On the Contribution of Hydrogeology to the Integrated Water Resources Management of Arid Environments based on Studies from the Middle East

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Global distribution of arid regions

Contributions

- **Assessment of groundwater budget**

  What are the in- and outflows to the aquifer system?

- **Assessment of groundwater resources**

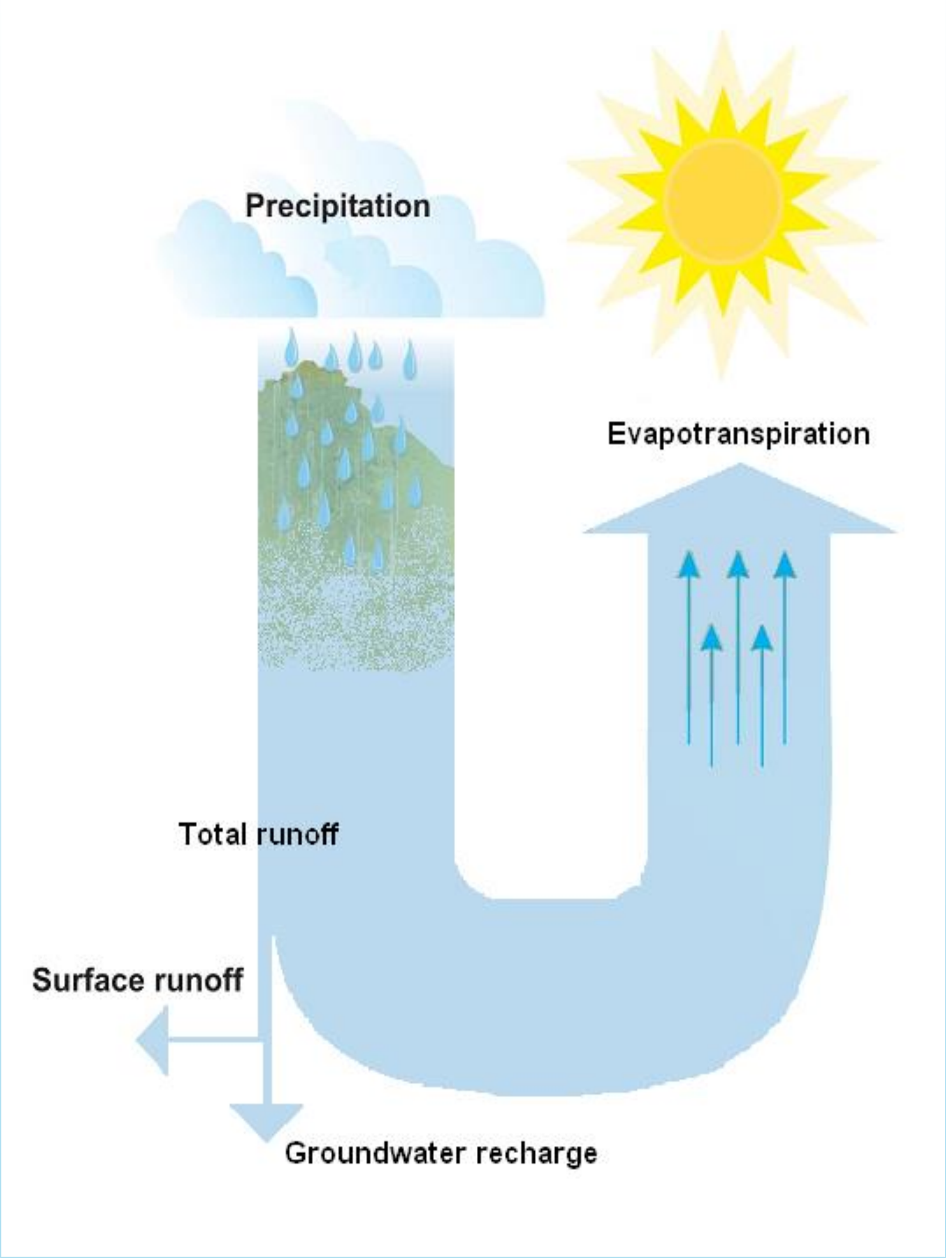
  How much groundwater is (still) available?
  What is the groundwater quality?

- **Management of groundwater resources**

  How can we make best use of the groundwater resource?
  Is a sustainable groundwater management possible?

Assessment of groundwater budget

Components of water budget

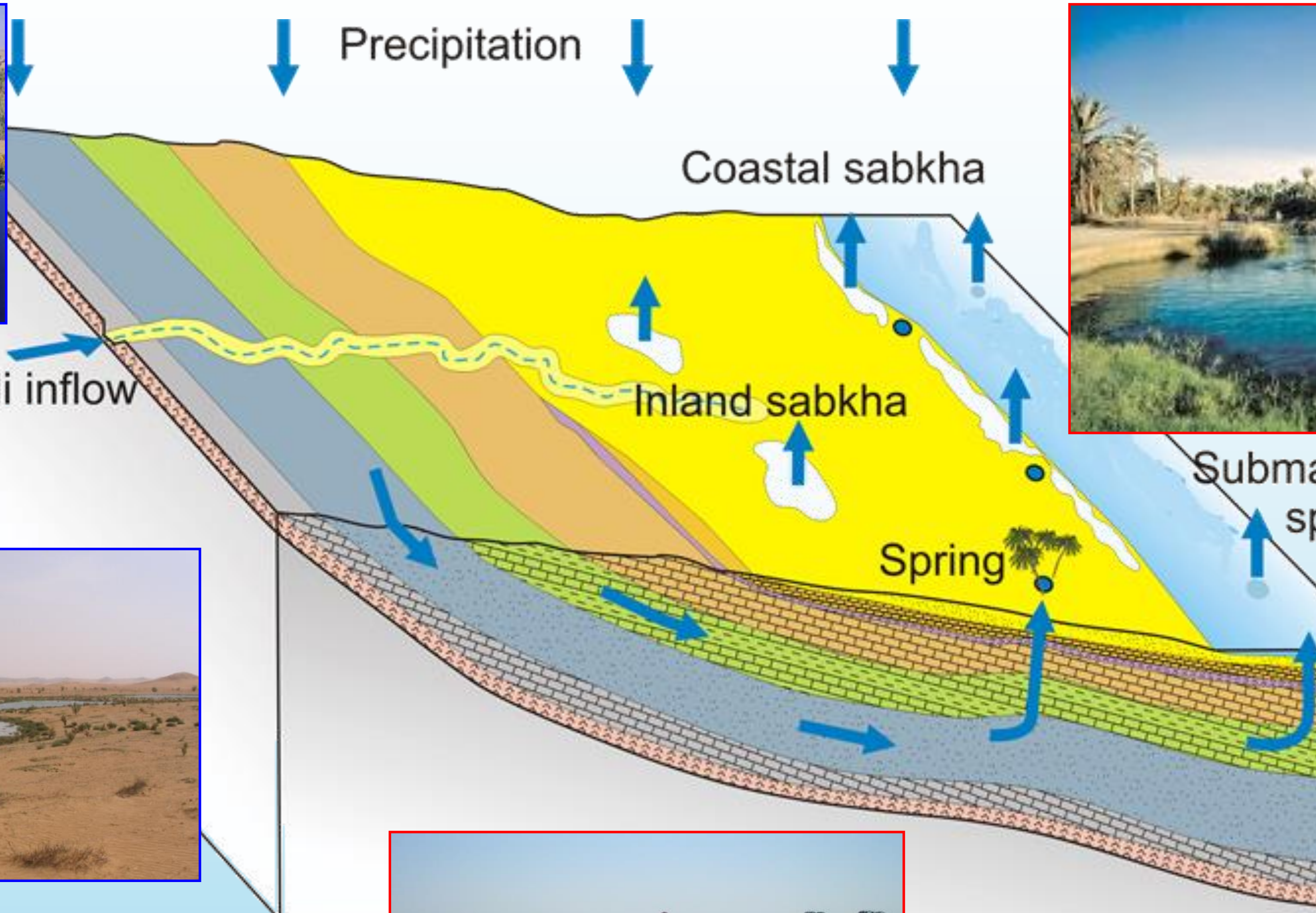


Water budget equation

$$P = E + R \pm \Delta S$$

P:	Precipitation
E:	Evapotranspiration
R:	Runoff
ΔS:	change in Storage

Groundwater budget: predevelopment state



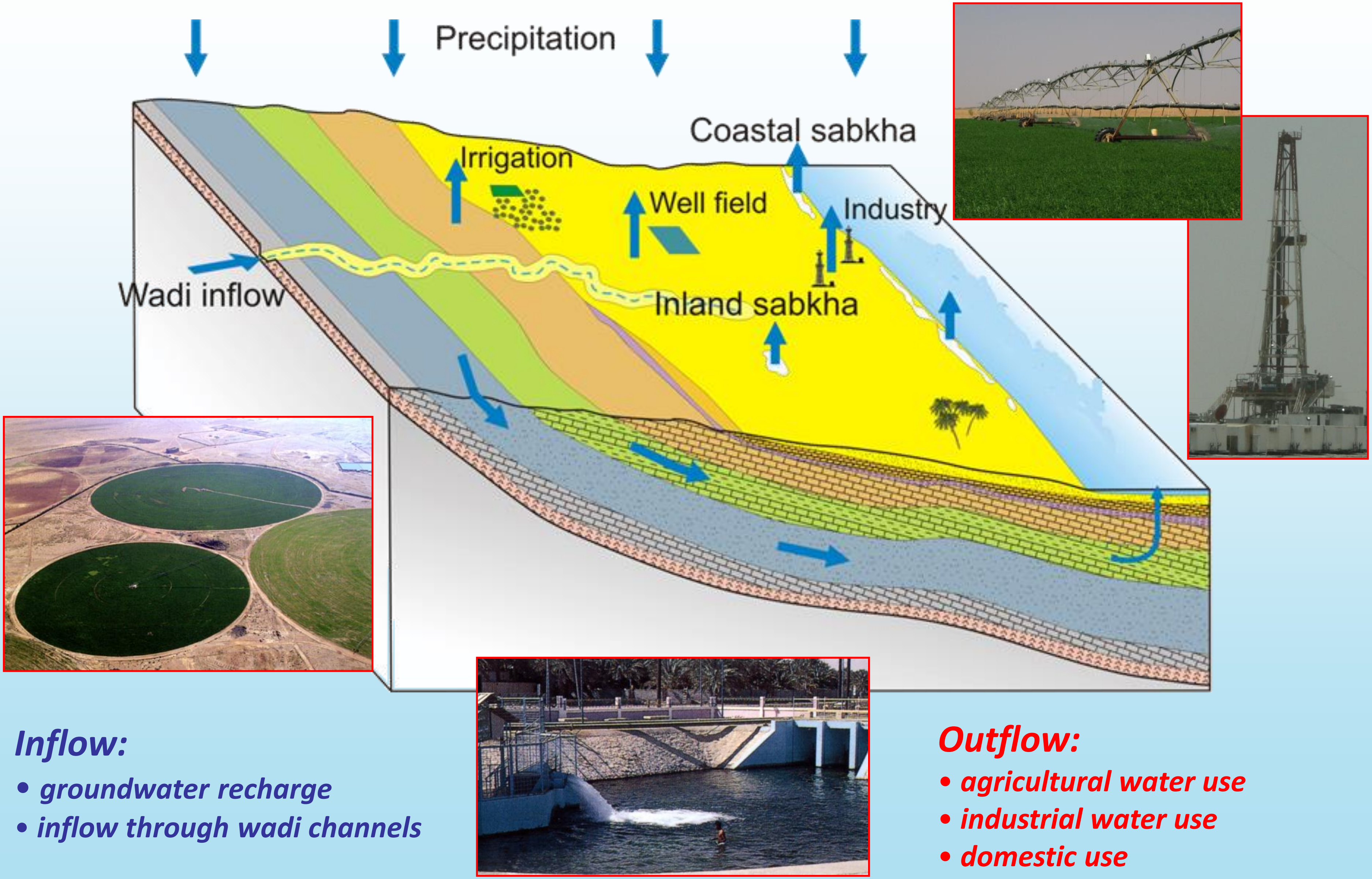
Inflow:

- *groundwater recharge*
- *inflow through wadi channels*

Outflow:

