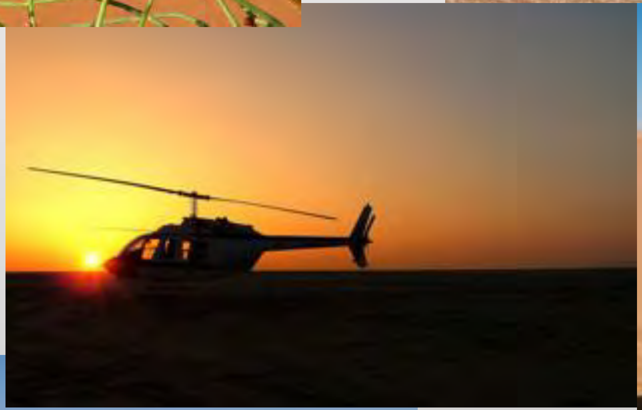
GRACE and geochemical–based approach to assess the age, origin, and optimum utilization of fossil aquifers in the Arabian Peninsula

Mohamed Sultan, Karem Fathy
Western Michigan University
Kalamazoo MI

Himanshu Save
Center for Space Research
Univ Texas Austin

GSTM 2017

The Landscape

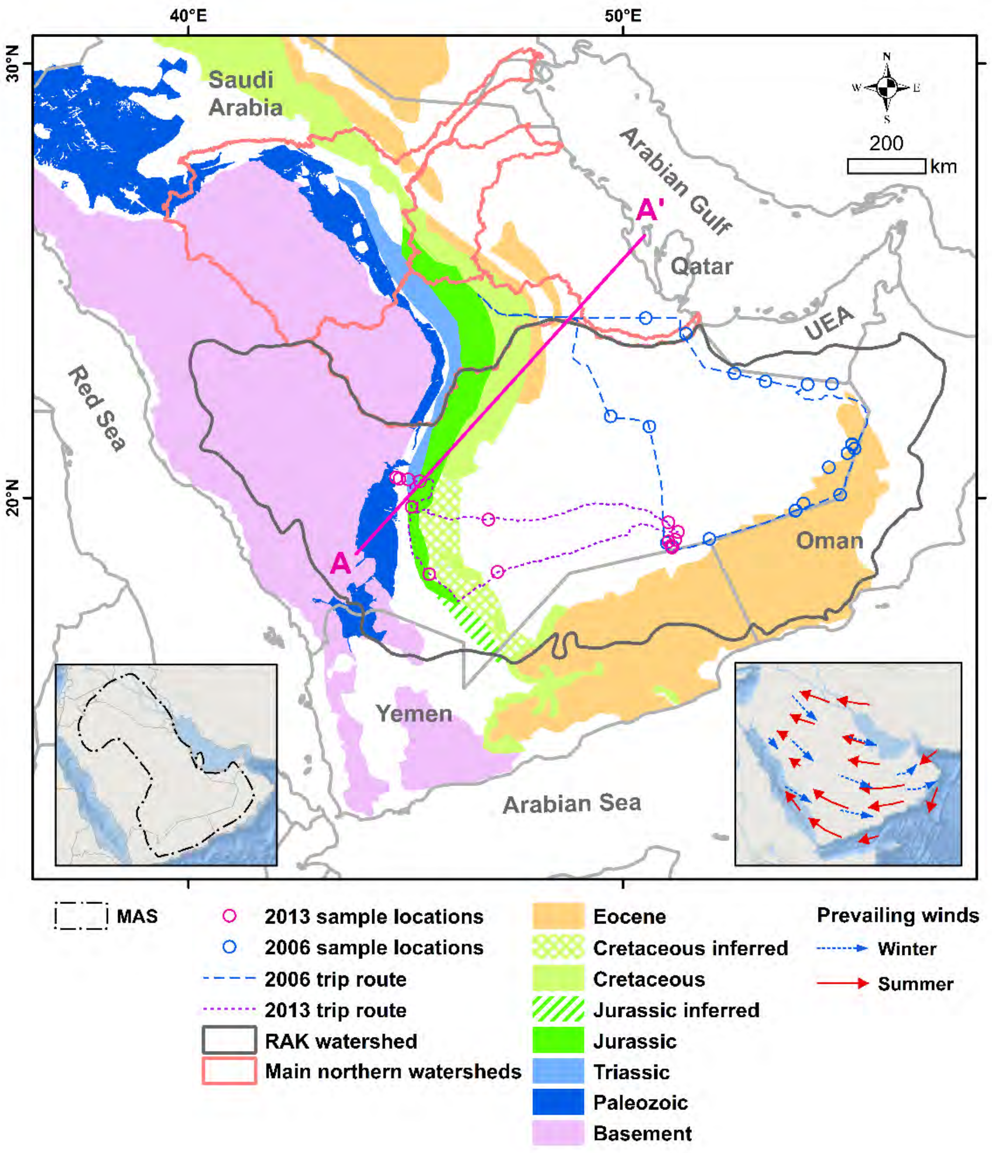


Approach/Justification

- Utilize observations from GRACE to differentiate between areas utilized in a sustainable manner from others witnessing excessive extraction and estimate optimum (sustainable) extraction rates for the overexploited areas;
- GRACE sustainability investigation focuses on:
  - water quantity, not quality,
  - does not address aquifer's geologic and hydrologic settings, and the age, origin, and history of its groundwater.
- For these reasons, we conduct additional geochemical studies over areas that show promising GRACE sustainability results.

Mega Aquifer System

- The MAS underlies the deserts of the Arabian Peninsula
- Occupies 2×10^6 km^2 in the KSA and in neighboring Iraq, Jordan, Oman, Yemen, and the United Arab Emirates.
- Southern sections of MAS underlies the Rub Al Khali (RAK) and are herein referred to as the Rub Al Khali Aquifer System (RAKAS).

