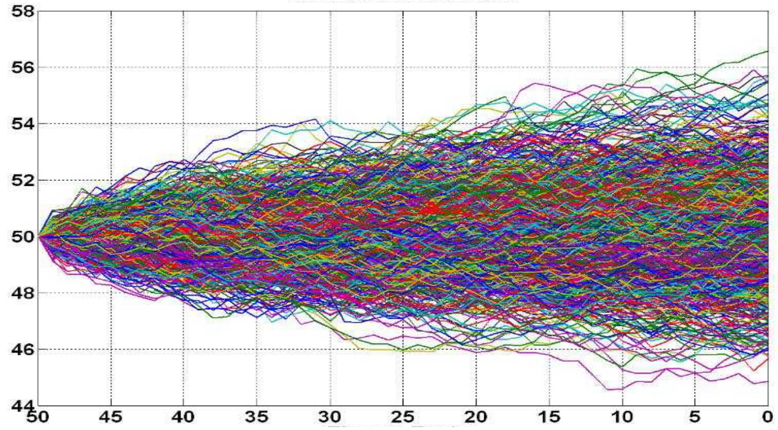
Methodology

- Thick aquifer (>150 m), multilayered, fractured, and highly heterogeneous
- Very limited data available on its hydraulic parameters (i.e., Horizontal and vertical Hydraulic, storage coefficients)
- Estimated abstraction by other sectors

Stochastic vs Deterministic Modeling

Embedding Uncertainty in Model Results

Output is provided as a probability distribution, with most probable value and confidence intervals



Data Collection & Aquifer System Conceptualization

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Mathematical Model Development

Aquifer System Conceptualization

Model Grid Design and Parameters Initialization

Model Calibration by History Matching

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Hydraulic Parameters Sensitivity Analysis

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Predictive Simulation

- Deterministic Simulation
- **Stochastic Simulation**
  - *Generation of 20 conditional realizations for principal parameter*
  - *Simulating groundwater levels and salinity for each realizations*
  - *Calculating upper and lower confidence intervals of wellfield salinity*
    Spatial/temporal ensemble average of aquifer heads and salinity

Groundwater Mathematical Modeling

Governing Equations and Simulation Code for Groundwater Flow

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)+b\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S\frac{\partial h}{\partial t}+b.W(x,y,z,t)$$

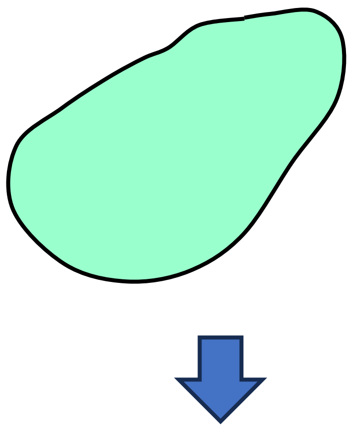
MODFLOW (FDM approximation)

Governing Equations and Simulation Code for Solute Transport in Groundwater

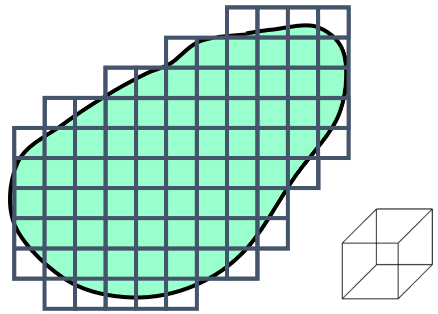
$$\frac{\partial C}{\partial t}=D_L\frac{\partial^2 C}{\partial x^2}+D_T\frac{\partial^2 C}{\partial y^2}-V_x\frac{\partial C}{\partial x}+\frac{q_s}{\theta}C_s+\sum R_n$$

MT3DMS (advective-dispersive FDM approximation)