- *spring discharge*
- *inland and coastal sabkhas*
- *Persian Gulf*

Groundwater budget: present state



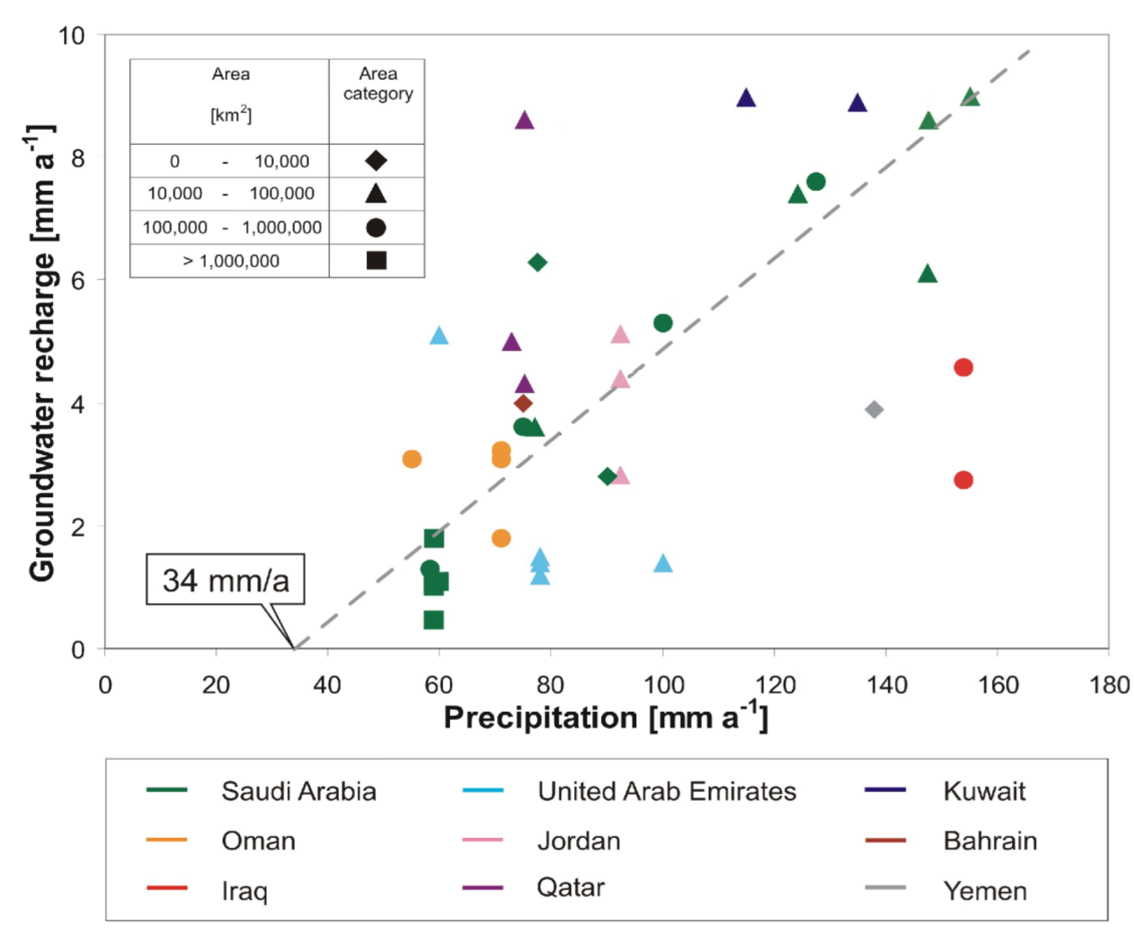
Inflow:

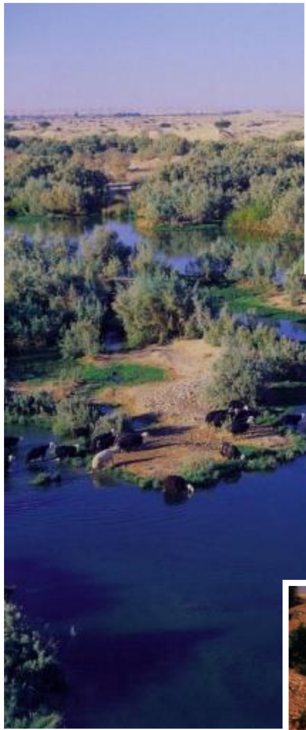
- *groundwater recharge*
- *inflow through wadi channels*

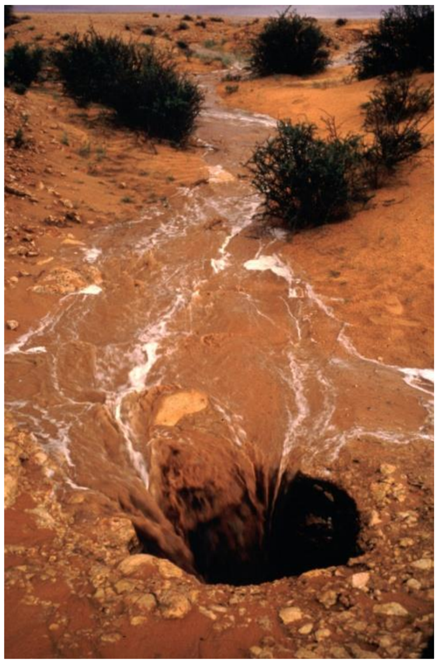
Outflow:

- *agricultural water use*
- *industrial water use*
- *domestic use*

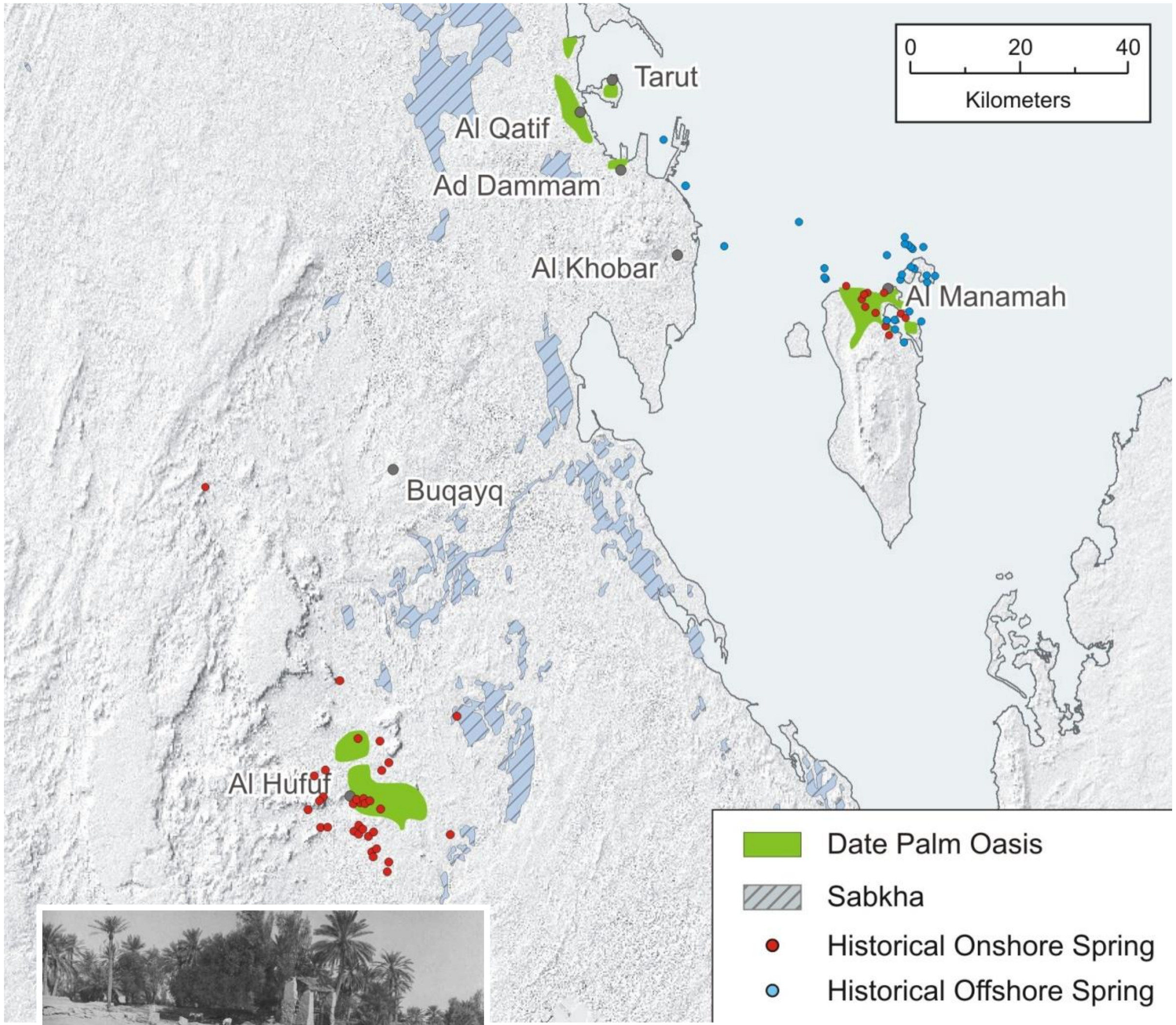
Groundwater recharge



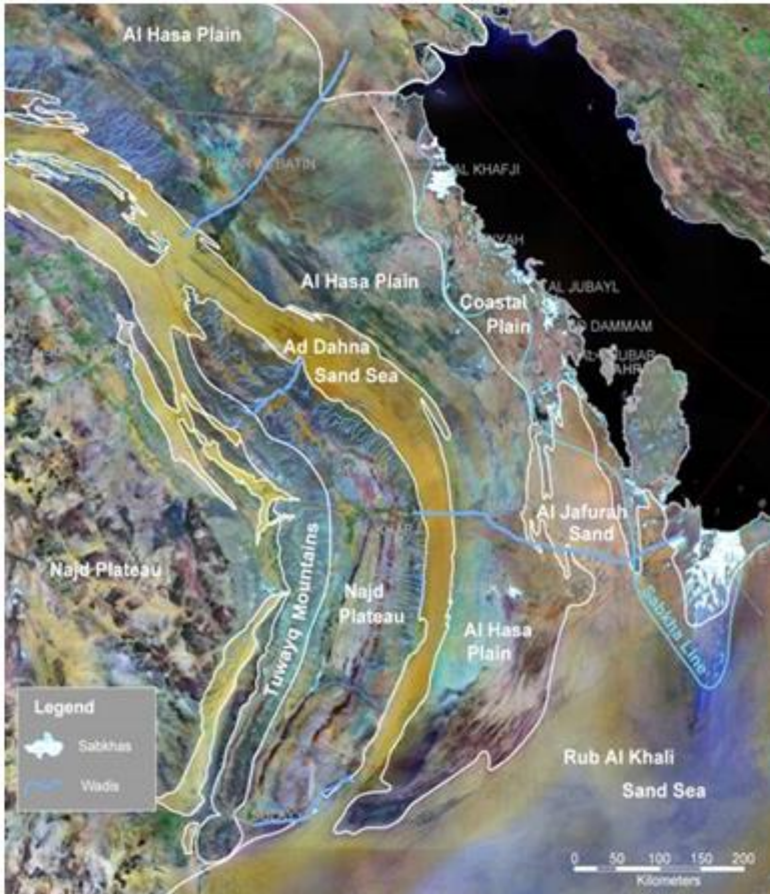


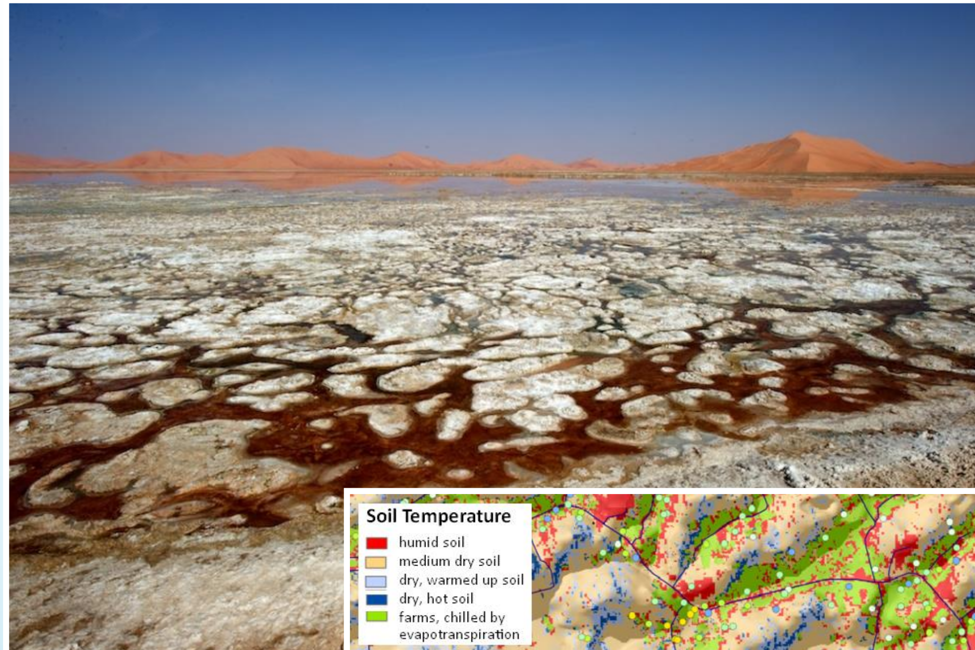


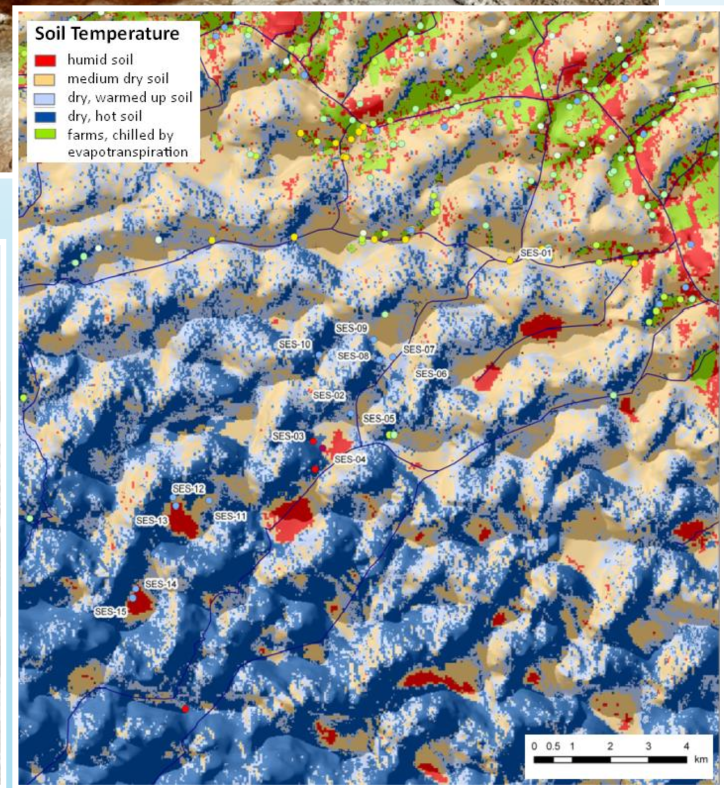
Natural discharge: springs

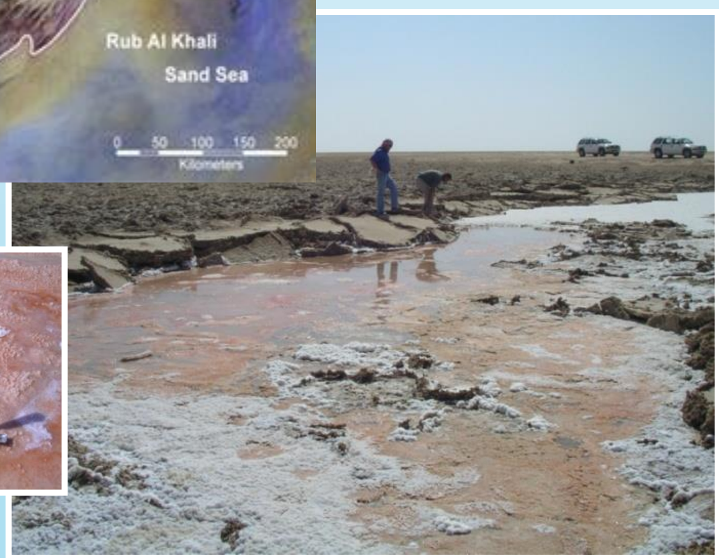


Natural discharge from inland and coastal sabkhas

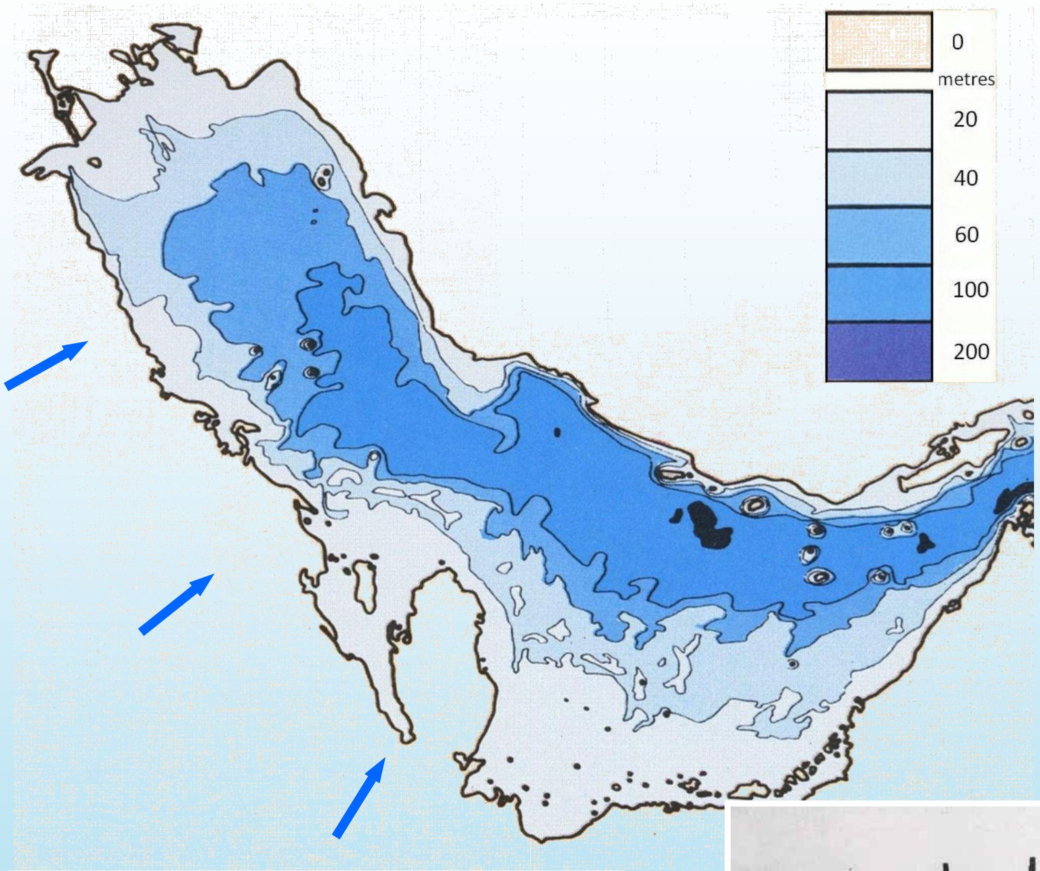






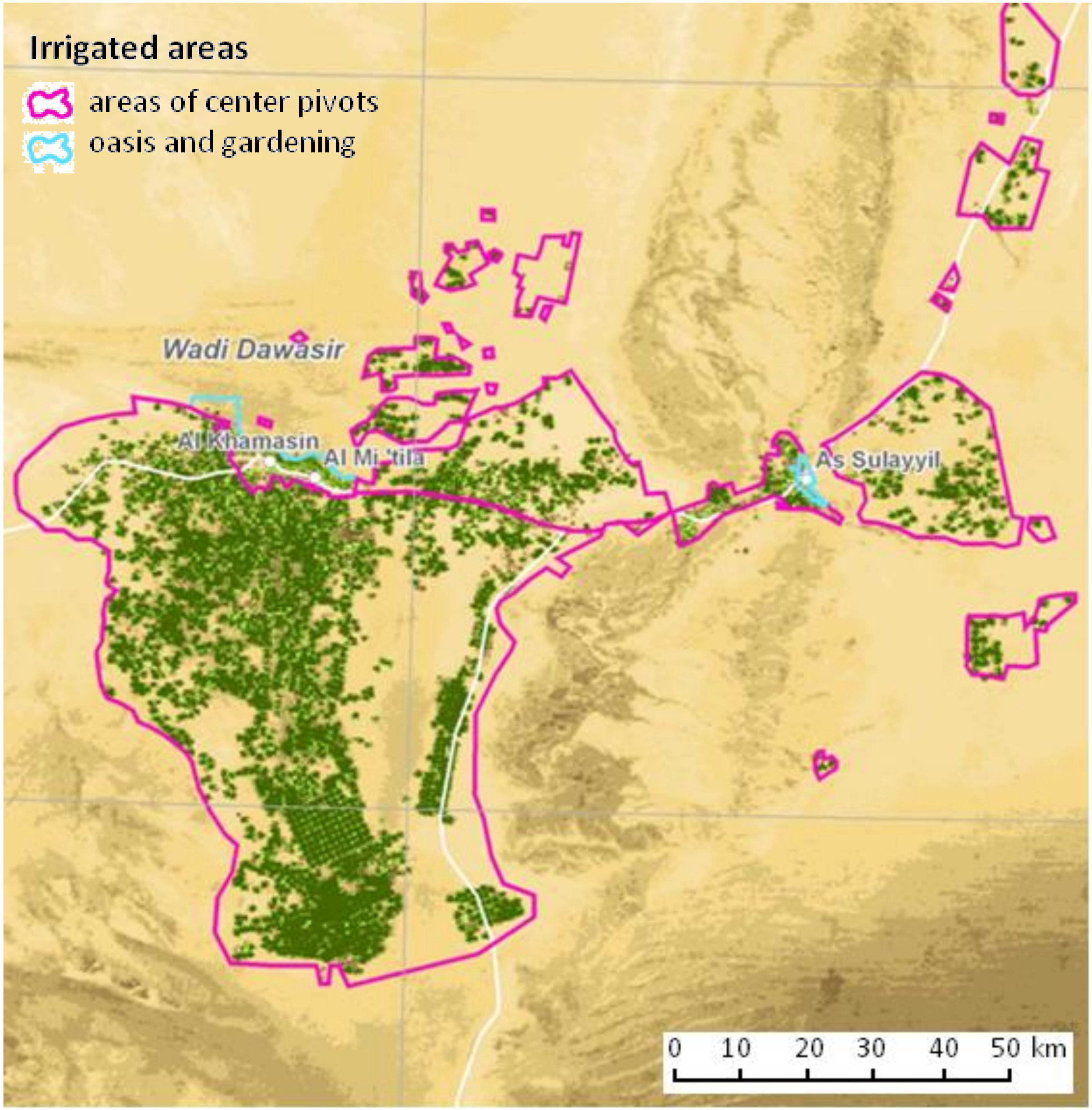


Natural discharge: Persian Gulf



Submarine springs

Discharge: agricultural water consumption



Center pivot

Estimation of agricultural water consumption

Calculation of irrigated areas: Normalized Difference Vegetation Index (NDVI)

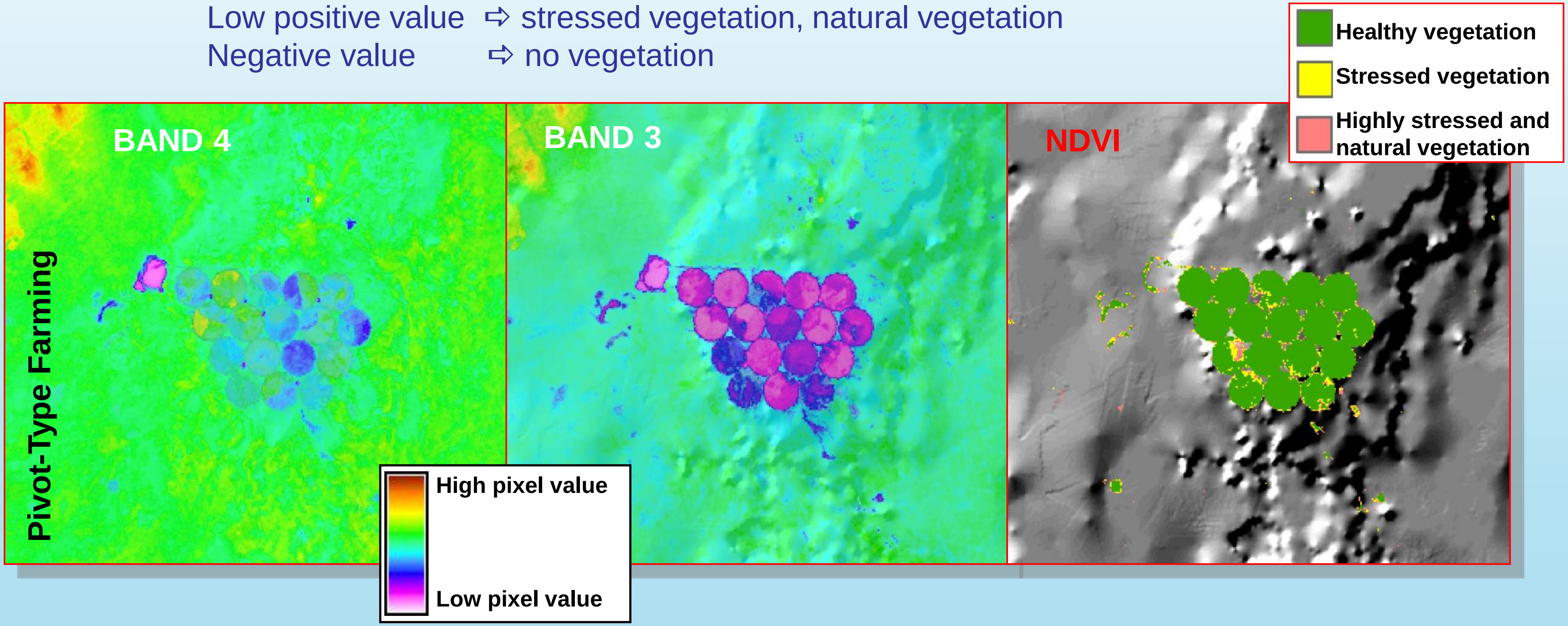
Healthy, irrigated vegetation

- ❑ absorbs visible red light (Band 3) ⇨ low pixel value
- ❑ reflects near infrared light (Band 4) ⇨ high pixel value

Normalized Difference Vegetation Index = **(Band 4 – Band 3) / (Band 4 + Band 3)**

Classification:

High value ⇨ healthy vegetation, well irrigated
Low positive value ⇨ stressed vegetation, natural vegetation
Negative value ⇨ no vegetation



Estimation of agricultural water consumption

Field survey for agricultural water demand

Production information

- Total farm size
- Crop acreage, cropping pattern
- Crop yields
- Use of fertilizers and agro chemicals
- Year of foundation and the enterprises perspectives on the future

Direct investigation on site

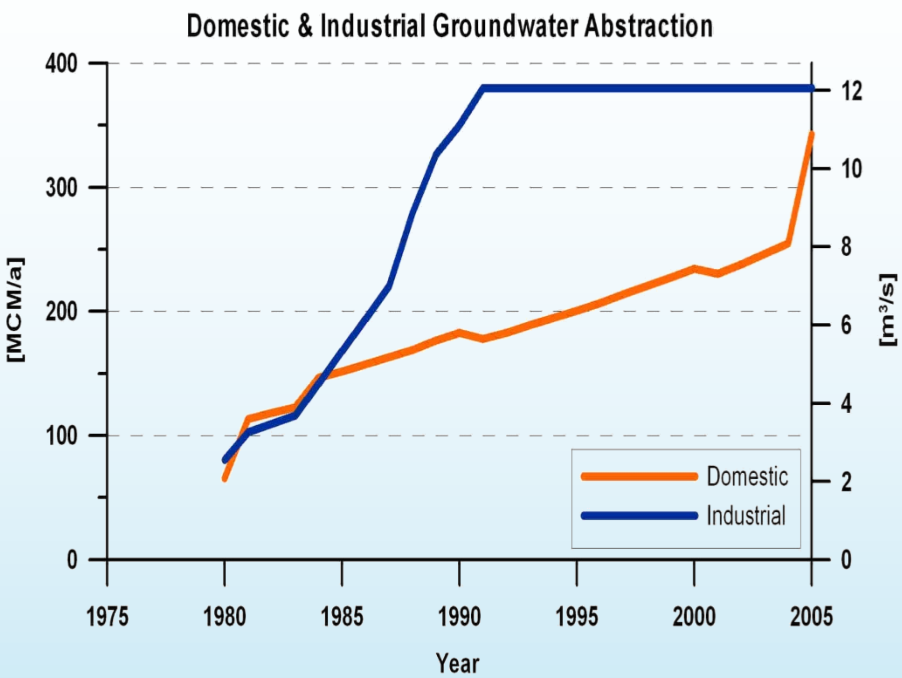
verifies the previously acquired information and record in addition:

- Crop type present
- Crop condition
- Field size
- Salinity of irrigation and drainage water
- Soil parameters: texture, colour, lithology

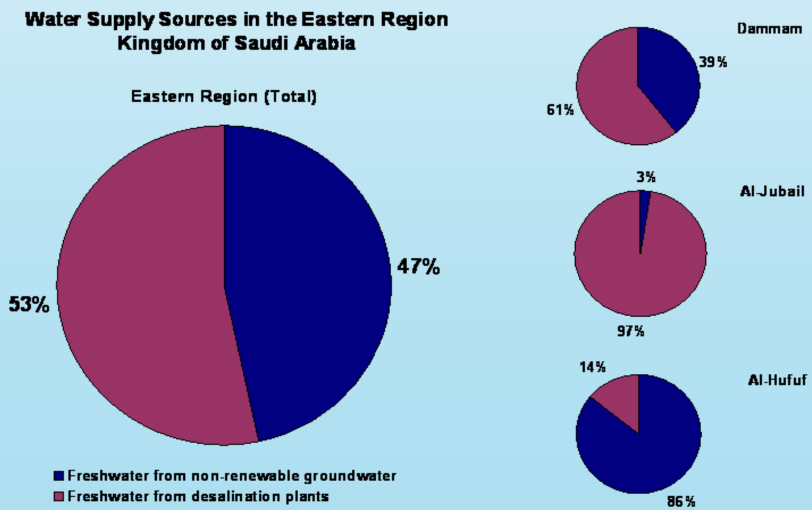
Water use information

- Well depth and groundwater level
- Irrigation area, type of irrigation
- Number of wells and pumps, capacities
- Total use of water per crop and per year
- Irrigation cycles

Domestic and industrial water demand



- Domestic groundwater consumption 2005: 351 MCM/a (11.1 m^3/s)
- Industrial groundwater consumption 2005: 380 MCM/a (12.0 m^3/s)

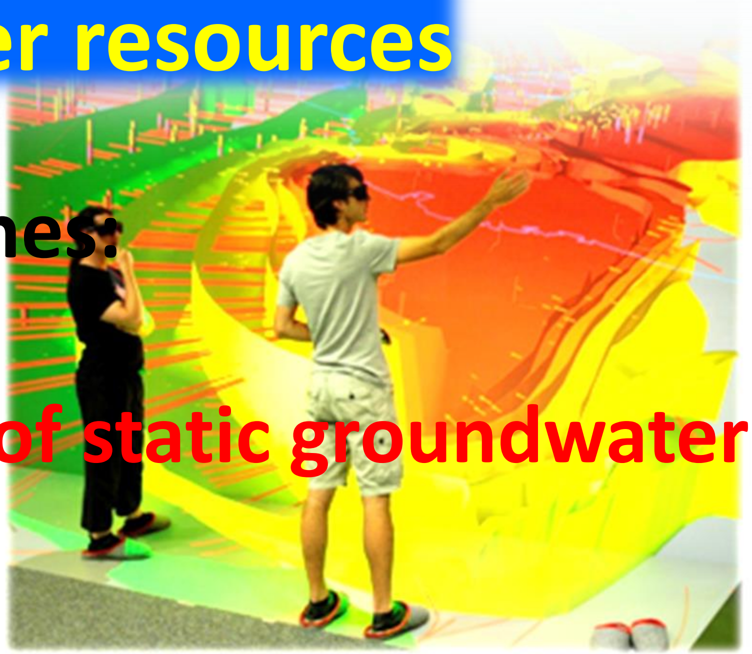


Estimation of groundwater budget

Inflow components:	Uncertainty (%)
Groundwater recharge	> 100
Wadi inflow	50
Outflow components:	
Natural discharge:	
Spring discharge	20
Inland and coastal sabkhas	75
Persian Gulf	> 100
Groundwater abstraction:	
Agriculture	20
Industry	15
Domestic water demand	15

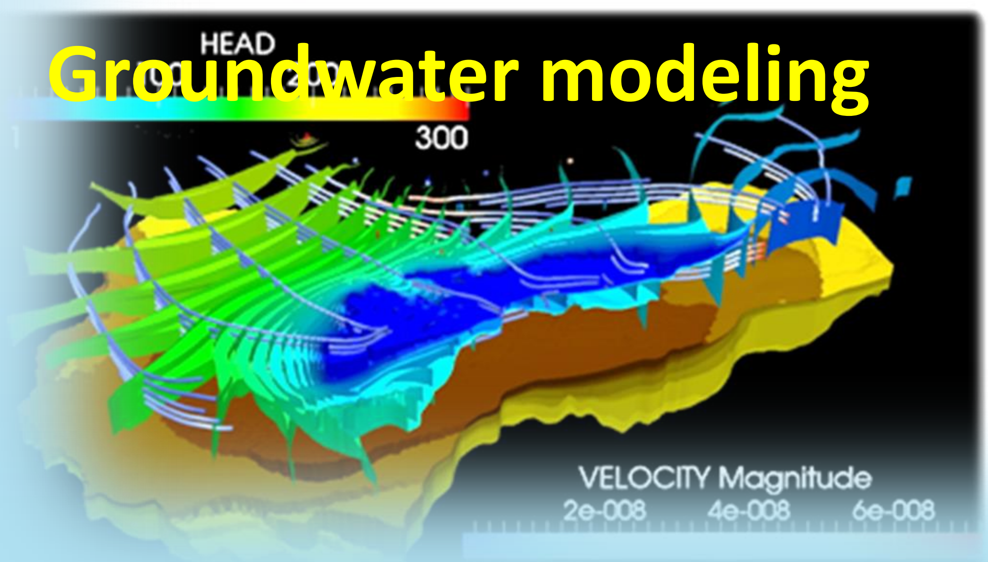
Process understanding: poor, moderate, good

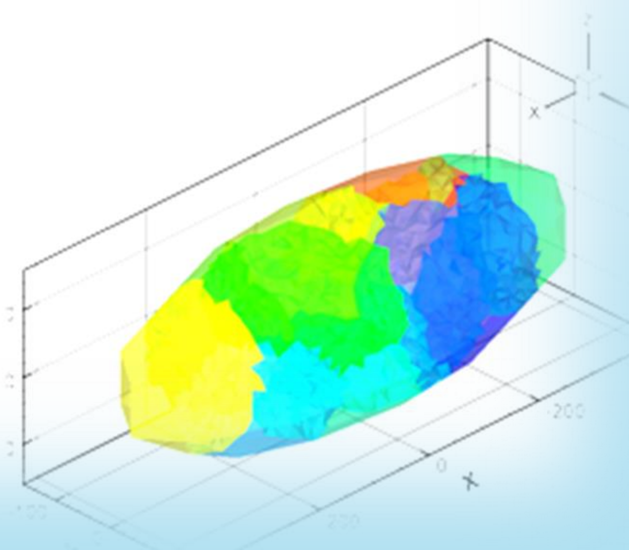
Estimation of groundwater resources



Two approaches:

- **Estimation of static groundwater resources**
- **Groundwater modeling**





Estimation of static groundwater resources

Data:	**Uncertainty (%)**
Aquifer geometry	**20**
Storage parameter (storage coefficient / specific yield)	**> 100**

Constraints:

Groundwater quality

Technical and economical possible abstraction:

- **drilling depth**
- **pumping height**
- **distance to consumer**

The estimation of total groundwater resources is academically! It leads to wrong expectations!

Sensitivity of flow equation in respect to T and S

Example Cooper-Jacob equation:

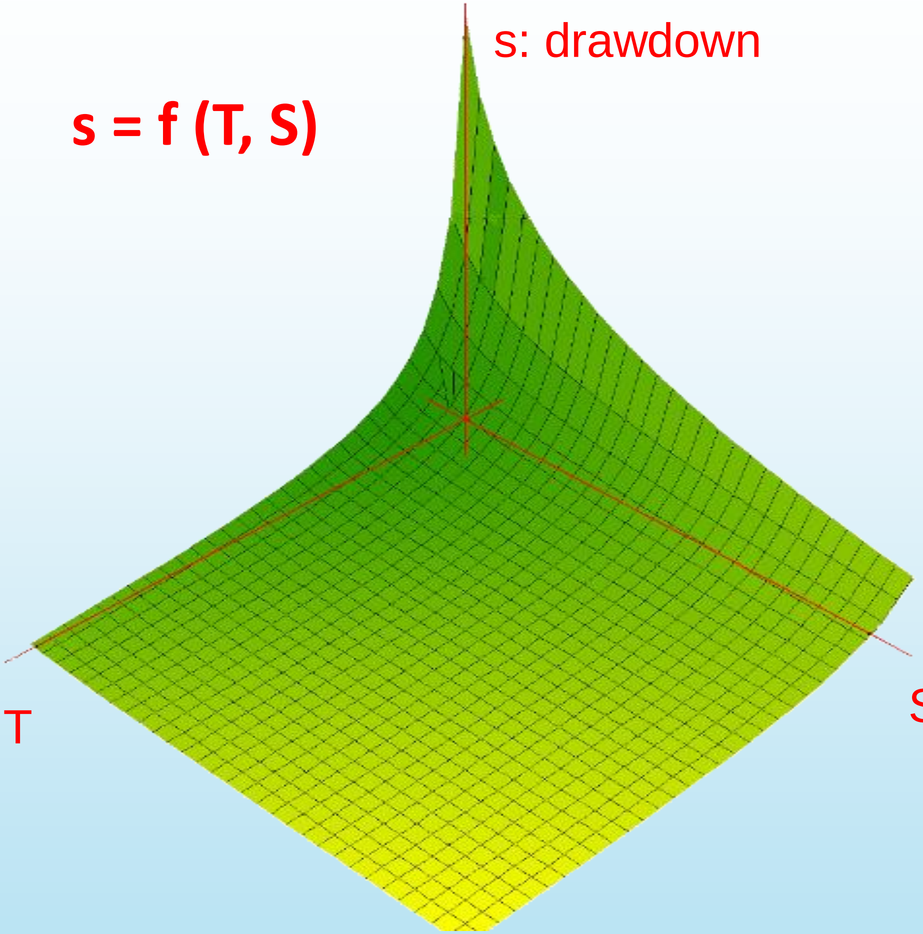
$$s = \frac{Q}{4\pi T}(-.5772 - \ln\frac{Sr^2}{4Tt})$$

Sensitivity of T and S in respect to s: estimation of

$$\frac{\partial s}{\partial T}\frac{T}{s} \quad \text{and} \quad \frac{\partial s}{\partial S}\frac{S}{s} \quad \text{gives:}$$

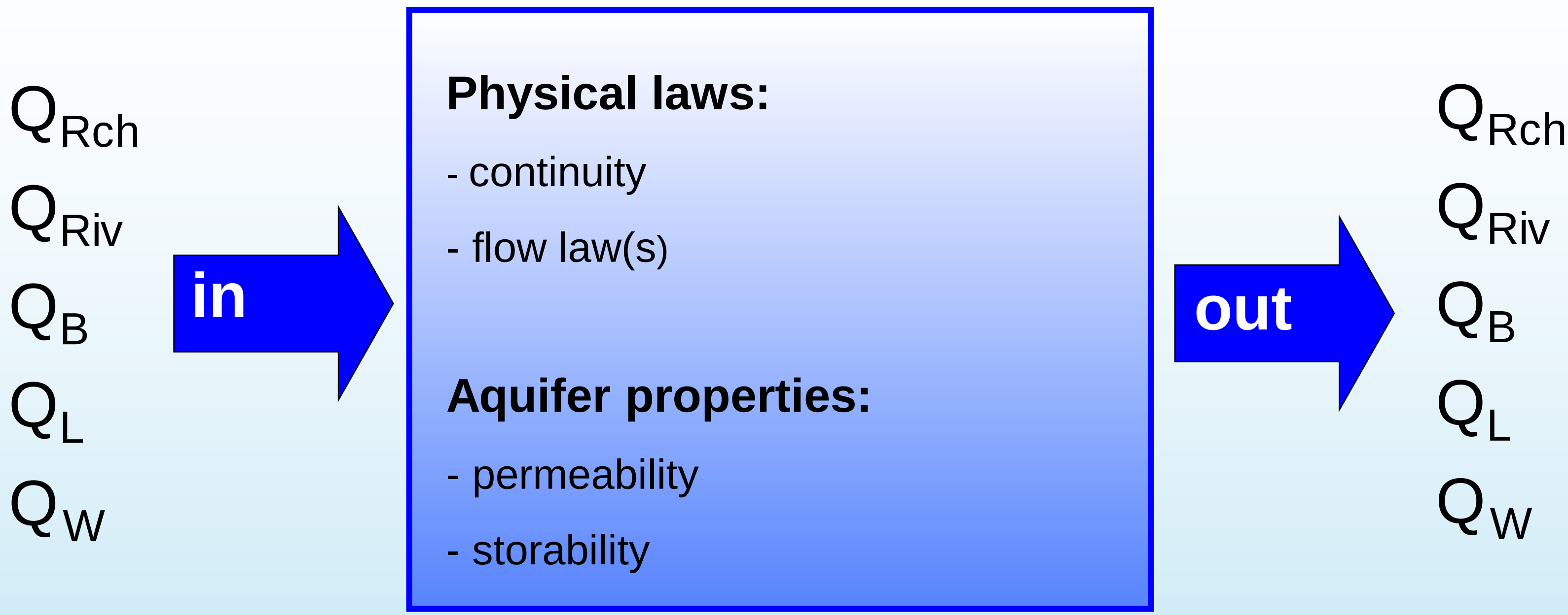
$$\frac{\partial s}{\partial T}\frac{T}{s} = -1 + \frac{1}{0.5772 - \ln(\frac{Sr^2}{4Tt})}$$

$$\frac{\partial s}{\partial S}\frac{S}{s} = -\frac{1}{0.5772 - \ln(\frac{Sr^2}{4Tt})}$$



The first term is always bigger than the second => T is always more sensitive than S!