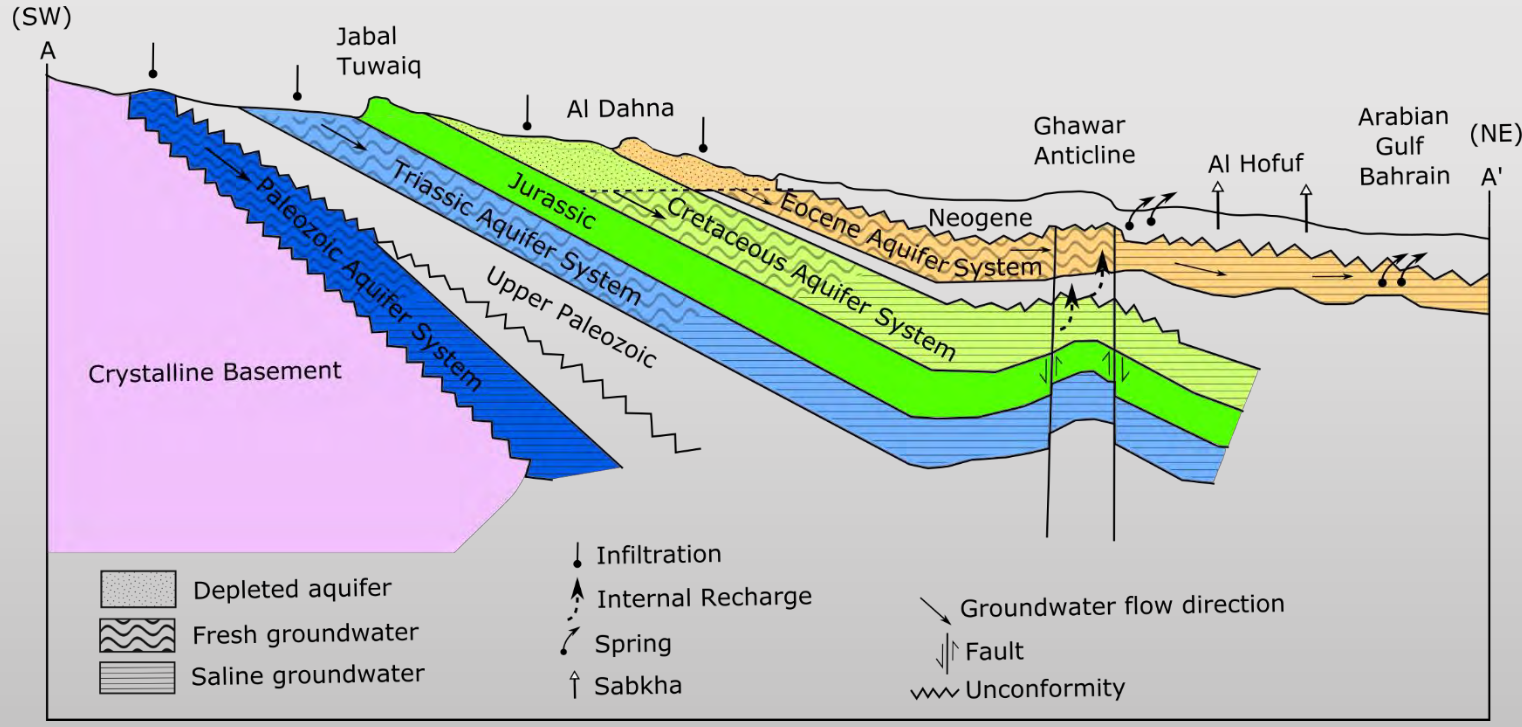


Cross section

- Thick sequences of the MAS unconformably overlie Red Sea Hills basement sequences

- MAS composed of Cambrian to recent sedimentary rocks dip gently & thicken to the east, up to 5 km near the Arabian Gulf

- Modern recharge from precipitation over Red Sea Hills.

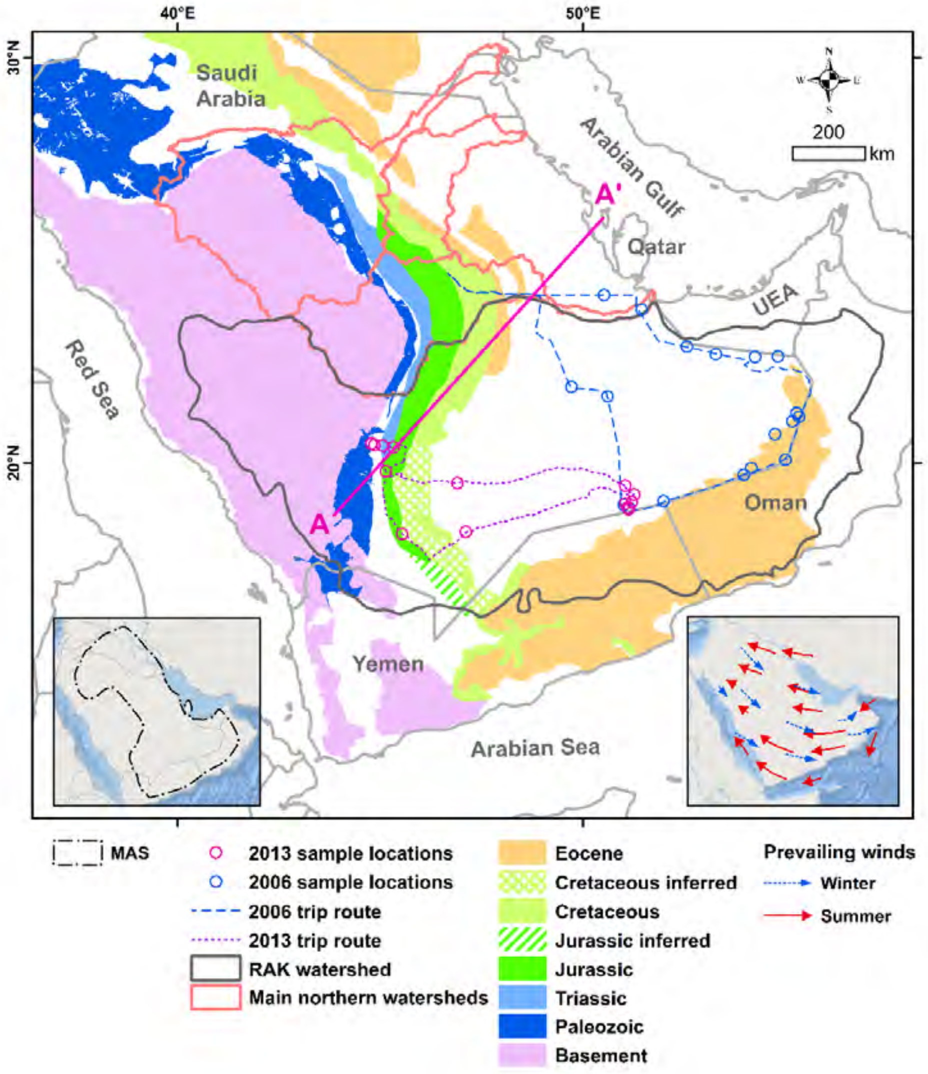


Cl-36 Ages

Sample ID	^{36}Cl atoms/kg	^{36}Cl/Cl ($\times 10^{-15}$)	^{36}Cl model age, kyr; $^{*}R_{I}$;$^{\dagger}R_{SE}$
EQ2-05	2.02E+08	46 ± 6	170 ($^{+70}/_{-60}$)
EQ2-07	2.15E+07	8 ± 3	>970
EQ2-19	1.12E+09	34 ± 4	320 ($^{+70}/_{-60}$)
EQ2-20	7.75E+07	20 ± 4	600 (+130/−100)
EQ2-21	1.17E+08	27 ± 4	420 ($^{+80}/_{-70}$)
EQ2-23	1.06E+08	20 ± 4	590 (+130/−100)
EQ2-24	---	28 ± 4	400 ($^{+80}/_{-70}$)
EQ2-46	2.99E+08	58 ± 6	54 (+50/−50)
EQ2-57	5.69E+08	61 ± 6	30 (+50/−40)
EQ2-58	8.44E+08	87 ± 7	<50
EQ2-59	1.62E+08	61 ± 5	30 (+40/−40)
EQ2-60	1.16E+09	65 ± 5	0 (+40/−40)
EQ2-61	1.81E+08	54 ± 6	90 (+60/-50)