Modeled region

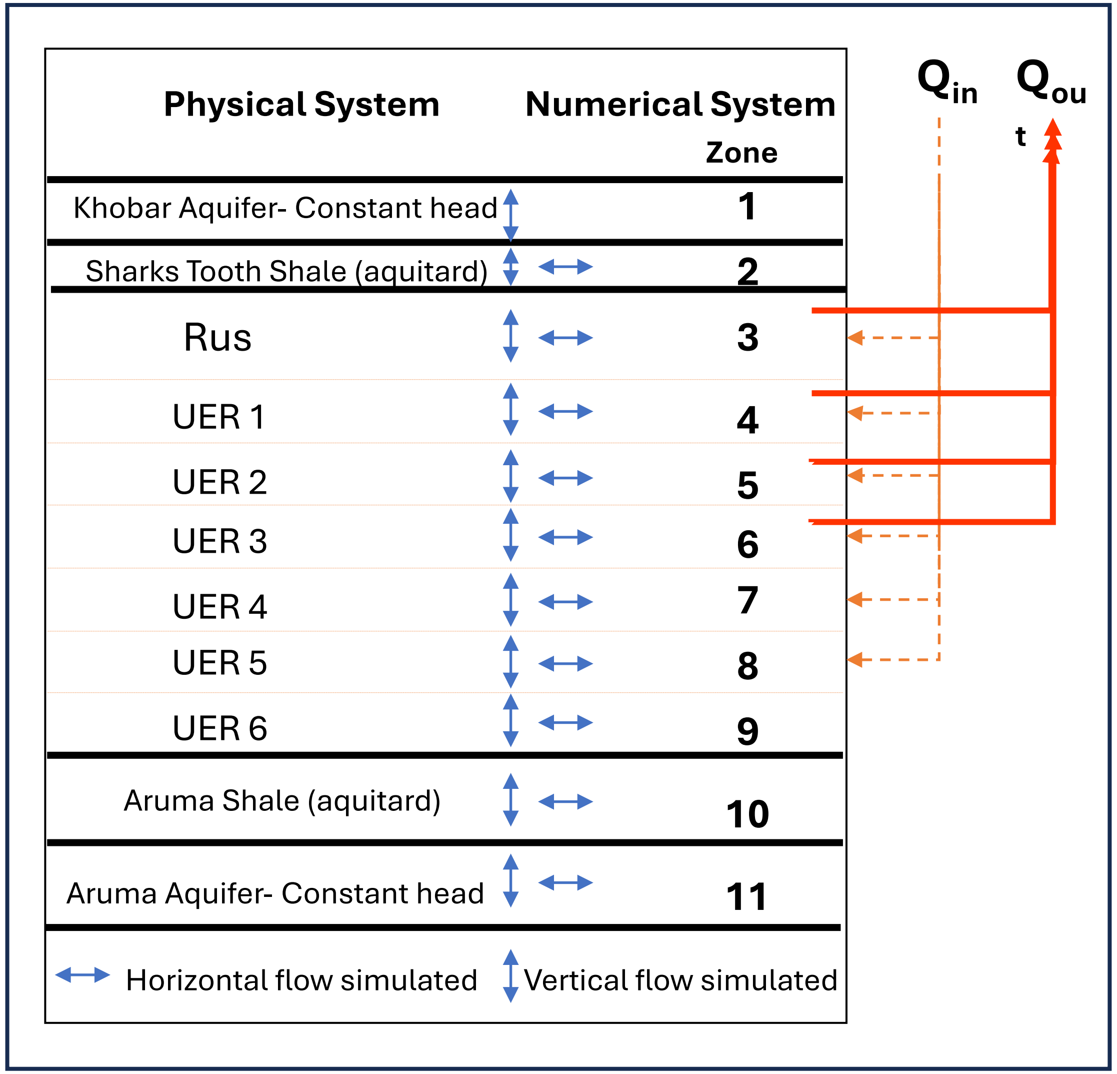


Finite Difference Method (FDM)

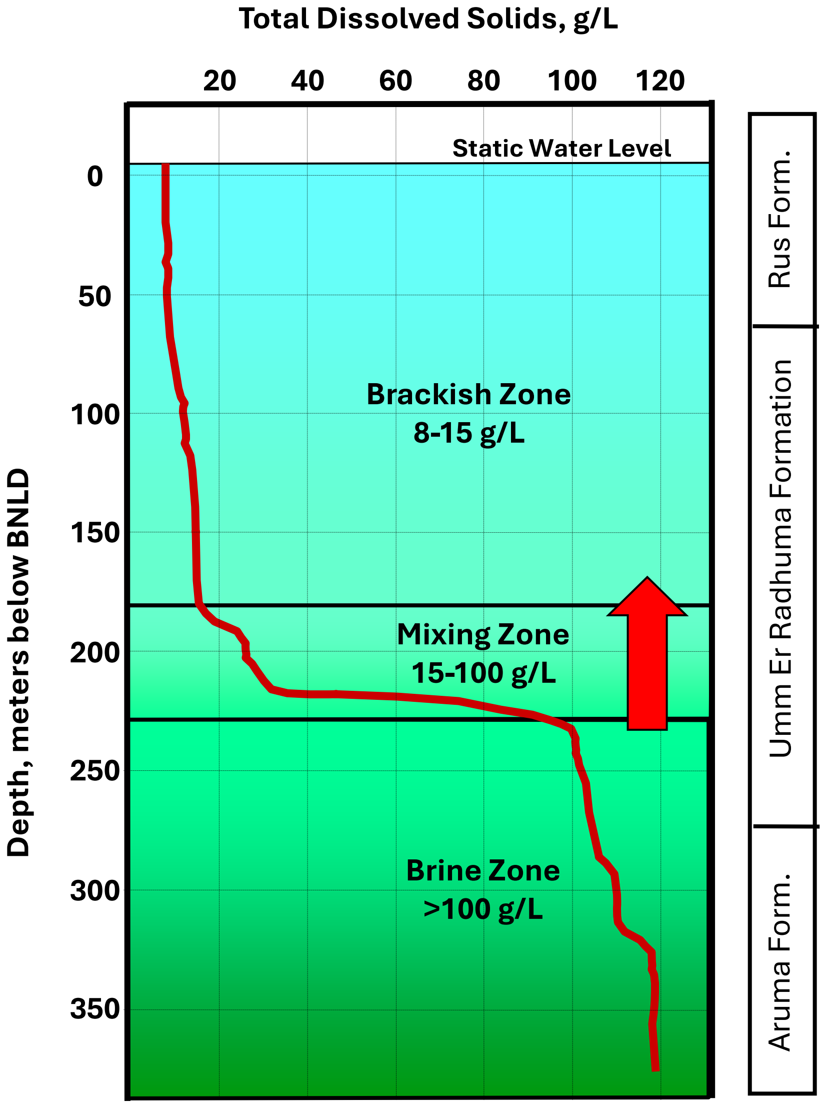


Groundwater Model Development (conceptualization)