Groundwater flow model



$$\text{Change in Storage} = (\pm Q_{Rch} \pm Q_{Riv} \pm Q_B \pm Q_L \pm Q_W)\,\Delta t$$

Solution: h = f (x,y,z,t)

Required: boundary and initial conditions

QRch: natural groundwater recharge or discharge

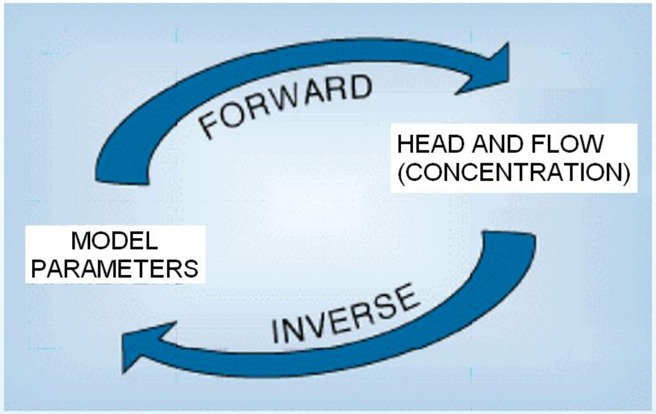
QRiv: exchange with surface water bodies

QB: subsurface flow over boundary

QL: leakage flow from and to adjacent aquifers

QW: abstraction or infiltration (e.g. wells)

Groundwater modeling: inverse problem



Given: heads / flows (concentrations)

Wanted: parameter distribution

Difficulties:
ill-posedness
no unique solution may exist
measurement errors make result unreliable

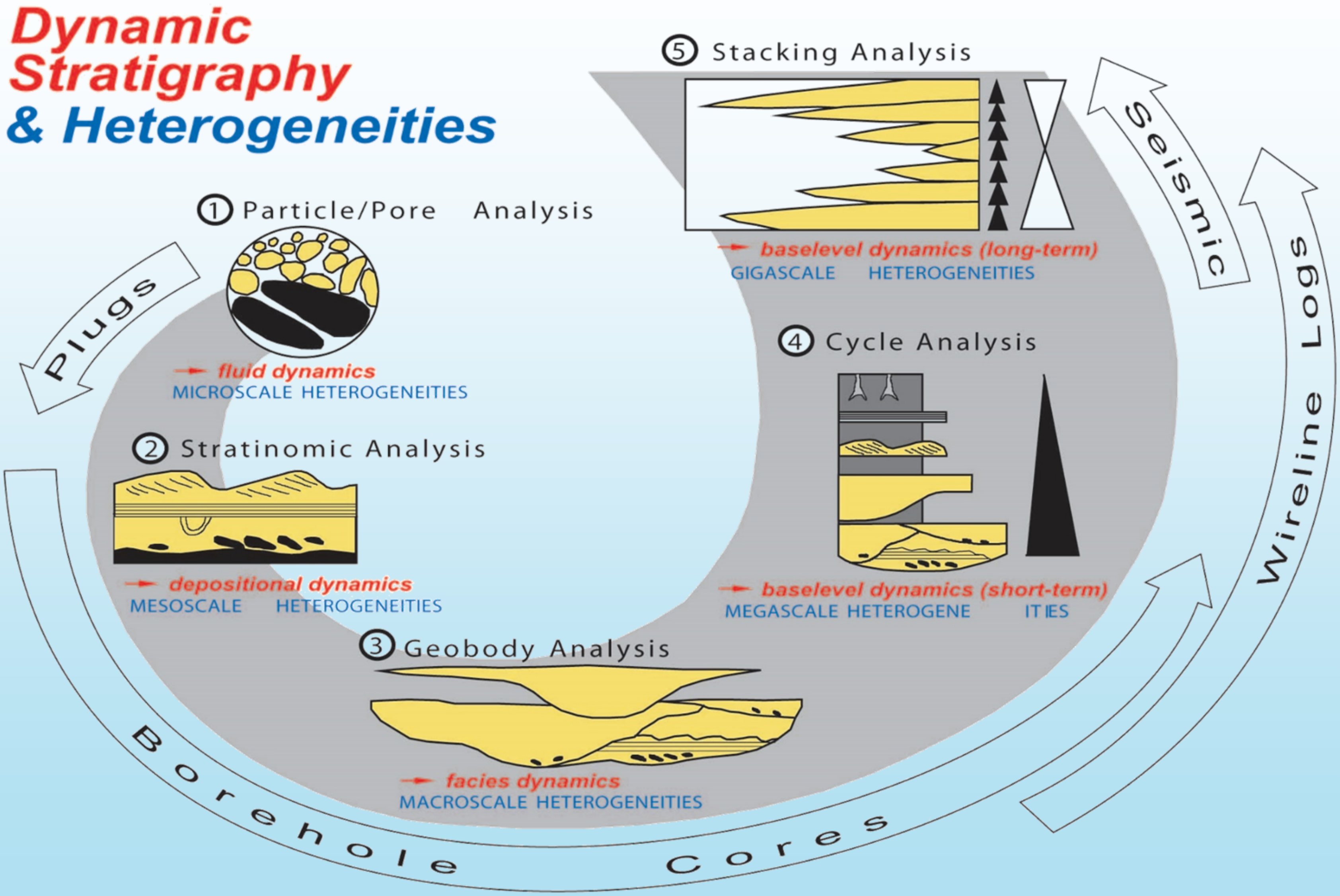
Ways out:
joint use of head and flow (and concentrations) measurements

estimation of uncertainty

continuous amendment of model

introduction of 'a priori' knowledge

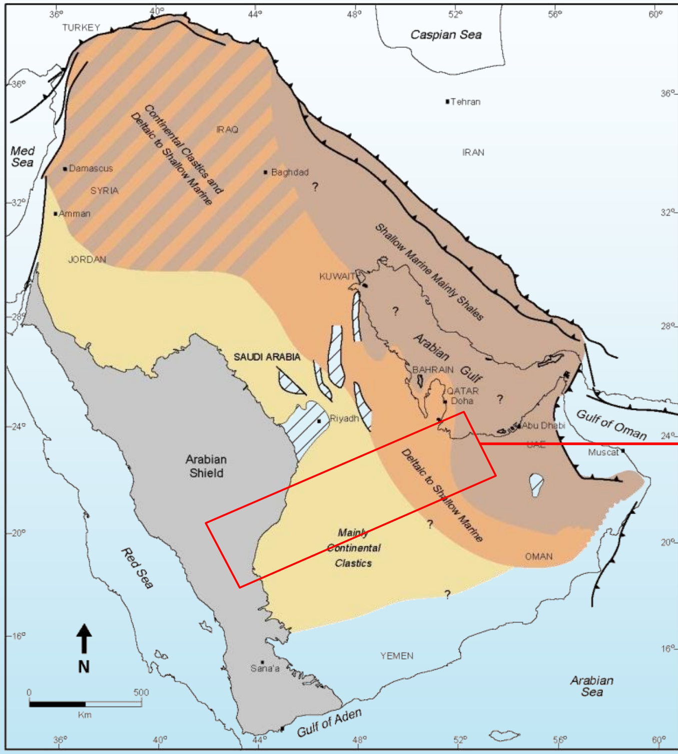
Aquifer analysis: micro- to macro scale



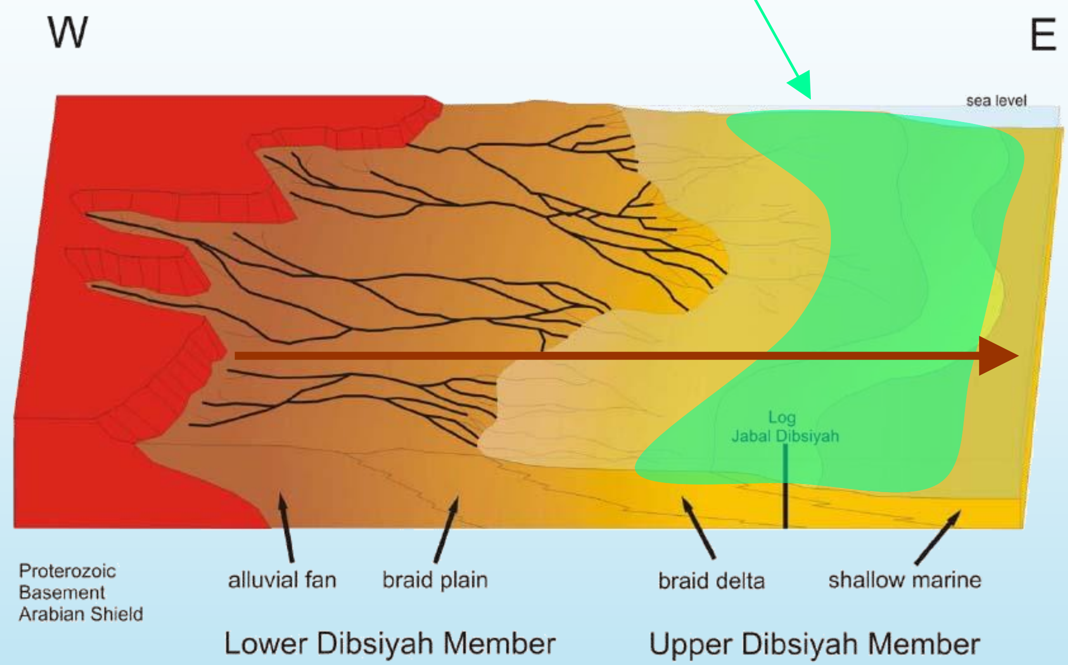
Aquifer properties: regionalization

Basin scale facies model

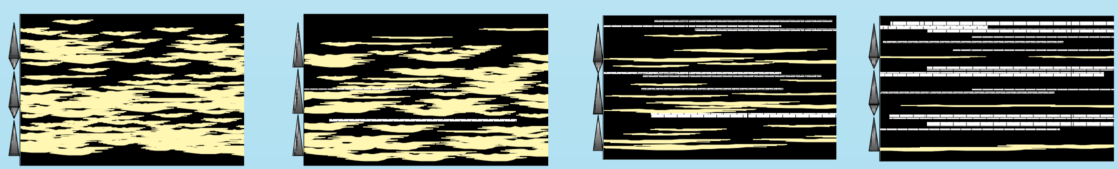
Late Cambrian: Environments of Deposition



Zone of bioturbation = zone of anisotropy



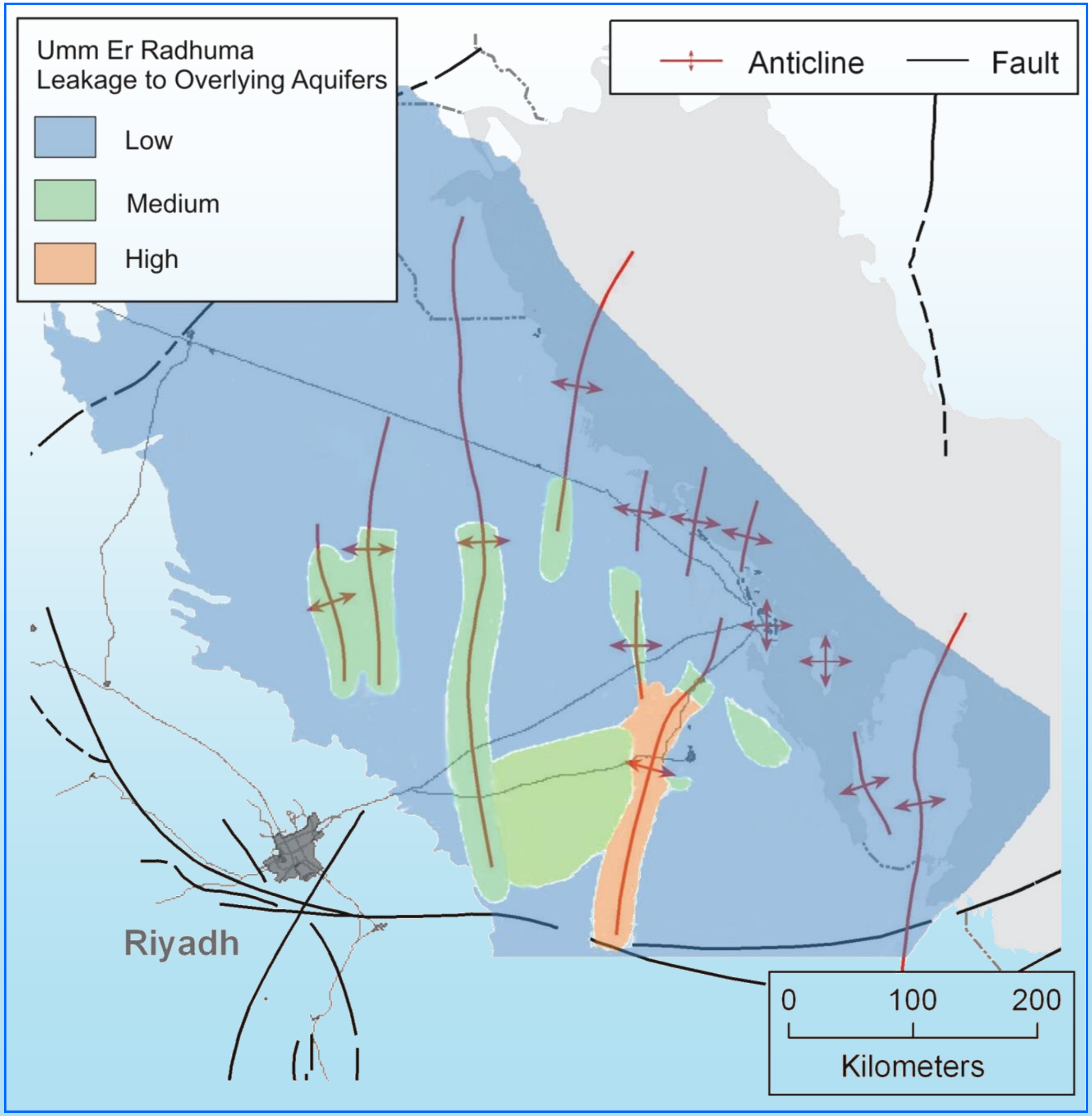
Fining trend = increase of aquicludes and aquitards