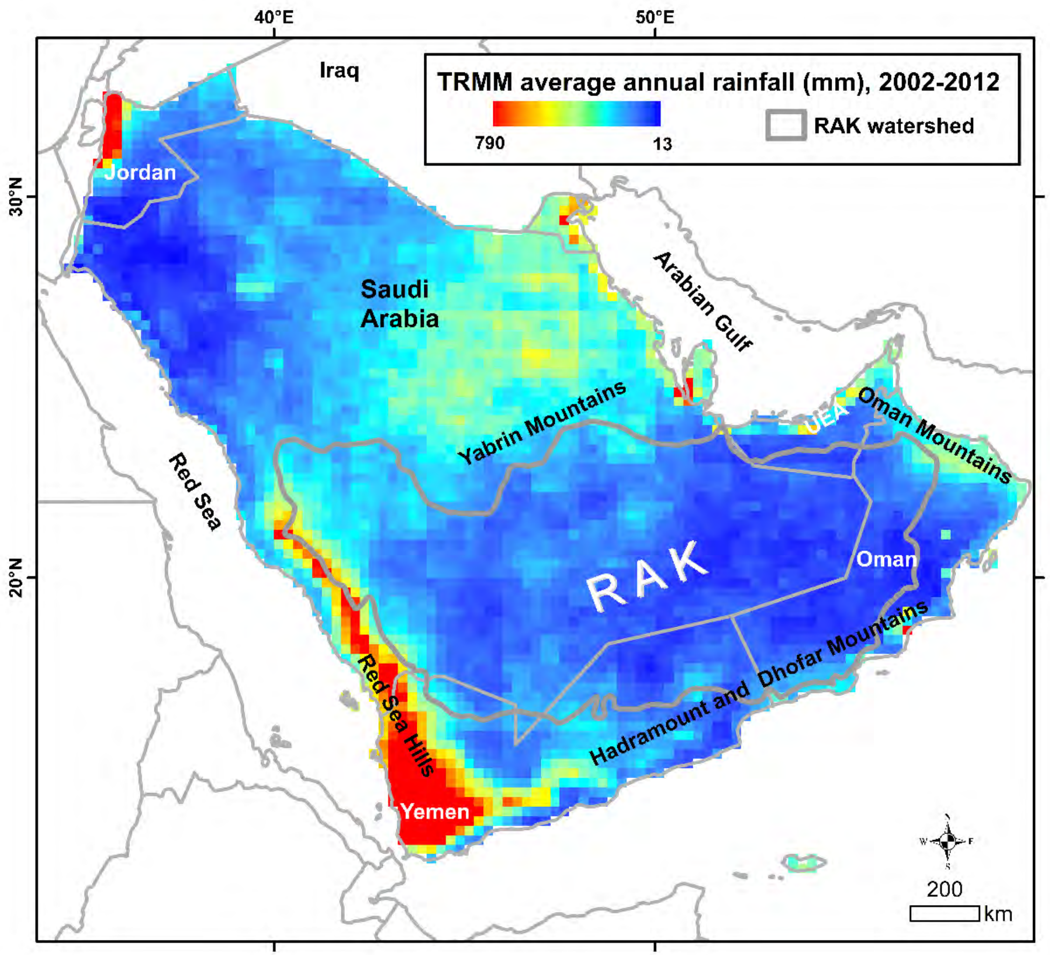
* Initial ^{36}Cl/Cl ratios = 65 ($\times 10^{-15}$)

† Subsurface secular equilibrium ratio = 5($\times 10^{-15}$)



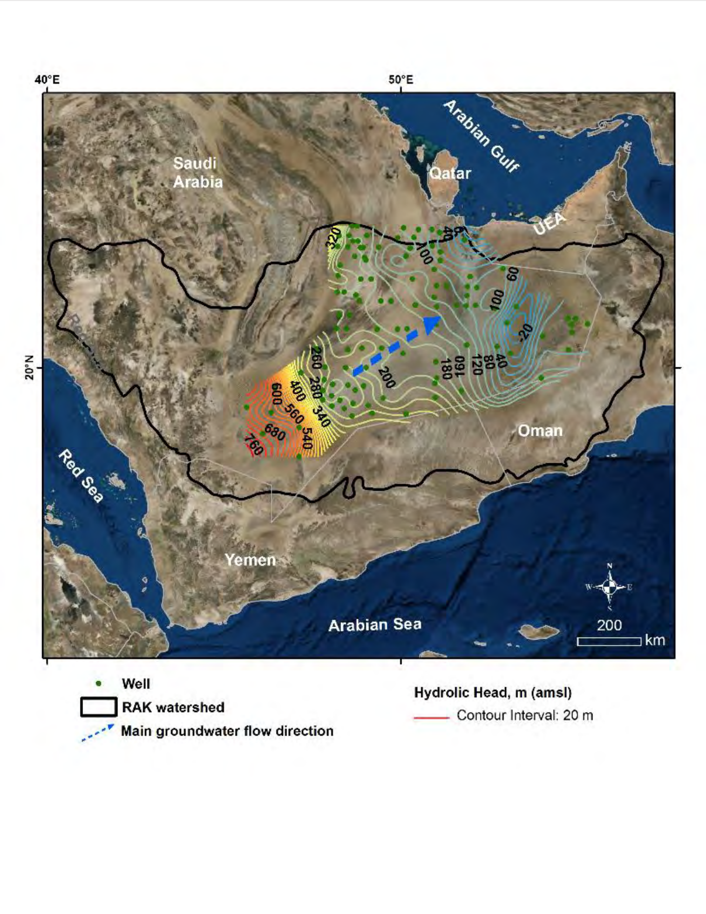
Average Annual Precipitation from TRMM; 2002 through 2012

- Precipitation over Arabian Peninsula is scarce except over the mountainous areas surrounding the RAKAS



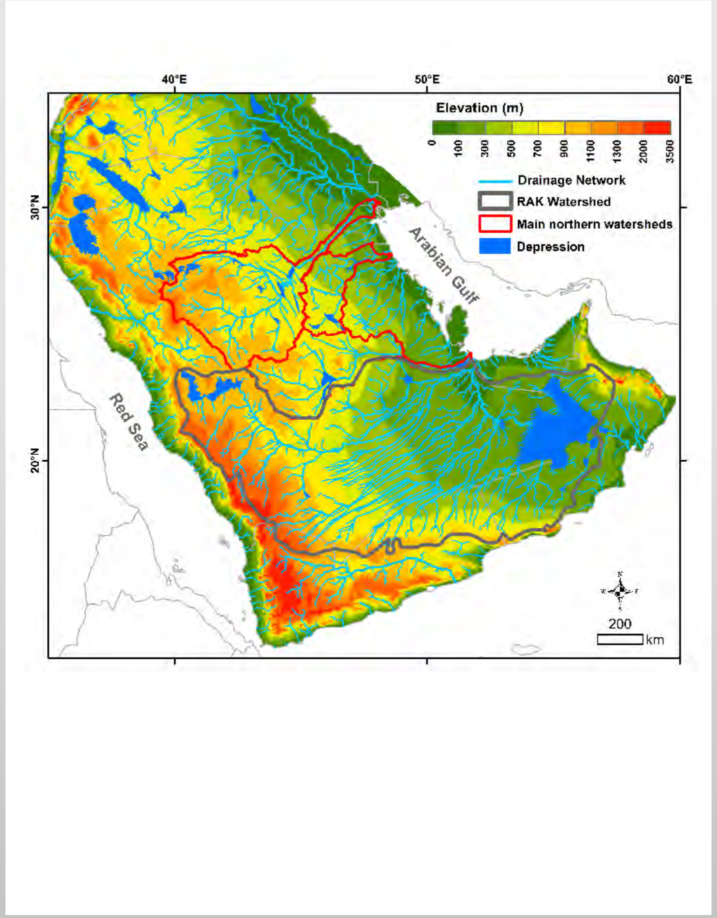
Ground water flow direction

- Orthogonal to contours showing water levels
- In Rub Al Khali Aquifer System: west to east groundwater flow
- Also true for central & northern Arabia
- Confined except in recharge areas



West to east drainage system

- Precipitation over Red Sea Hills is channeled by extensive drainage networks to recharge aquifers cropping out at the foothills of the Red Sea mountains



GRACE data

- CSR Mascon solutions (Save et al., 2016) were used to estimate temporal variations in TWS over investigated area for the period April 2002 to June 2016.