Conceptual Model of Aquifer C System Used in Numerical Simulation

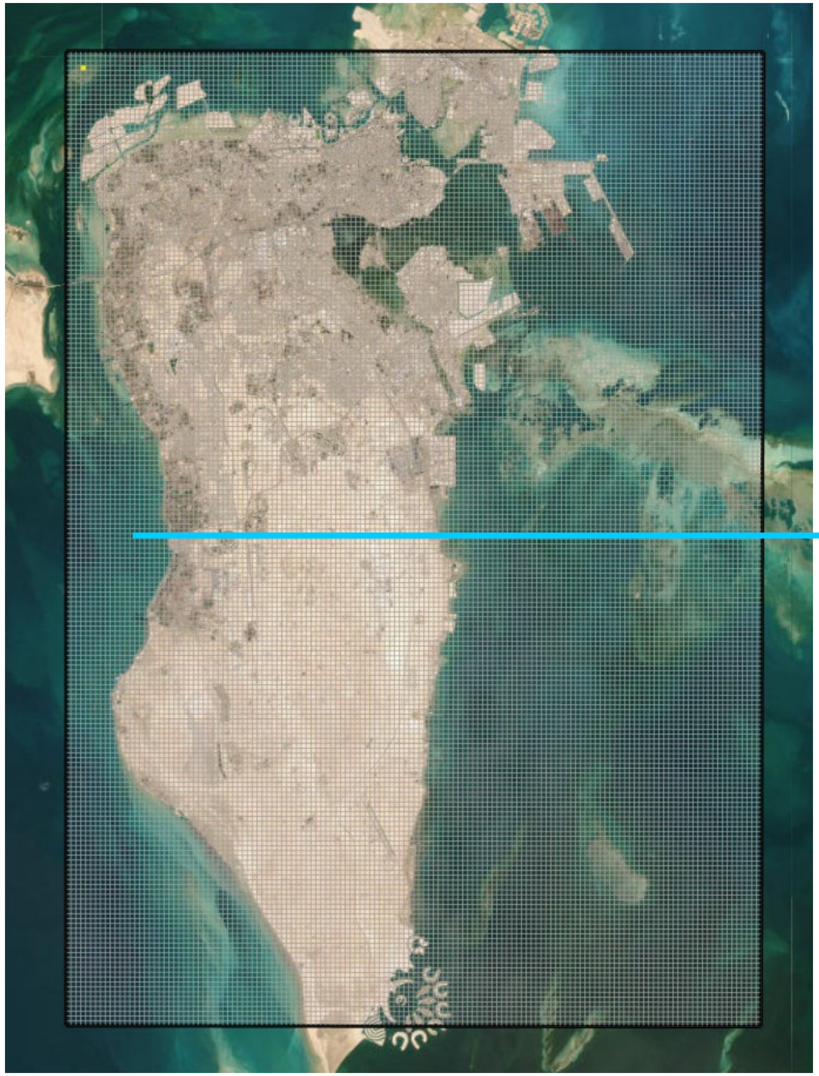


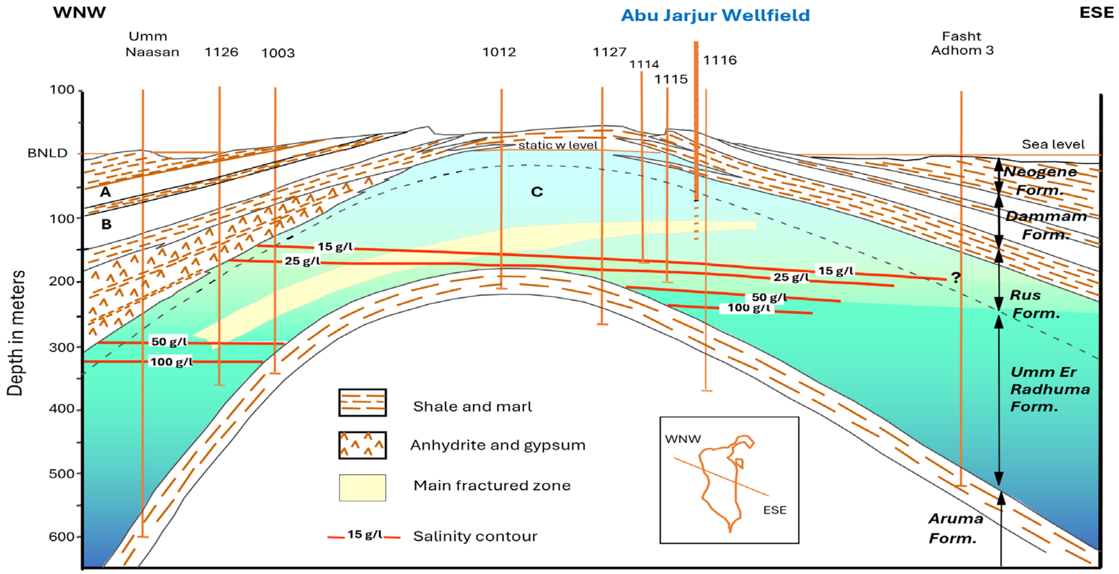
Typical Salinity Profile of C Aquifer in East Bahrain (Pre-development Conditions)