10km wide, 50m thick

box dimens

Tectonics



Main anticline structures and faults within the aquifer system

Processes:

1. Faulting

- intense fracturing along anticlines

2. Dissolution of gypsum

- collapse structures
- increase of fracturing

3. Karstification

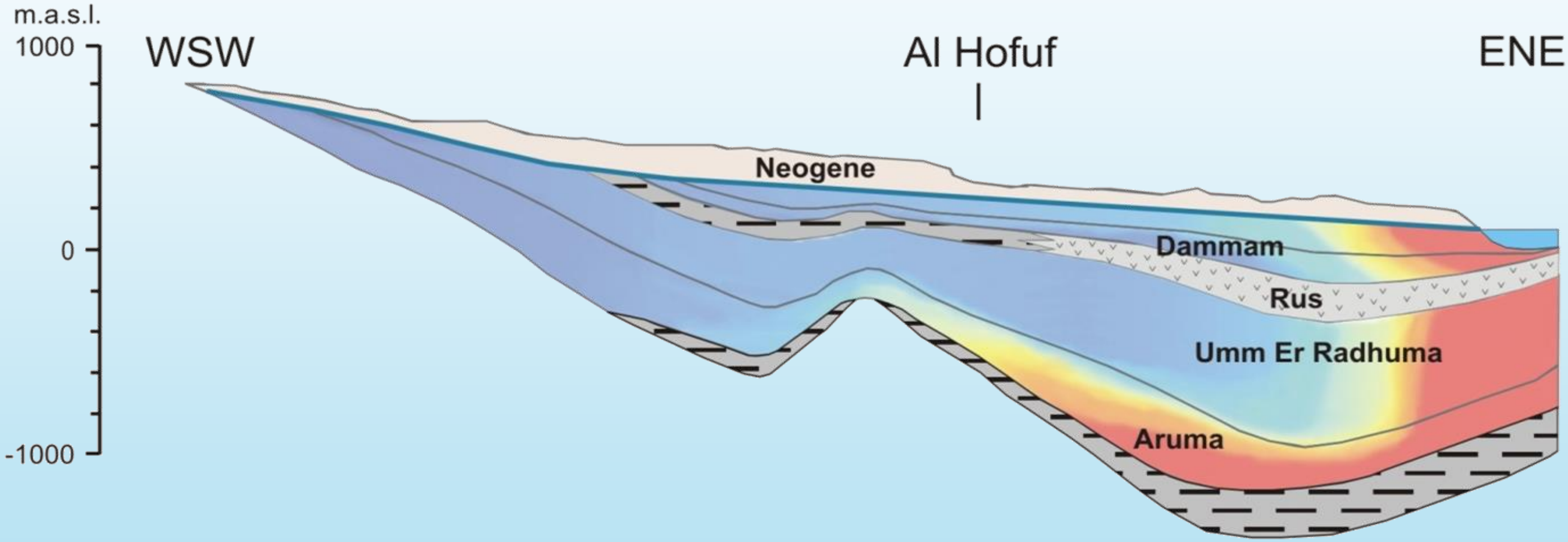
- dissolution of limestones
- enlargement of fractures

The processes show a positive feedback effect!

Hydrochemical information

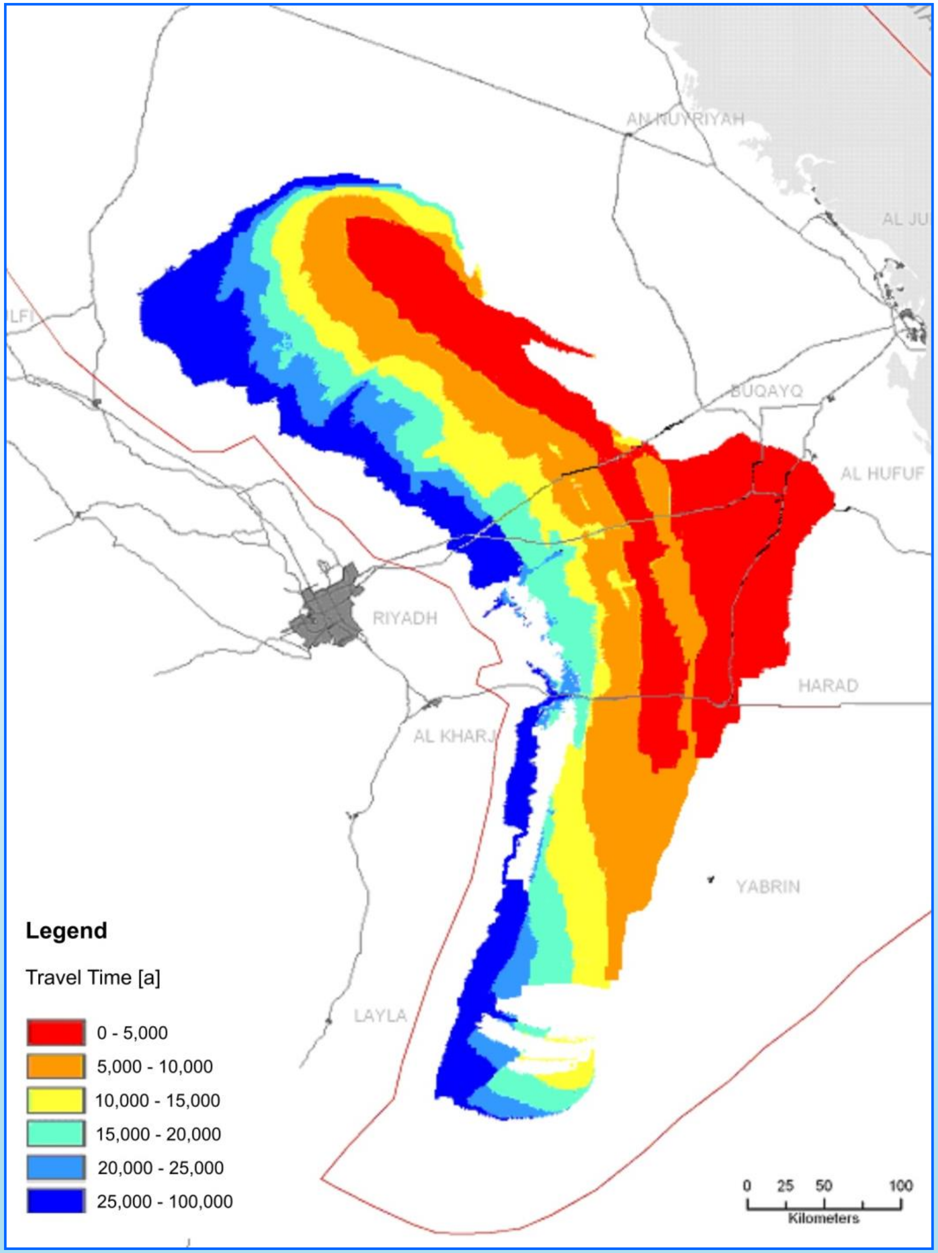
Distribution of the total dissolved solids concentration of the ground-water

Hydro chemical evolution of groundwater along flow path



Major Cations Major Anions	Calcium Bicarbonate	Calcium, Sodium Sulphate, Chloride	Sodium, Calcium Chloride, Sulphate
Processes	Solution of Carbonates O_2 decreases	Solution of Evaporites Ionic Exchange	Ionic Exchange Solution of Evaporites

Isotopes information: groundwater age

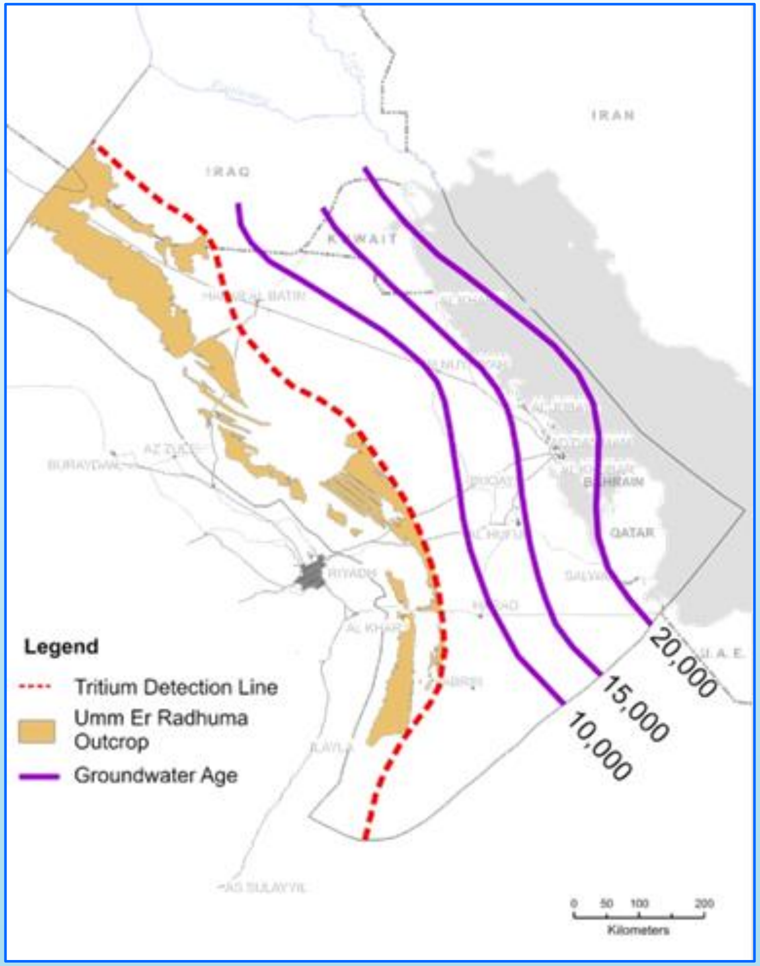


Simulated travel time to Al Hassa oasis

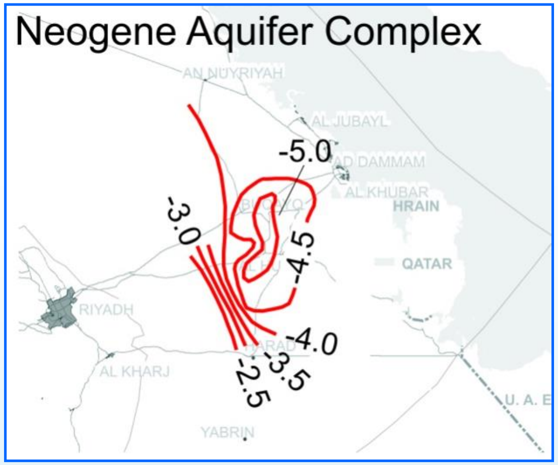
Mean residence time 12,000 a

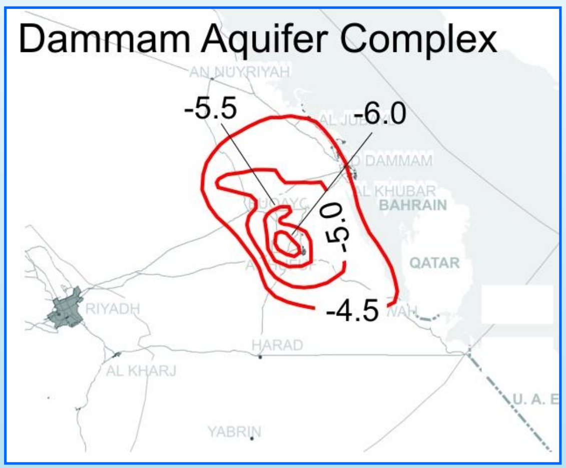
Groundwater age Umm Er Radhuma aquifer

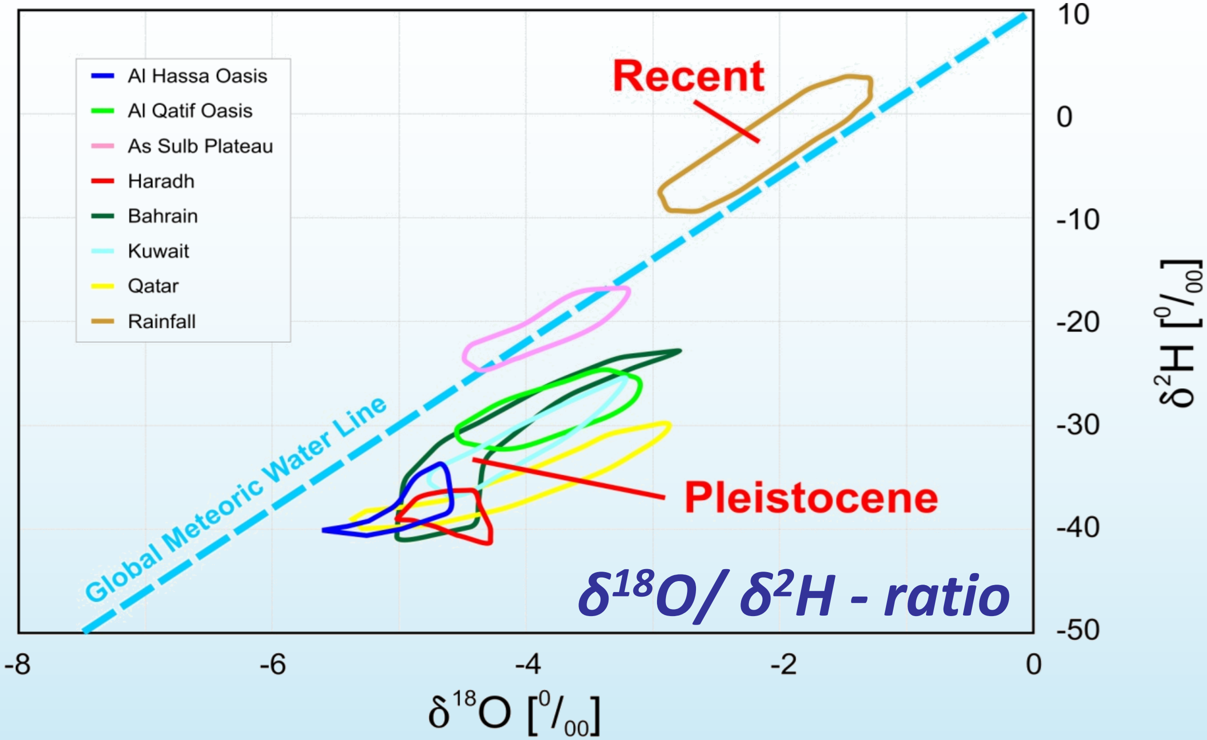
^{14}C-groundwater age and ^{3}H-detection line