- All mascon solutions were utilized without (1) any post-processing and/or filtering or (2) application of any empirical scaling factors (Save et al., 2016)

- Change in groundwater storage over the MAS extracted using:

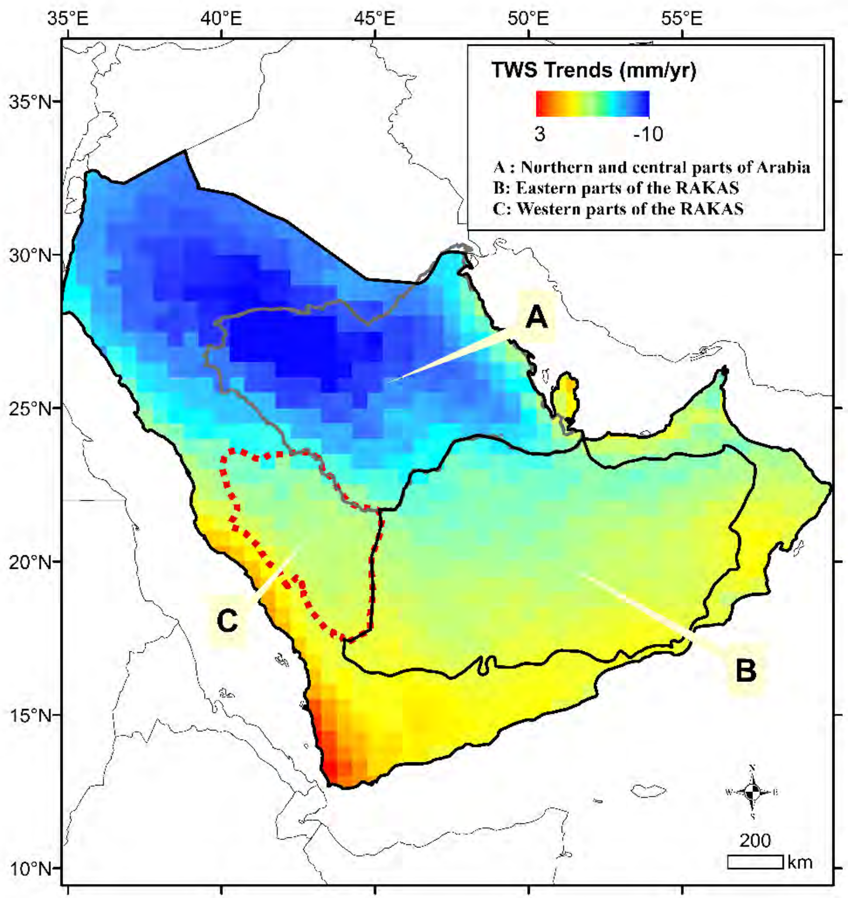
$\Delta GWS = \Delta TWS - \Delta SMS$ (from GLDAS)

Three areas targeted for agricultural development

Northern & central MAS (area A: 0.58×10^6 km^2; cultivated land: 4684 km^2; groundwater extraction: 6.6 km^3/yr),

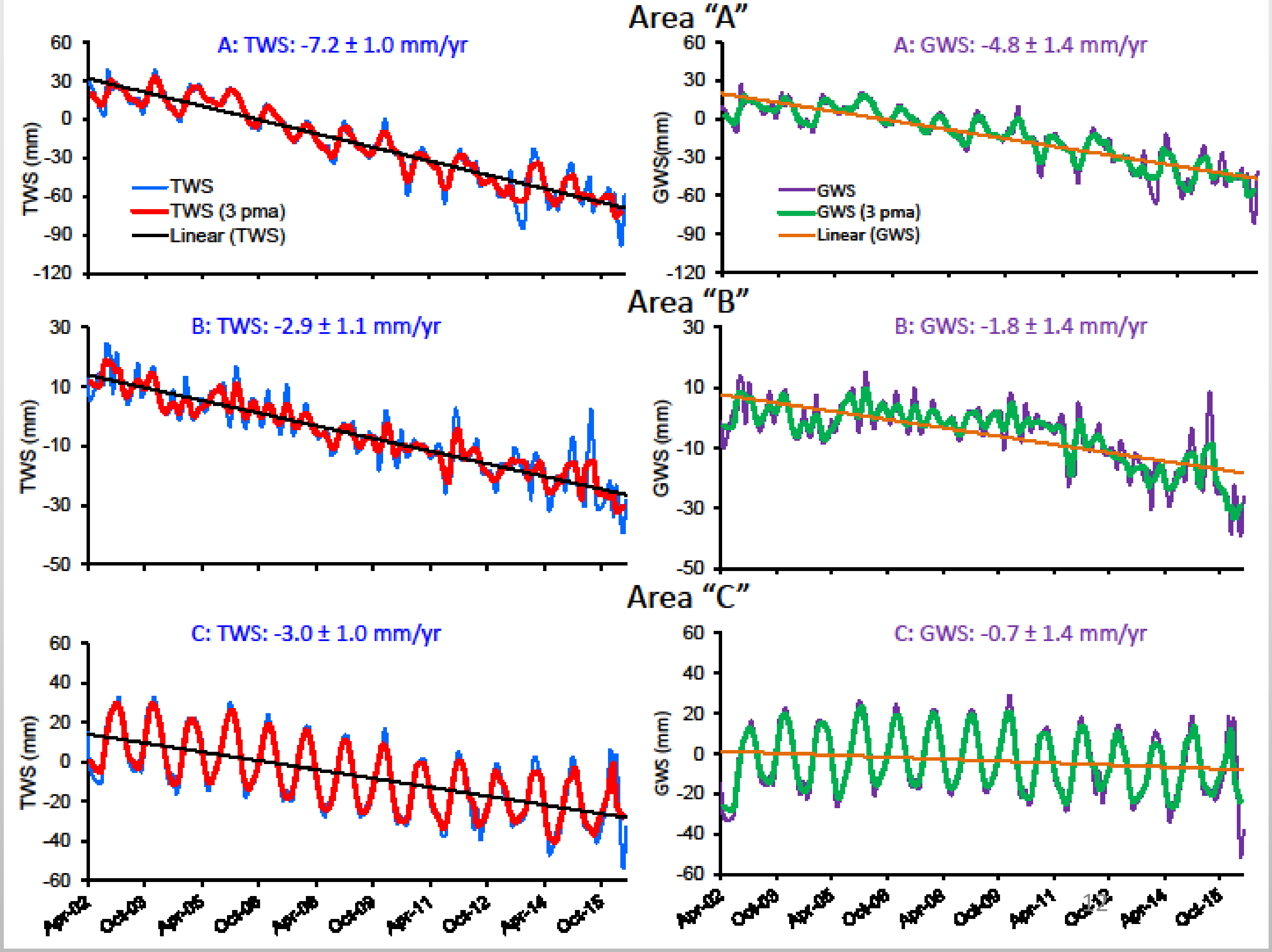
Eastern RAKAS (area B: 0.89×10^6 km^2; cultivated land: 871 km^2; groundwater extraction: 1.2 km^3/yr),

Western RAKAS (area C: 0.22×10^6 km^2; cultivated land: 966 km^2; groundwater extraction: 1.4 km^3/yr).