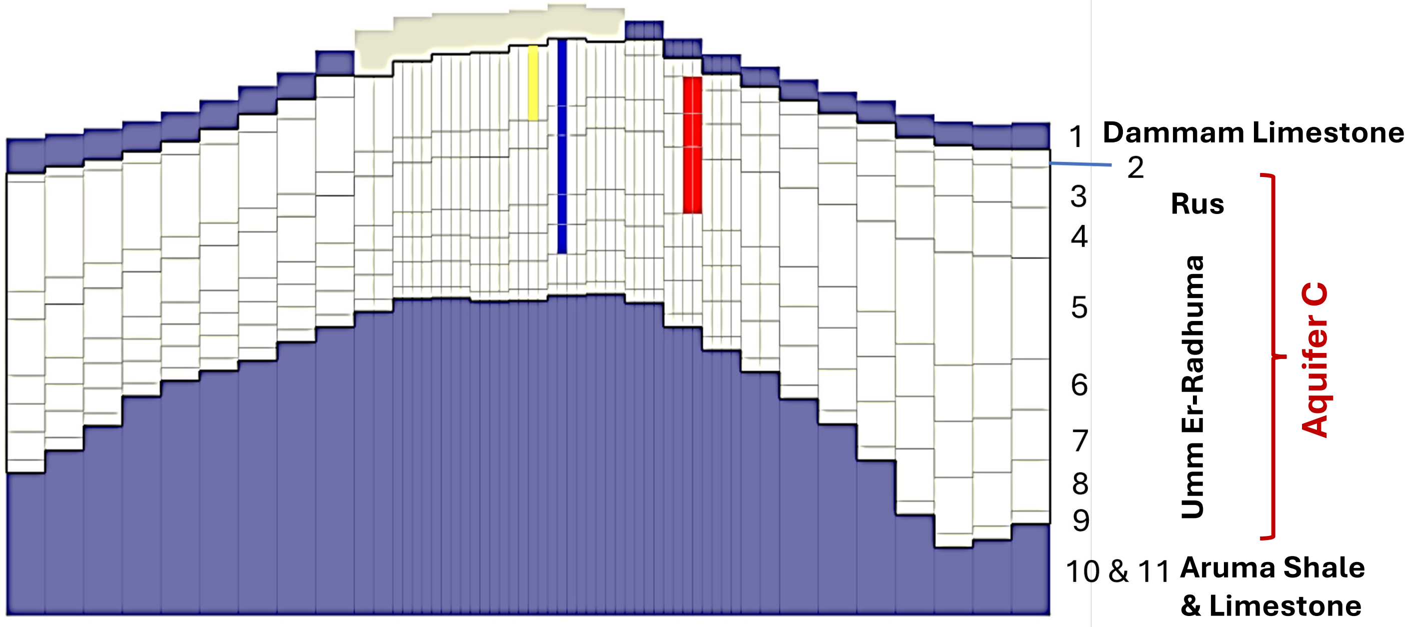


Groundwater Model Development (Grid design and parameters initialization)