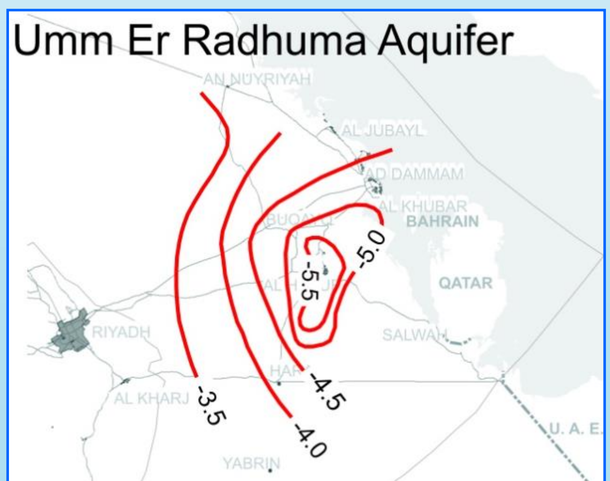


Stable Isotopes: $\delta^{18}O$ and $\delta^{2}H$



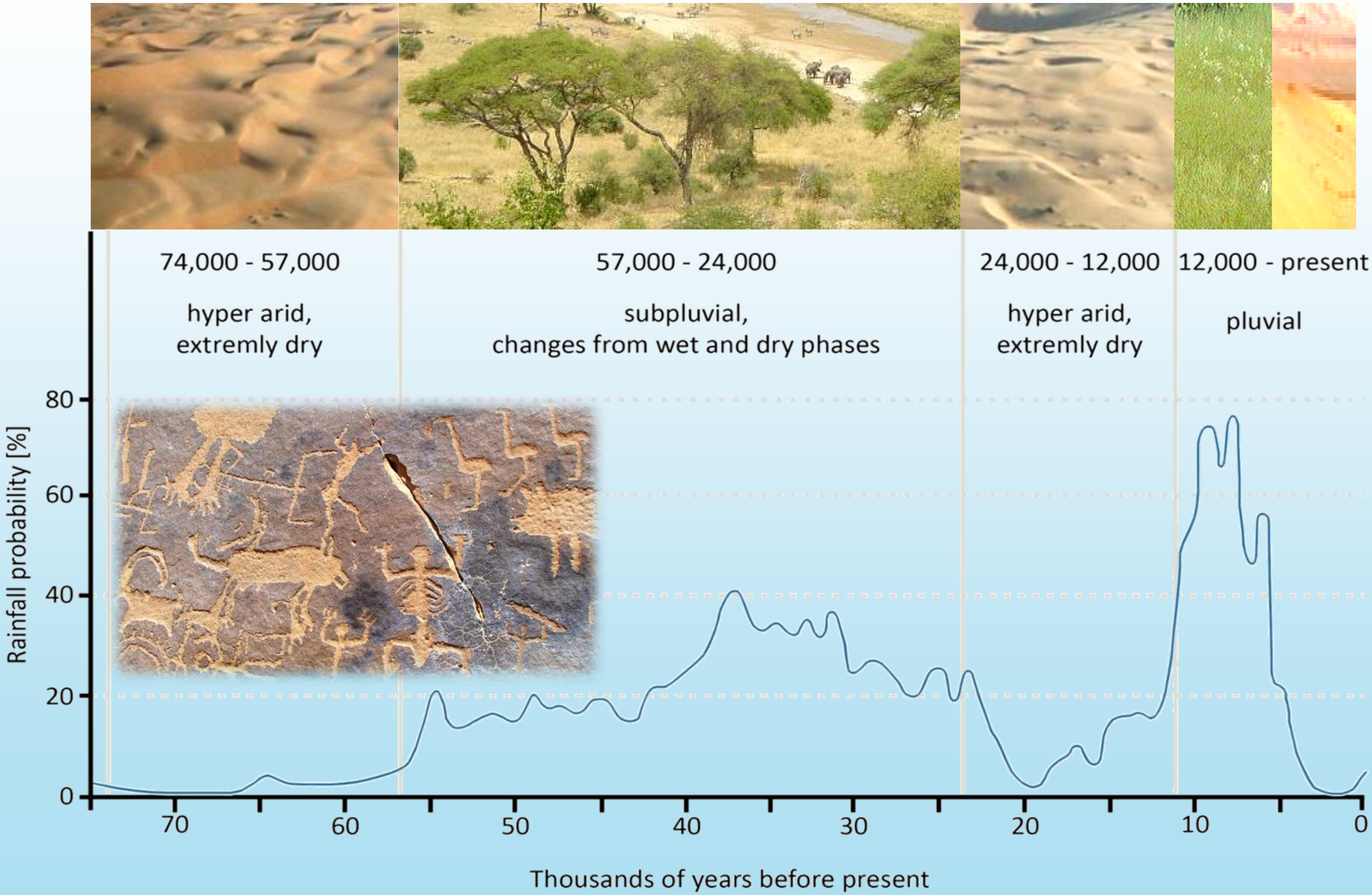






Spatial distribution of $\delta^{18}O$-values

Climate development

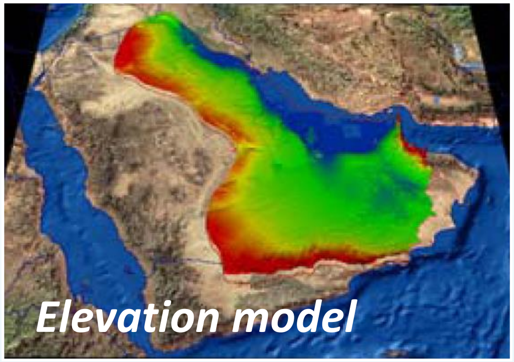


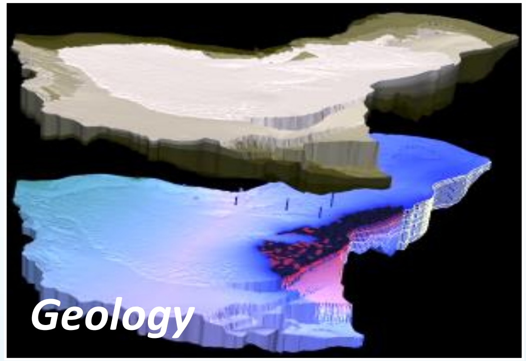
Water management

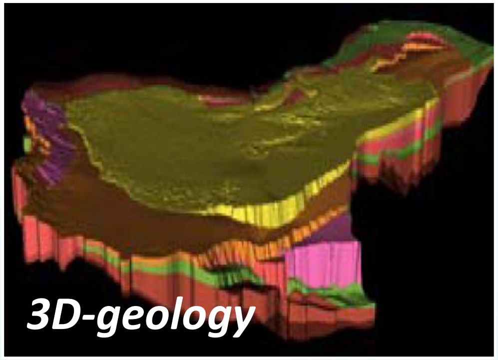
Tools:

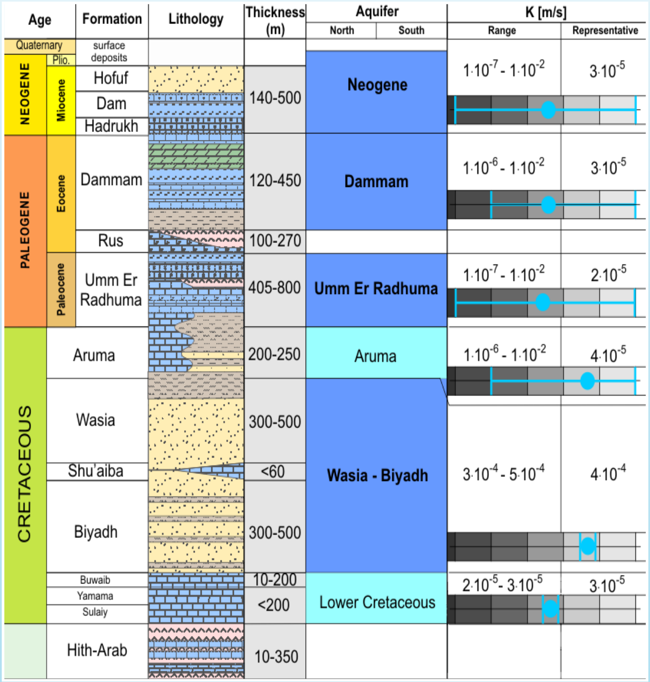
- Groundwater models
- Economic models for costs and infrastructure
- Water demand prognostic models

Groundwater model



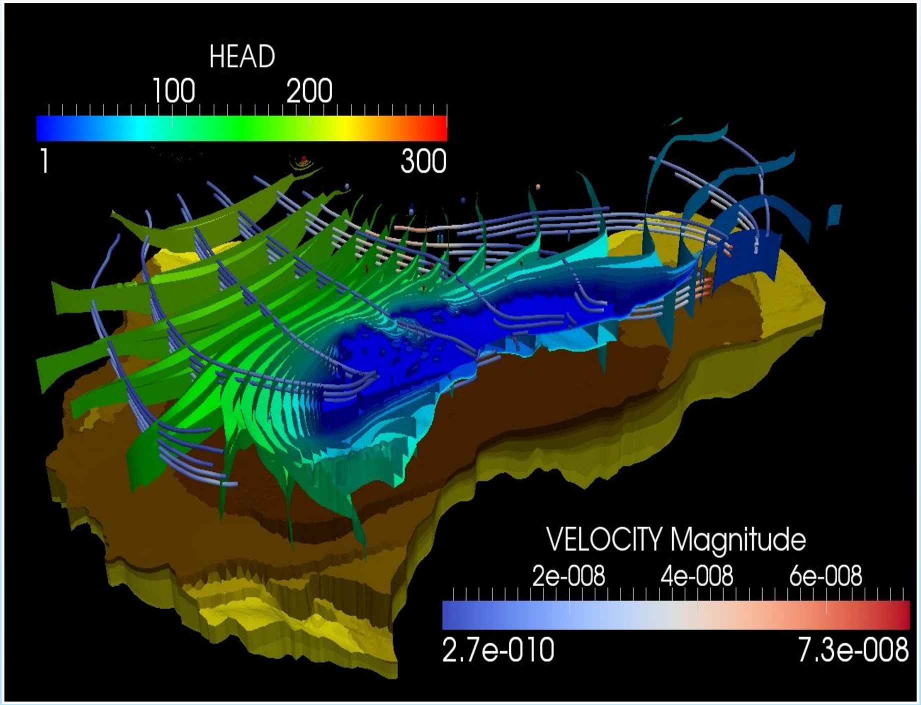






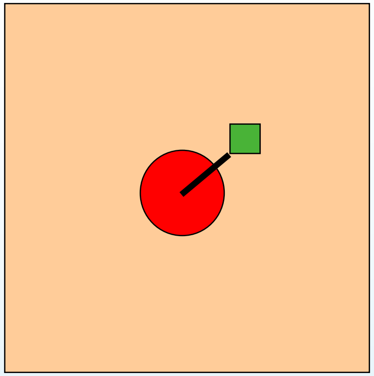
Age		Formation	Lithology	Thickness (m)	Aquifer (North / South)	K [m/s] Range	K [m/s] Representative
Quaternary		surface deposits					
NEOGENE	Plio.						
NEOGENE	Miocene	Hofuf		140-500	Neogene	$1 \cdot 10^{-7}$ - $1 \cdot 10^{-2}$	$3 \cdot 10^{-5}$
NEOGENE	Miocene	Dam					
NEOGENE	Miocene	Hadrukh					
PALEOGENE	Eocene	Dammam		120-450	Dammam	$1 \cdot 10^{-6}$ - $1 \cdot 10^{-2}$	$3 \cdot 10^{-5}$
PALEOGENE	Eocene	Rus		100-270			
PALEOGENE	Paleocene	Umm Er Radhuma		405-800	Umm Er Radhuma	$1 \cdot 10^{-7}$ - $1 \cdot 10^{-2}$	$2 \cdot 10^{-5}$
CRETACEOUS		Aruma		200-250	Aruma	$1 \cdot 10^{-6}$ - $1 \cdot 10^{-2}$	$4 \cdot 10^{-5}$
CRETACEOUS		Wasia		300-500	Wasia - Biyadh	$3 \cdot 10^{-4}$ - $5 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
CRETACEOUS		Shu'aiba		<60			
CRETACEOUS		Biyadh		300-500			
CRETACEOUS		Buwaib		10-200	Lower Cretaceous	$2 \cdot 10^{-5}$ - $3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$
CRETACEOUS		Yamama		<200			
CRETACEOUS		Sulaiy					
		Hith-Arab		10-350			