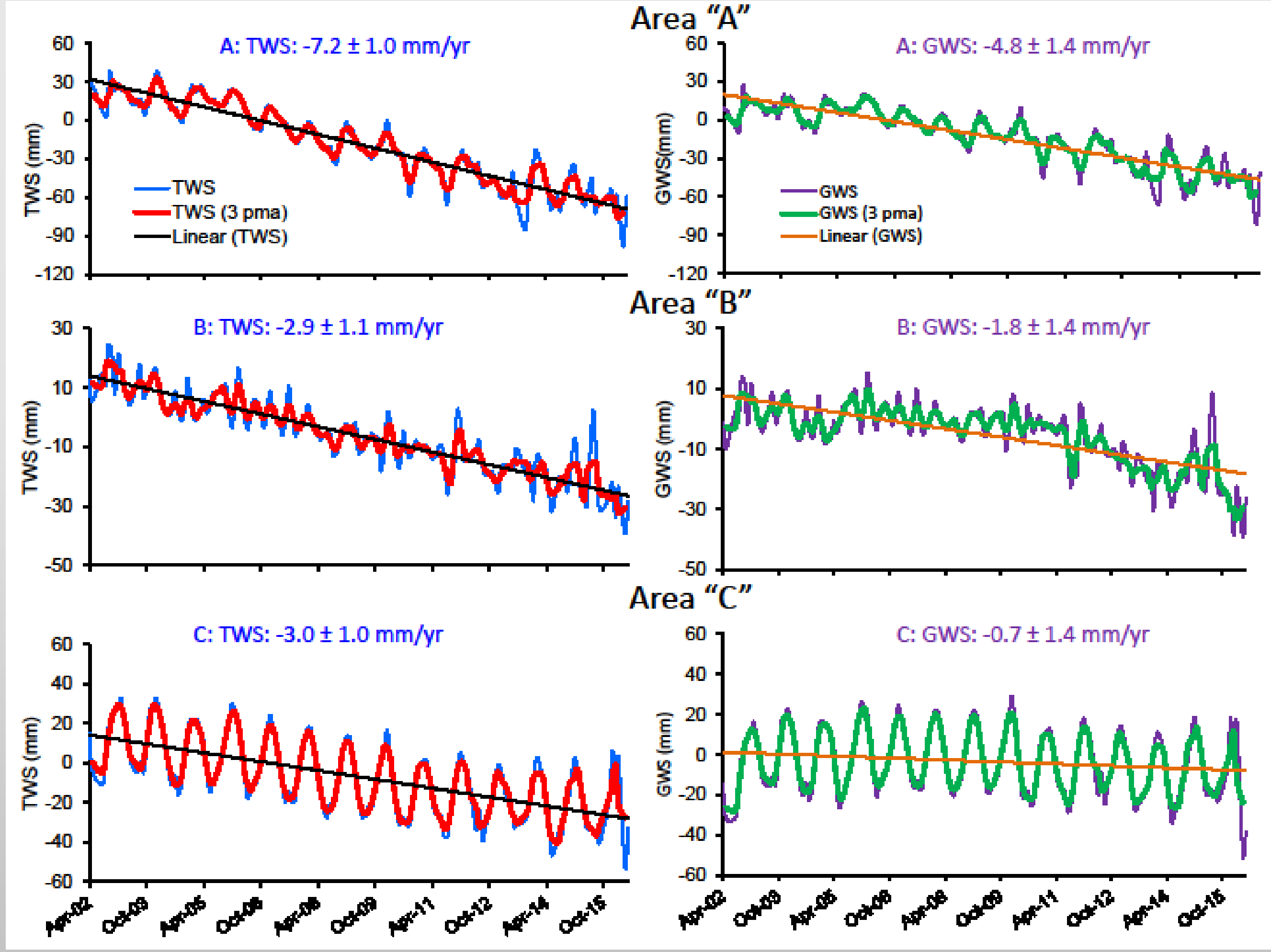
Time series and secular trends for TWS

- High depletions in TWS over area “A” (–7.2 ± 1.0 mm/yr; –4.2 ± 0.6 km^3/yr),
- Moderate depletions over area “B” (–2.9 ± 1.1 mm/yr; –2.5 ± 1.00 km^3/yr), and
- Moderate depletions in area “C” (–3.0 ± 1.0 mm/yr; –0.7 ± 0.2 km^3/yr).



Time series and secular trends for GWS

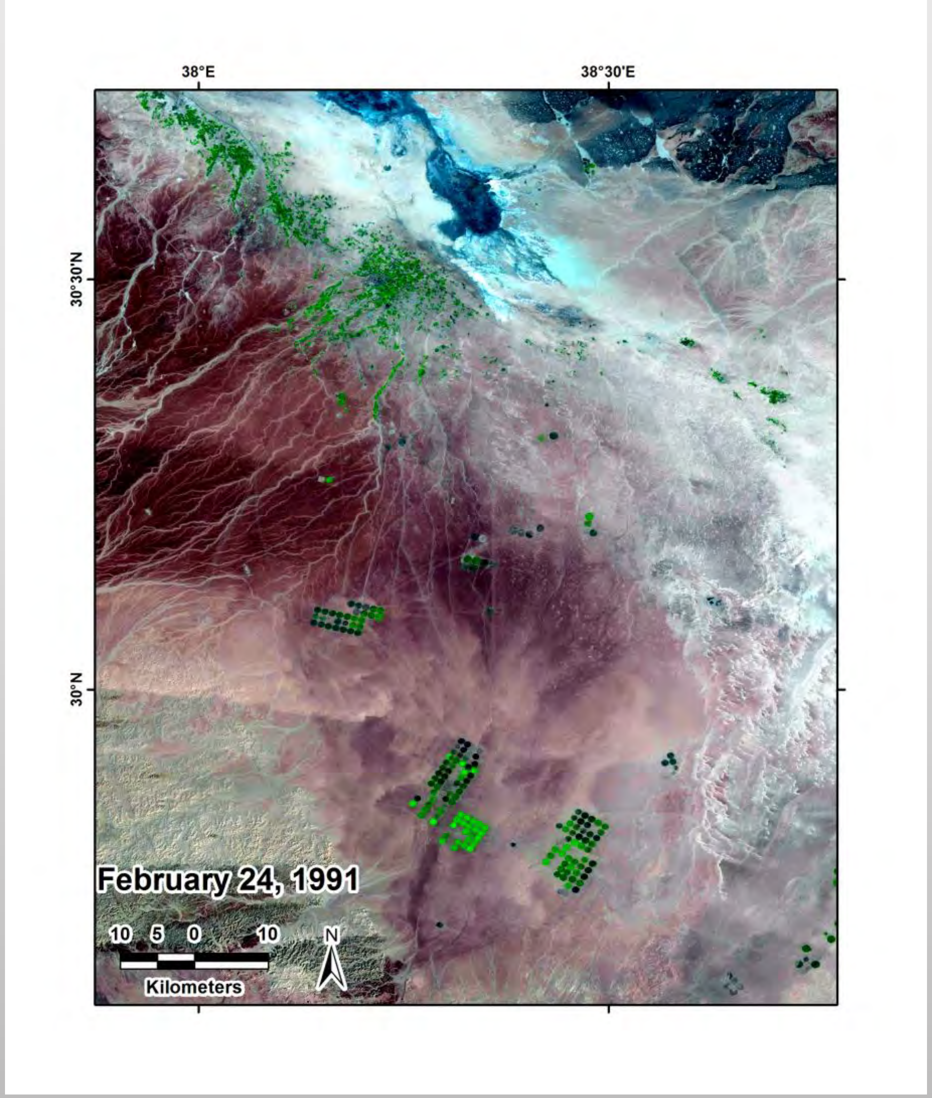
- High depletion rates for area A (–4.8 ± 1.4 mm/yr; –2.8 ± 0.8 km^3),
- Low depletions for area B (–1.8 ± 1.4 mm/yr; –1.6 ± 1.2 km^3), and
- Near-steady conditions for area C (–0.73 ± 1.4 mm/yr; –0.2 ± 0.3 km^3).