Model Grid Design used in Numerical Simulation





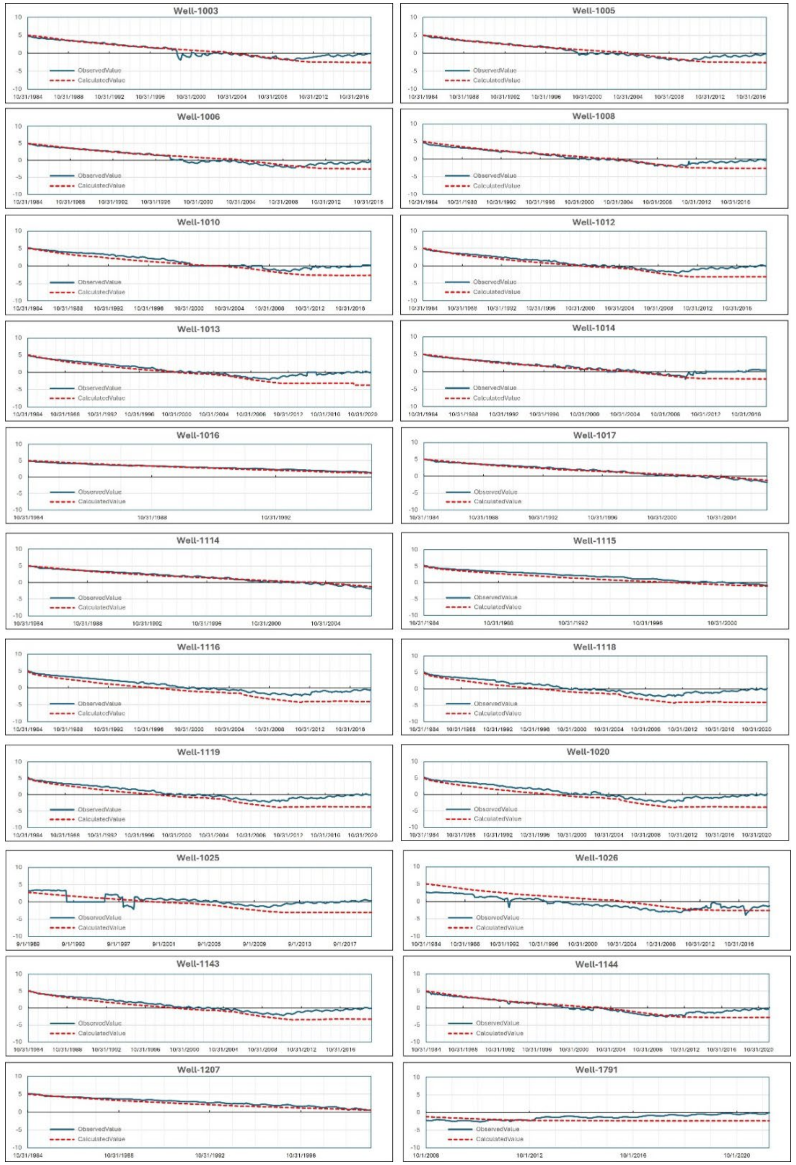


Groundwater Model Development

Calibration by History Matching

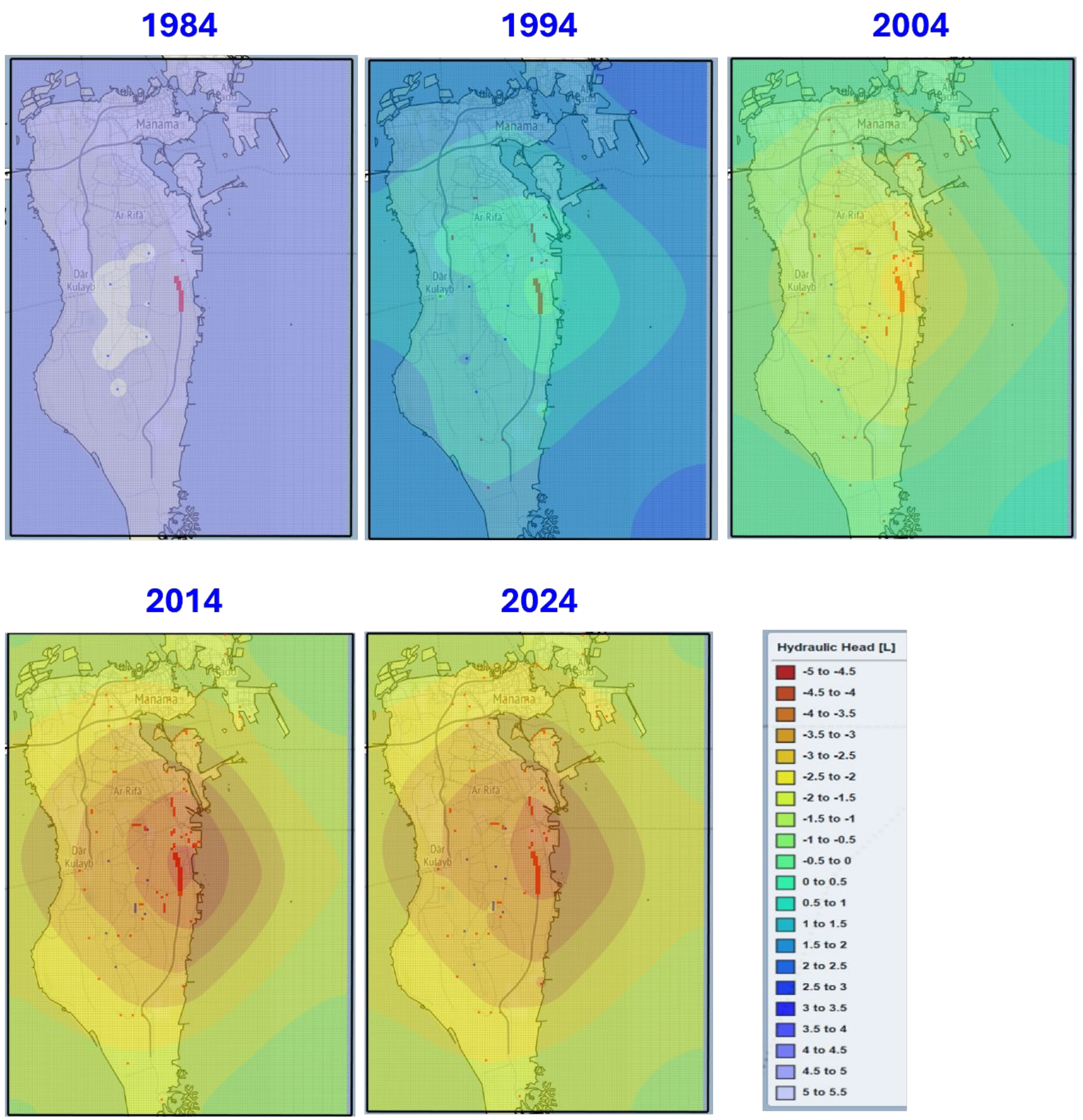
Reconstructing aquifer abstraction history (1984-2024) to reproduce observed water levels and salinity levels by changing hydraulic parameters