Hydrogeological model



Groundwater model

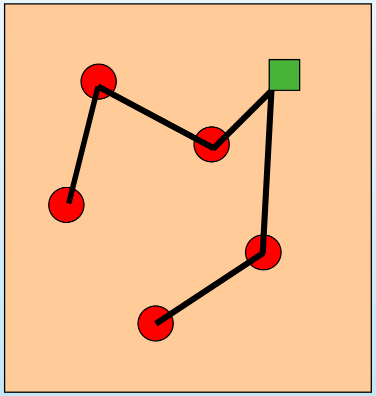
Optimization of abstraction strategy



One big well field in the neighborhood of consumer

+ low transportation costs
+ simple implementation

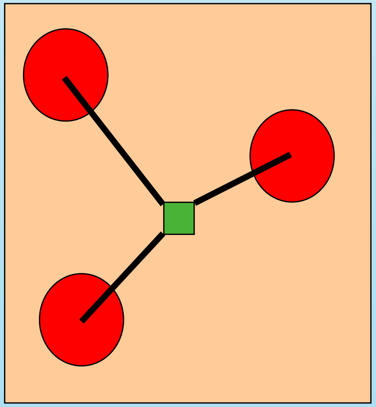
- high pumping costs
- rapid aquifer depletion



Several small well fields in large distance from consumer

+ low pumping costs

- high transportation costs
- implementation difficult



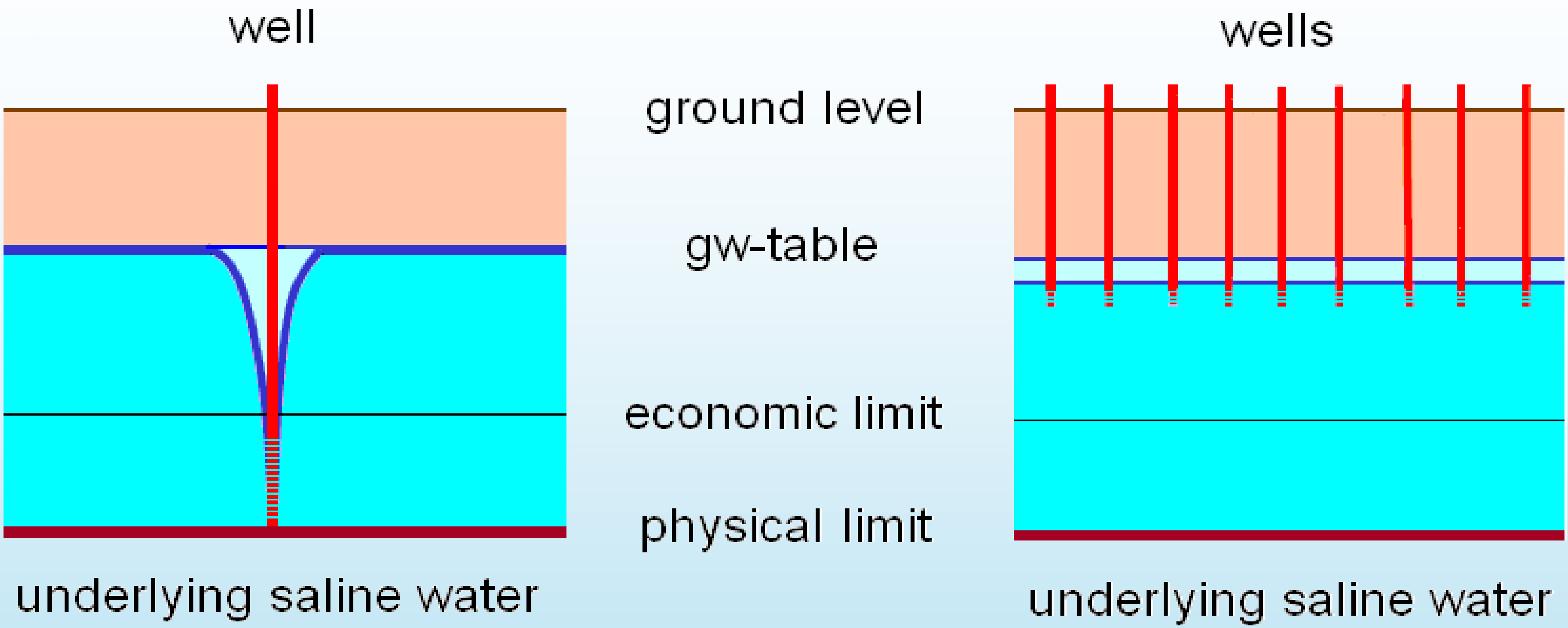
Rotation between several big well fields. Possibility for the recovery

+ long operation time

- maintenance costs for inactive wells

Intelligent scheme makes a huge economic difference!

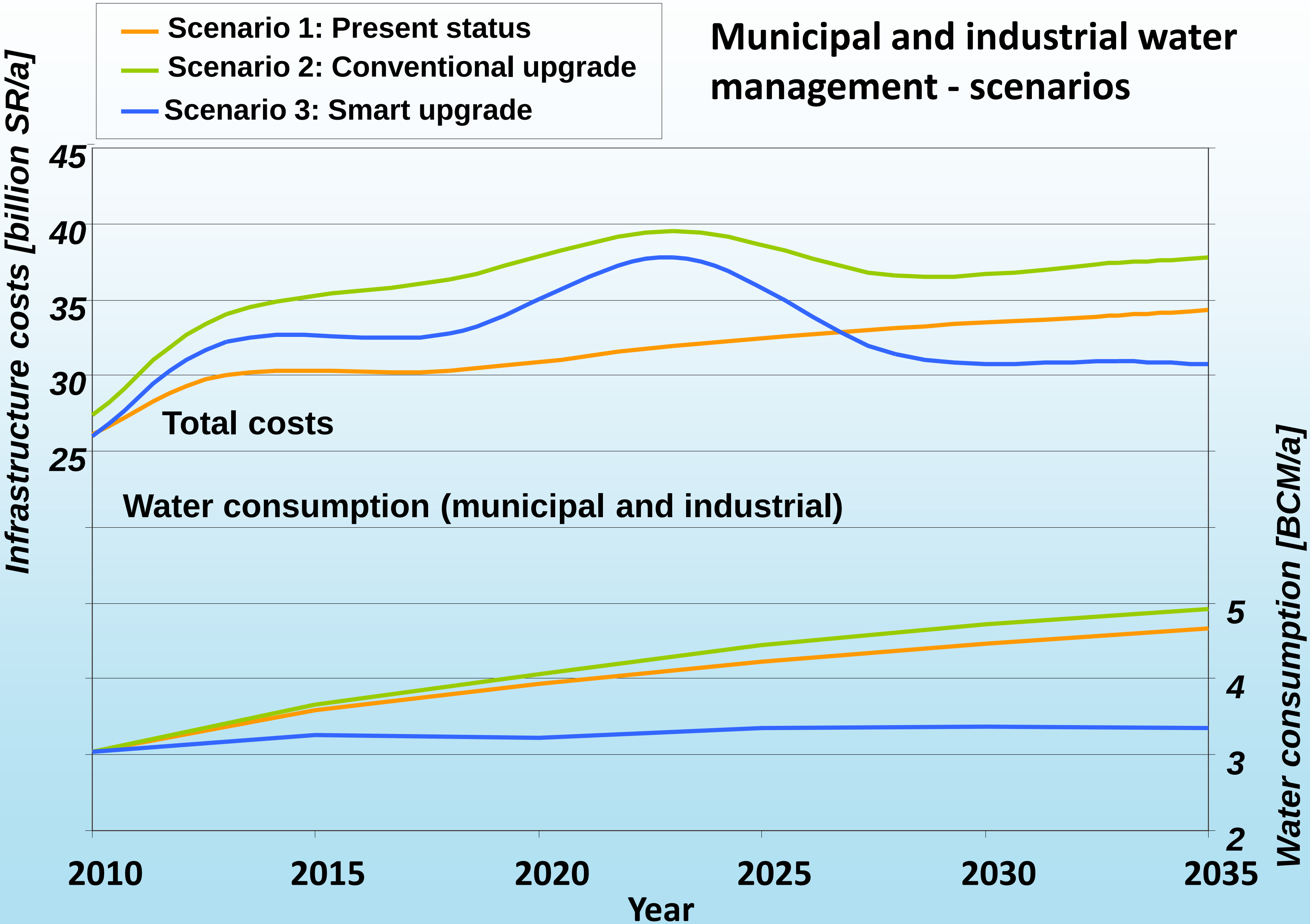
Water quality: upconing of salt water



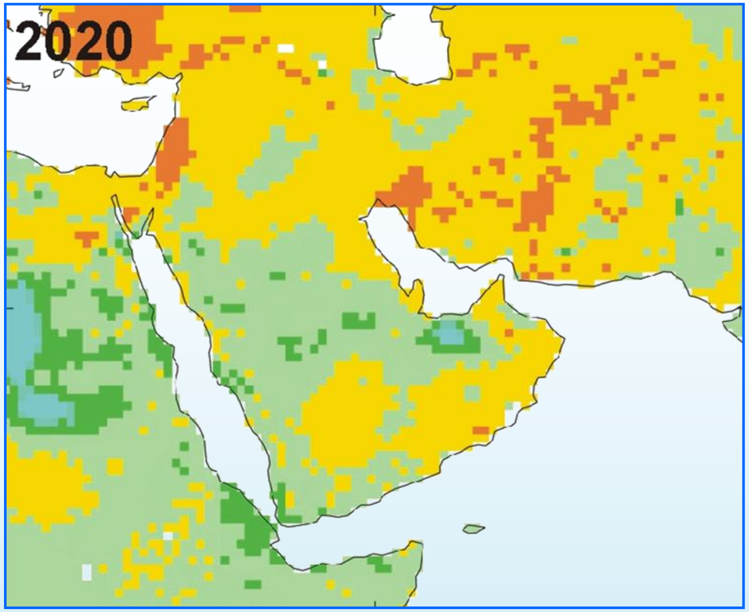
deep cone of depression brings up salt water fast!

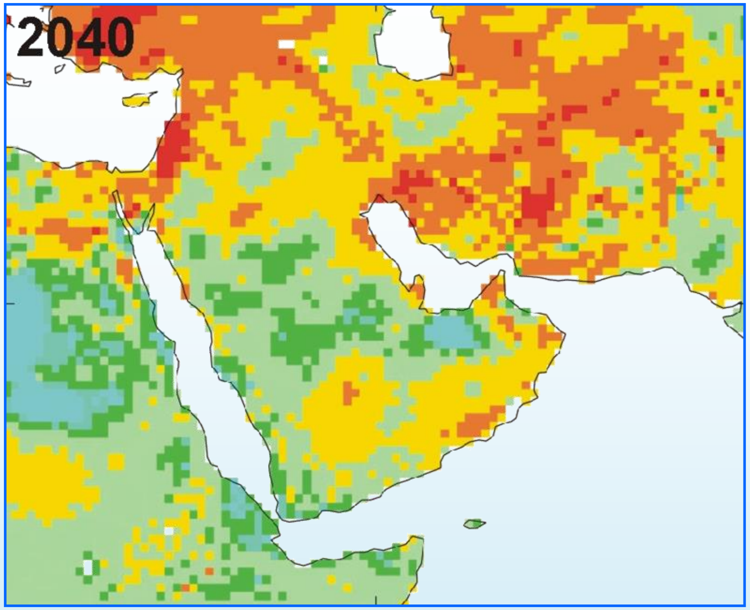
Constraint for optimization favoring distributed abstraction

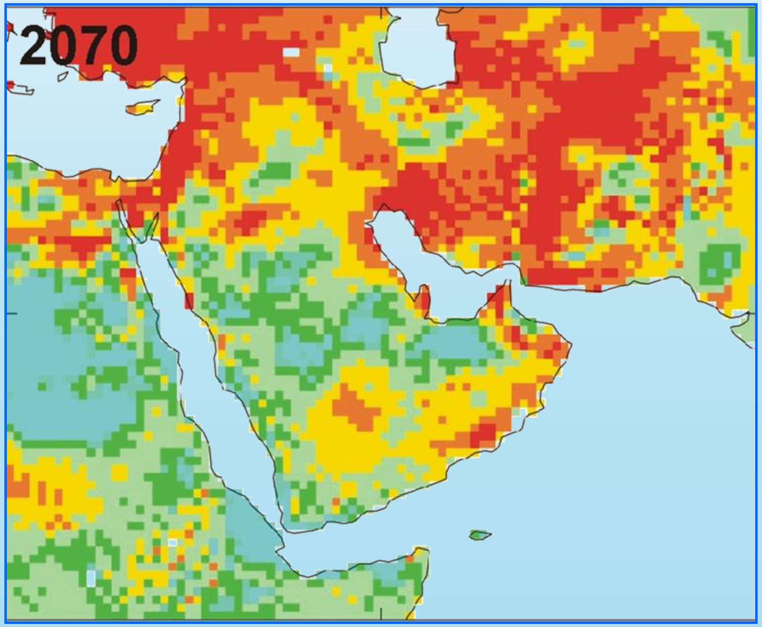
Prognostic water demand models

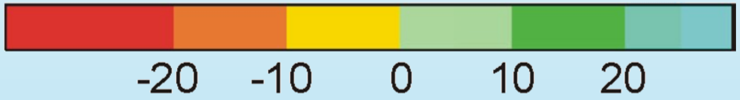


Impact of climate change









Regional climate model predictions for precipitation changes (in %) across the Persian Gulf region compared to the year 1990 (from Hemming et al. 2007)

Thank you very much for your kind attention

'The Geologist' by Carl Spitzweg, 1860

Thank you very much for your kind attention

‘ The Geologist’ today