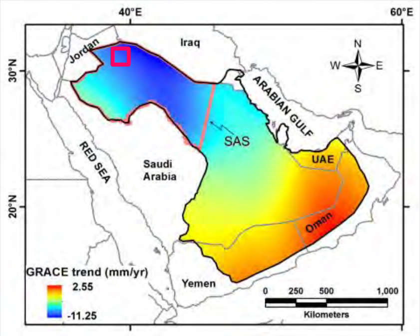


Causes of observed depletions in Area “A”: excessive extraction

- Observed depletions in area “A” correlate:
    - Spatially with distribution of reclaimed desert areas
    - Temporarily with the timing of agricultural development
- Area “A” is over exploited & extraction is unsustainable
- Extraction from an aquifer, whose depletion cannot be balanced by capture, is described as being unsustainable and aquifer is overexploited
- Extraction in area “A” could become sustainable if extraction is reduced by 2.8 km^3.
- At current levels of extraction, only the southern parts of the MAS (RAKAS in areas “B” and “C”) can be used for sustainable agriculture in Arabia.

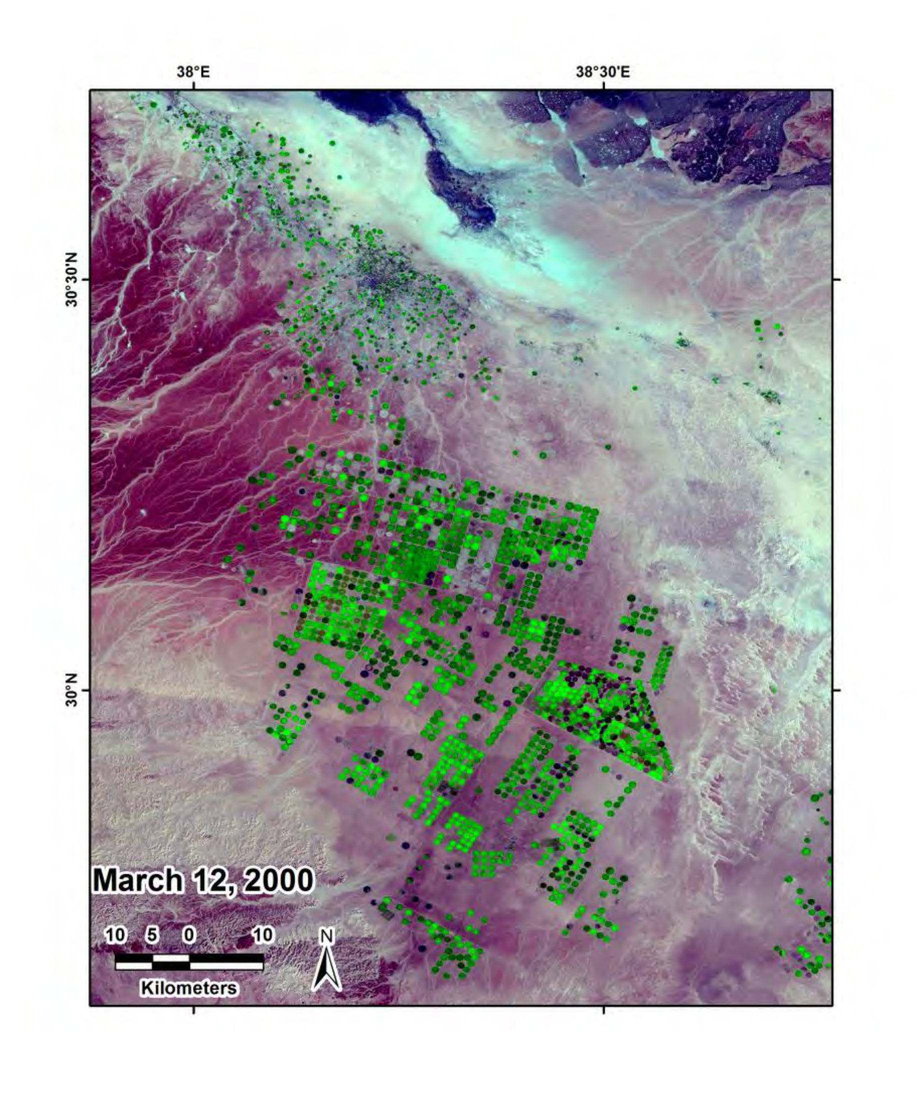
Wadi Al Sarhan, Northern MAS – February 1991