simulated and observed potentiometric hydrographs (1984-2024)

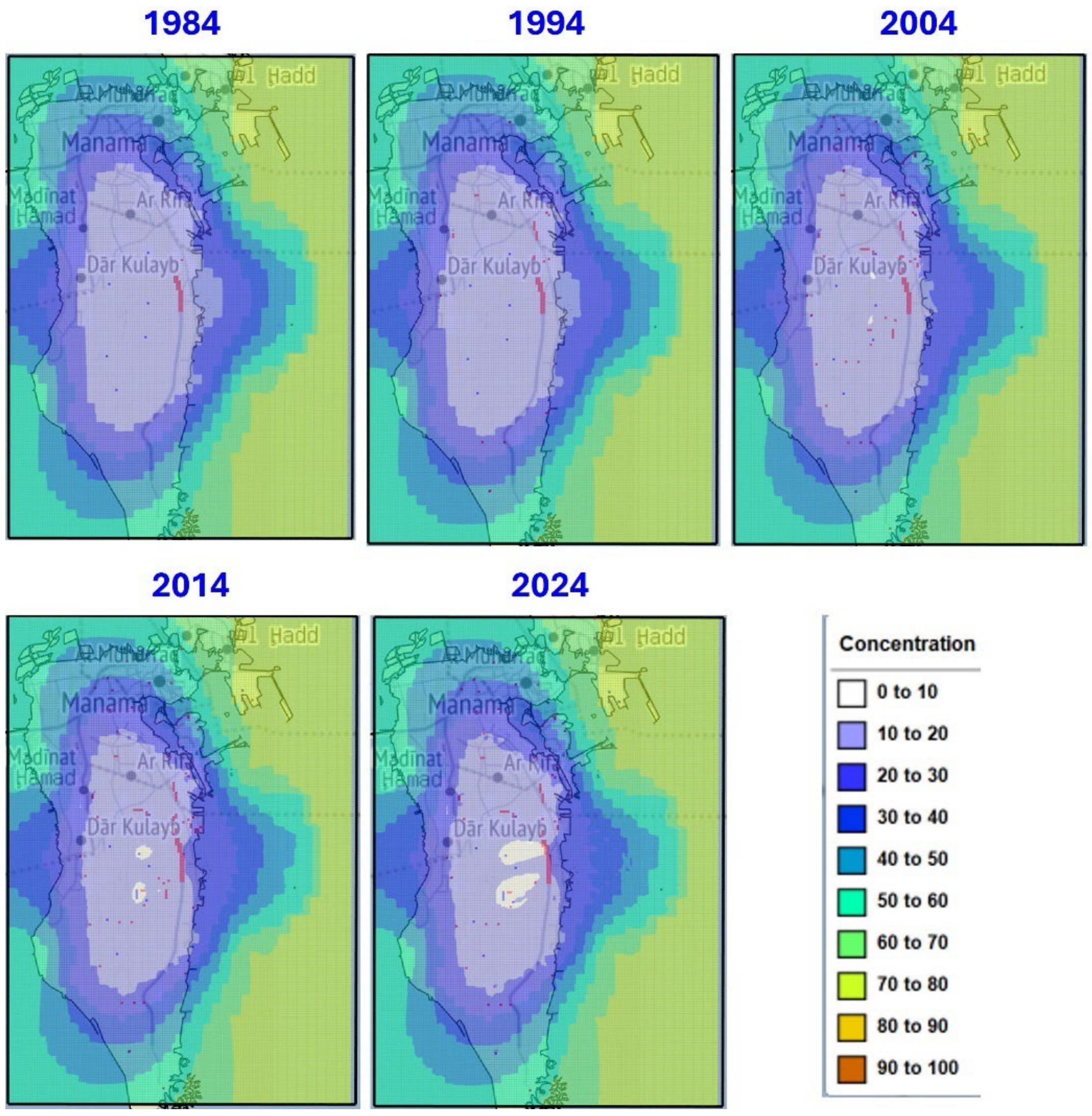


Simulated vs observed TDS in RAJ wellfield individual wells (1984-2024)