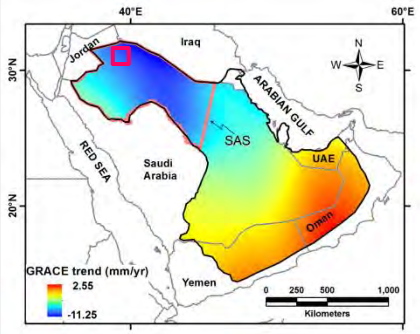




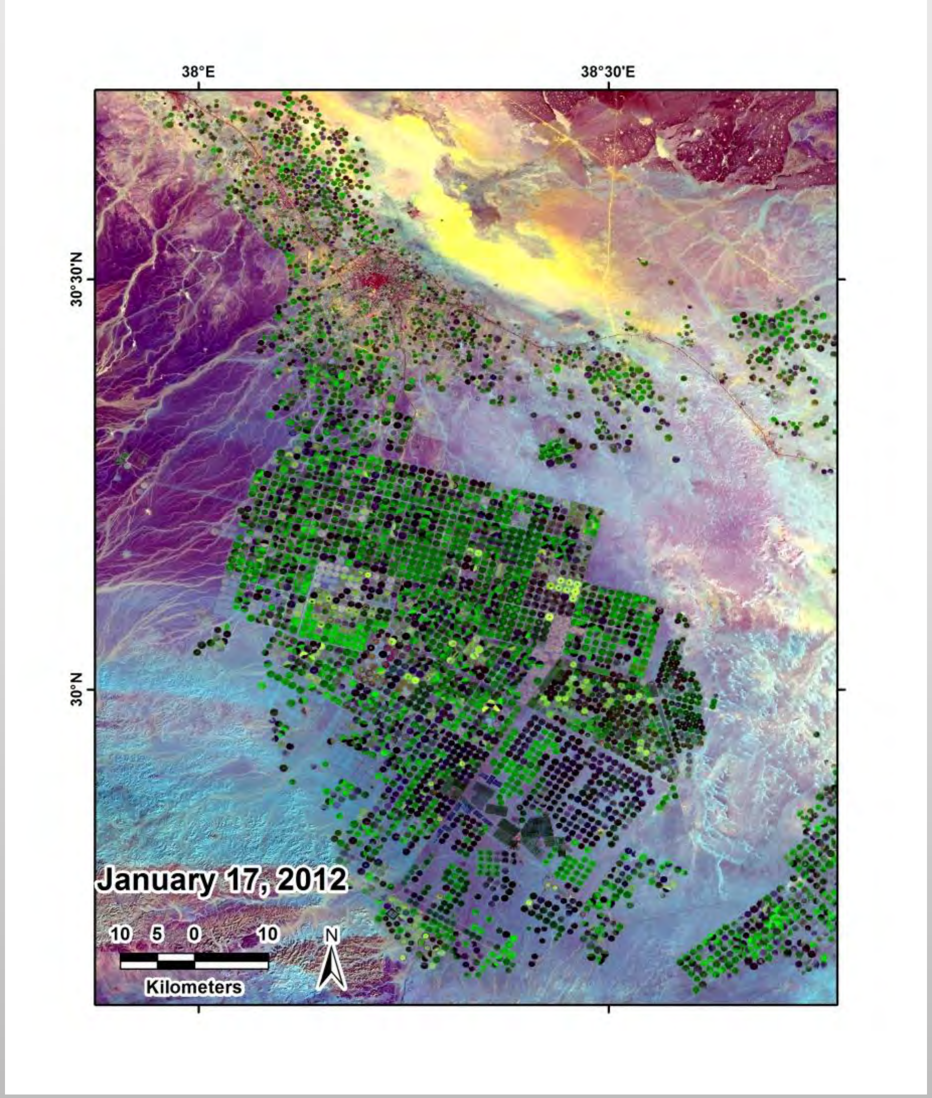
Wadi Al Sarhan

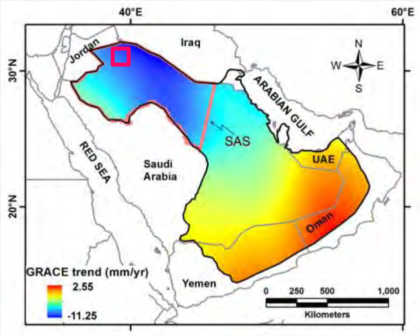
Wadi Al Sarhan, Northern MAS – March 2000





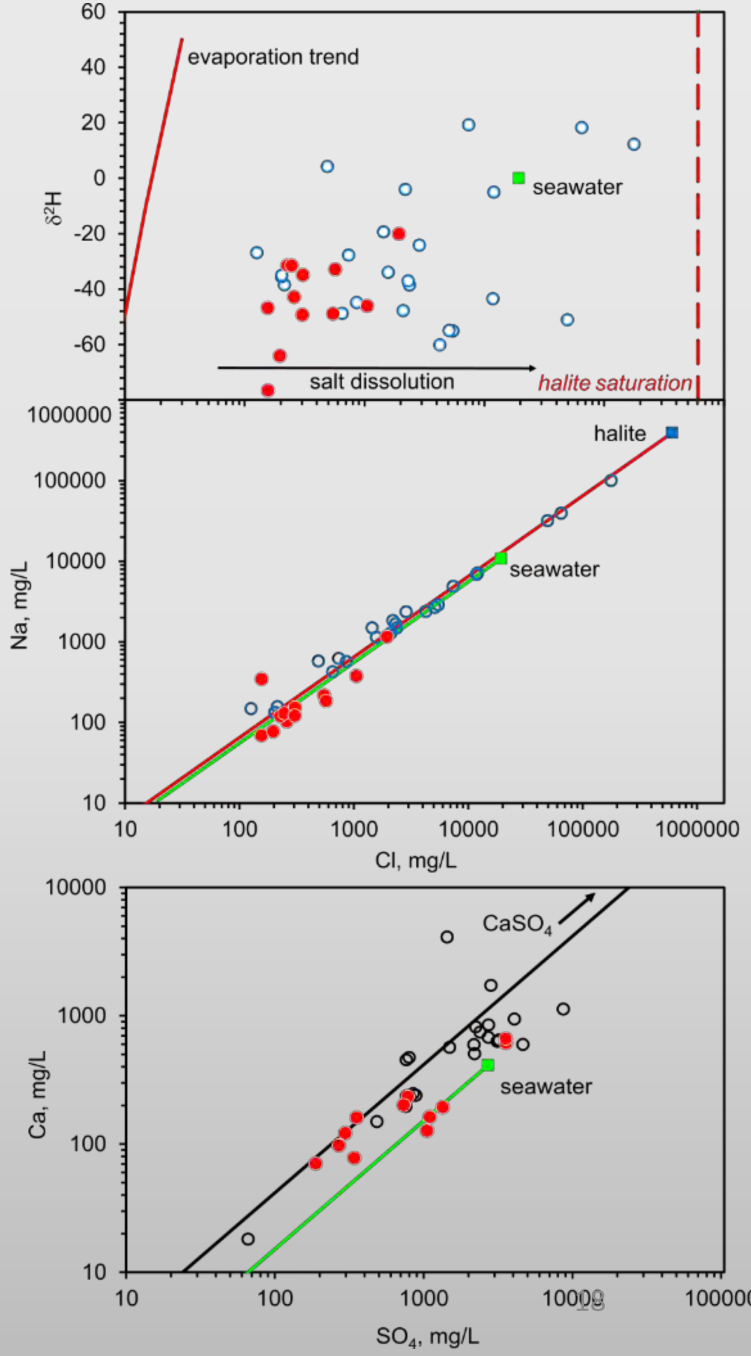
Wadi Al Sarhan, Northern MAS – January 2012