Simulated water level maps in the C aquifer (zone 5) for the period 1984 to 2024



simulated salinity maps in the C aquifer (zone 5) for the period 1984 to 2024



Sensitivity Analysis of Model Hydraulic Parameters

Sensitivity Coefficient

Input variable (hydraulic parameter)

$$S = \frac{P_0}{\varphi_0}\left[\frac{\delta\varphi}{\delta P}\right]_0$$

performance measure (output variable = wellfield salinity

Importance Coefficient

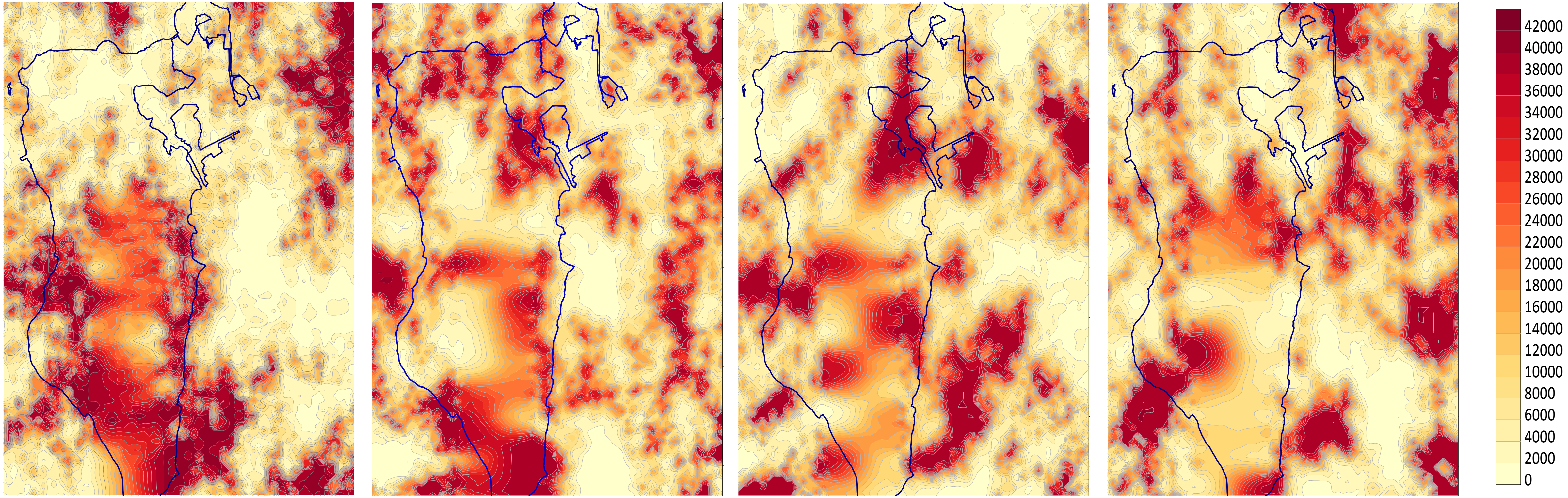
expected parameter range

$$I = \frac{R_P}{\varphi_0}\left[\frac{\delta\varphi}{\delta P}\right]_0 = \frac{R_P}{P_0}(S)$$

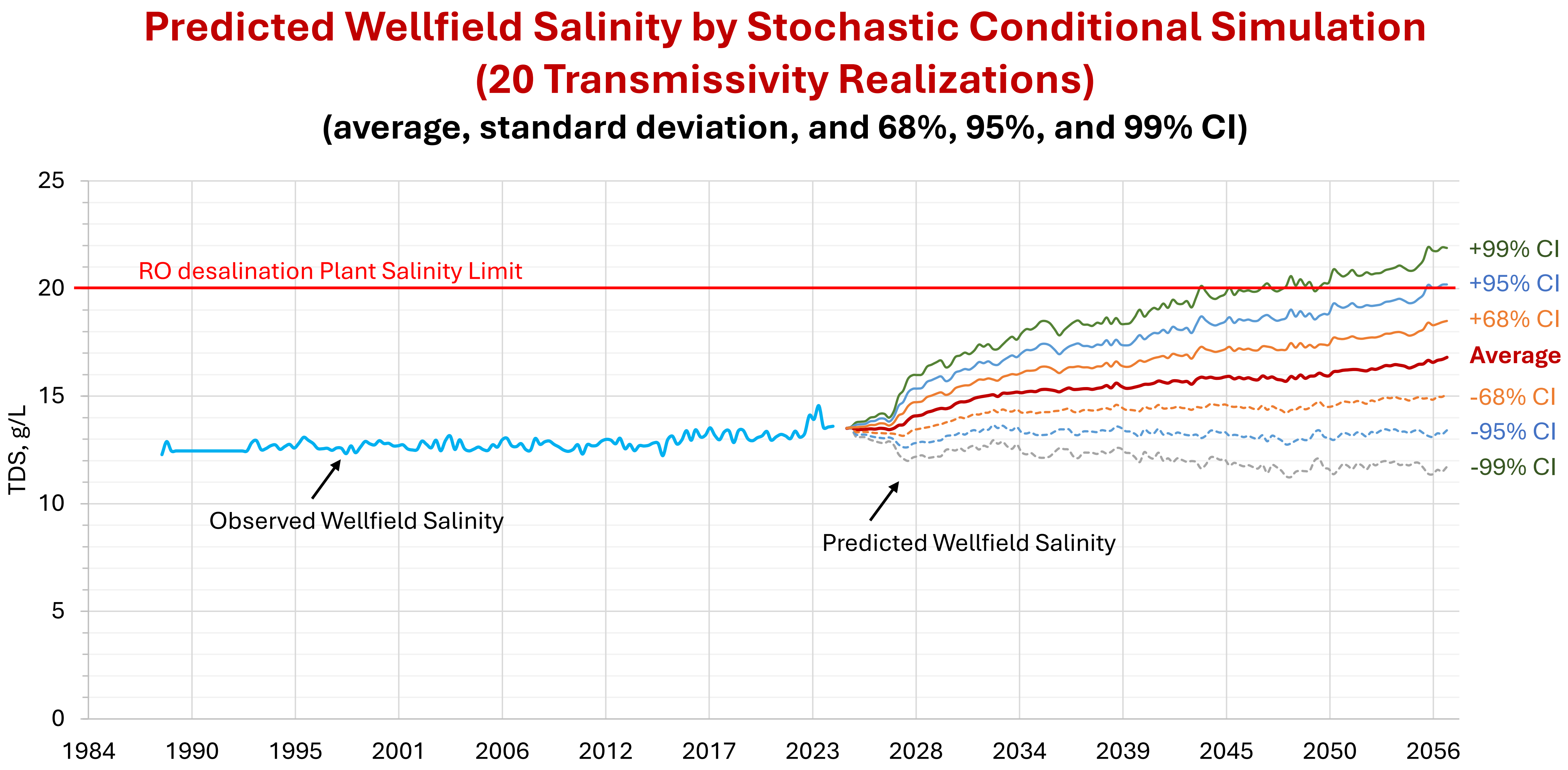
Rank	Parameter	Sensitivity Coefficient		Importance Coefficient, I	Overall Ranking
		S+	S-		
	Aquifer's Hydraulic Conductivity (doubled and halved)				
4	Zone 3 (Rus)	-0.06	-0.03	0.080	4
3	**Zone 4 (UER)**	**-0.10**	**-0.02**	**0.106**	**3**
1	**Zone 5 (UER)**	**-0.12**	**-0.05**	**0.147**	**1**
2	**Zone 6 (UER)**	**0.02**	**0.22**	**0.127**	**2**
5	Zone 7 (UER)	0.00	0.13	0.065	6
6	Zone 8 (UER)	0.00	0.11	0.054	7
7	Zone 9 (UER)	0.03	0.00	0.035	10
	Aquitard's Vertical Hydraulic Conductivity (doubled and halved)				
1	Zone 2 (Sharks Tooth Shale)	0.02	0.04	0.034	11
2	Zone 10 (Aruma Shale)	0.00	0.00	0.000	x
	Aquifer's Porosity (doubled and halved)				
5	Zone 3 (Rus)	0.00	0.00	0.000	x
2	Zone 4 (UER)	0.03	0.04	0.054	7
3	Zone 5 (UER)	-0.04	0.01	0.052	8
1	Zone 6 (UER)	-0.07	0.01	0.078	5
4	Zone 7 (UER)	-0.02	0.01	0.022	15
5	Zone 8 (UER)	0.00	0.00	0.000	x
5	Zone 9 (UER)	0.00	0.00	0.000	x
	Aquifer's Storge Coefficient (increased and decreased by one order of magnitude)				
5	Zone 3 (Rus)	-0.01	0.04	0.027	14
1	Zone 4 (UER)	-0.01	0.07	0.043	9
6	Zone 5 (UER)	-0.01	-0.02	0.022	15
5	Zone 6 (UER)	0.01	-0.04	0.027	14
3	Zone 7 (UER)	-0.02	-0.30	0.033	12
2	Zone 8 (UER)	-0.01	0.01	0.035	10
4	Zone 9 (UER)	0.01	-0.04	0.030	13

Stochastic Simulation

Example conditioned realizations of the hydraulic conductivity of zone 5 (from a total of 20 realizations)



Predictive simulation



Recommendations

- Continuous monitoring of abstraction, water levels and salinity of aquifer C
- To use prepared wellfield protection area (30 years) in new wells licensing
- To prolong aquifer life in feeding RAJ wellfield, two management schemes need to be investigated:
  - **Modification of the present wellfield design**
    - modifying individual wells spacing and number
    - scheduling of pumping
    - raising wells intake intervals
  - **Augmenting aquifer storage by MAR**
    - Rainwater or surplus tertiary/secondary treated wastewater
- Hydrogeological investigation and model "**post-auditing**" and prediction to be made periodically (recommended every 2 years)

Wellfield Protection Area

Thank You

Q & A