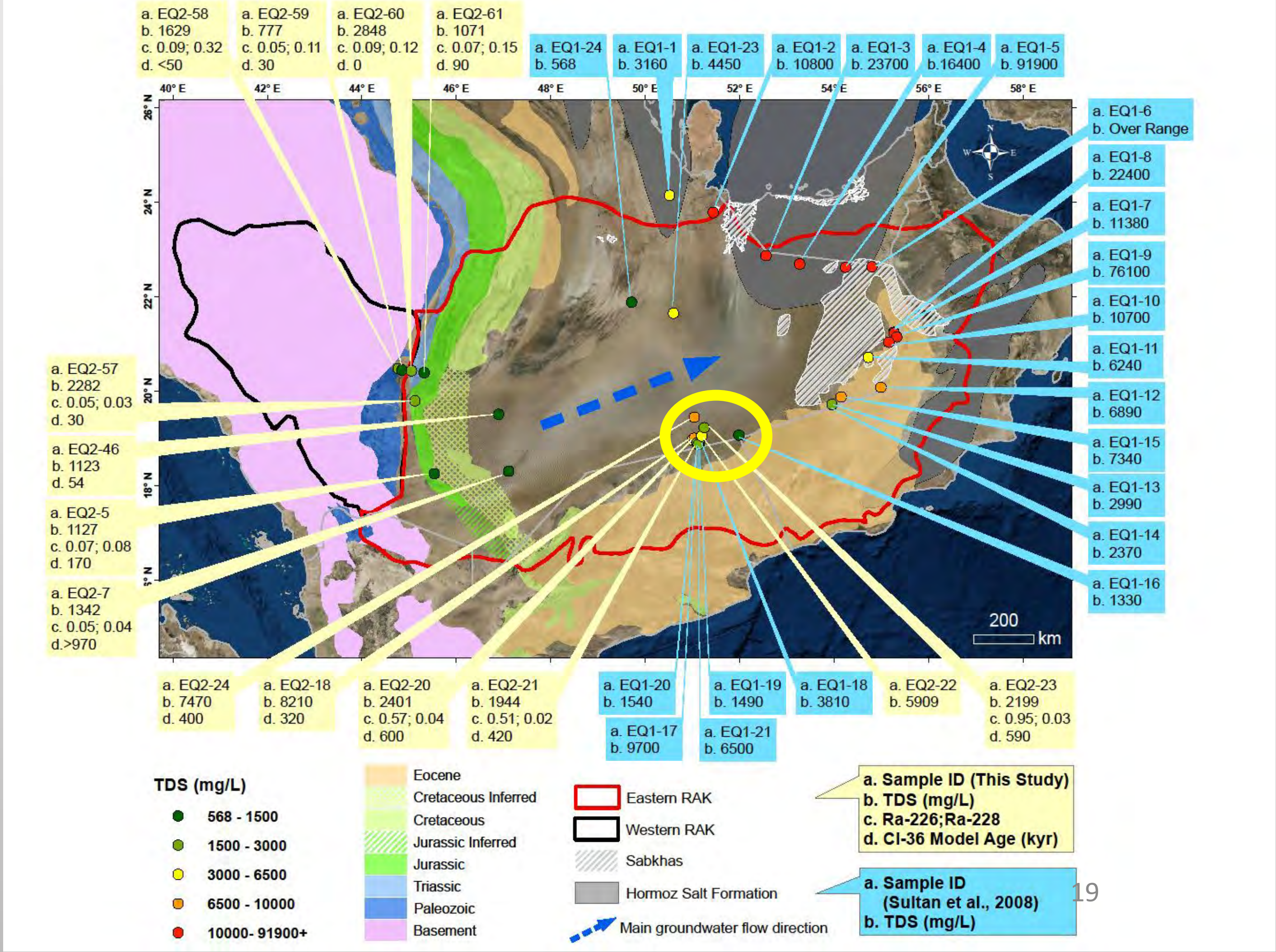
Area B or C is more favorable? TDS

- Area "C" has low TDS: 800 – 2800 mg/L
- Area "B" up to 90,000 mg/L through dissolution of subsurface evaporite and/or surficial sabkha salts
- Hypothetical evaporation of meteoric water ($\delta^2H = -50$ ‰; chloride concentration = 10 mg/L) does not explain observed compositions
- Salinzation through dissolution of subsurface evaporites and/or surficial sabkha salts occurred



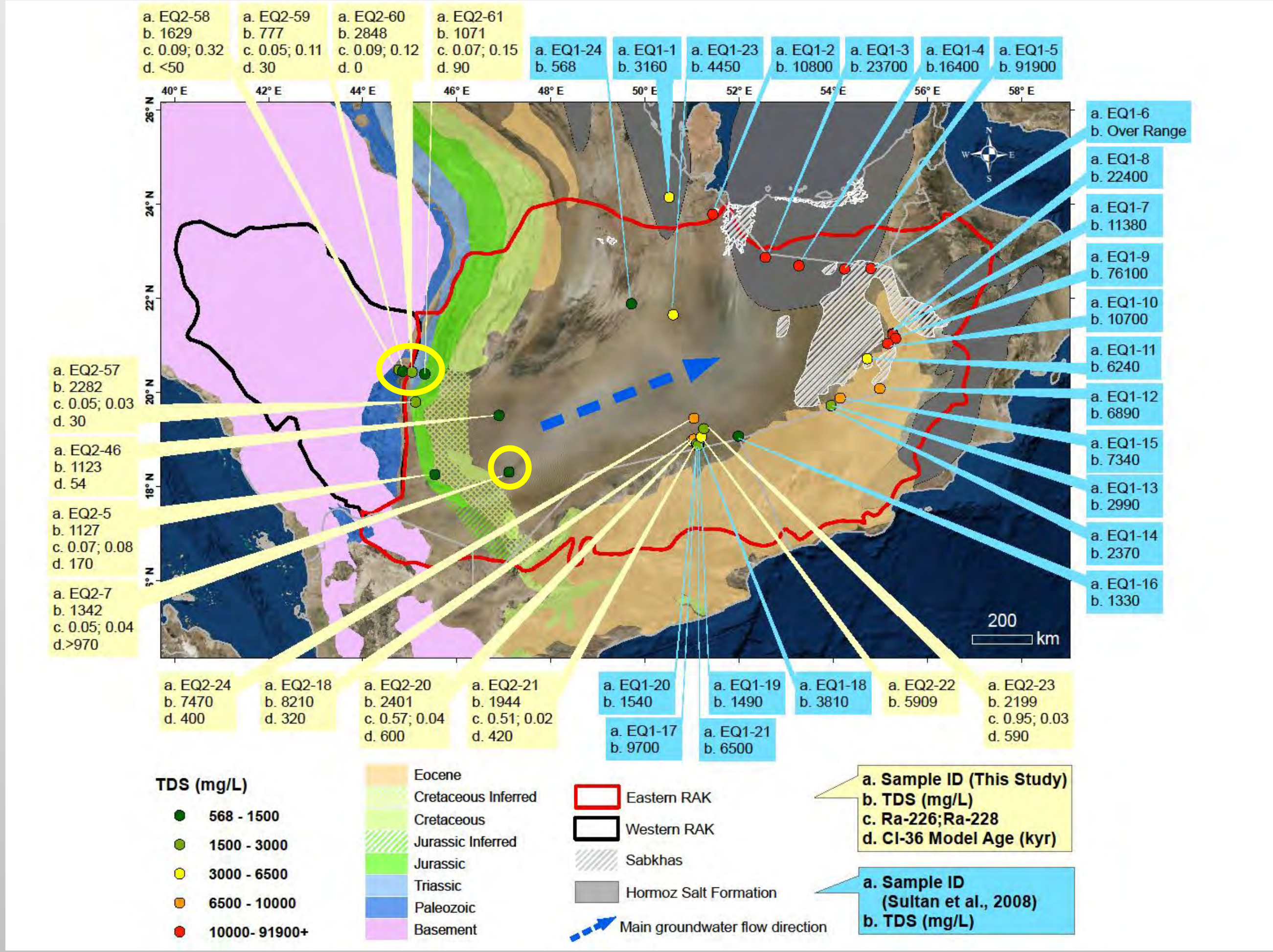
Area “B” or “C” is more favorable? Natural radioactivity

- Radium isotopes (^{226}Ra and ^{228}Ra) represent a health hazard
- combined activity > 0.185 Bq/kg (US EPA regulatory limit for drinking water)
- EQ2-20, EQ2-21, and EQ-23 from Eocene aquifer (East RAK), have Ra activities > US EPA regulatory limit



Area "B" or "C" is more favorable? Evidence for modern recharge

- If modern recharge is occurring
  - higher contributions from modern precipitation in recharge areas
  - decreased contributions with increasing distance from mountains &/or depth of wells.
- Upper Paleozoic Wajid
  - EQ2-60
    - enriched (δD of −46.1 ‰ and $\delta^{18}O$ of −5.9 ‰)
    - shallow well (TD of 60 m), 41 km from basement
  - EQ2-7
    - (δD of −76.7 ‰ and $\delta^{18}O$ of −10.1 ‰)
    - deep (TD of 1137 m) well, 267 km away from the basement.



Findings

Analysis of GRACE & LSMs revealed:

- Central & northern sections of MAS are experiencing high groundwater extraction (6.6 km^3/yr) and depletion rates (−4.8±1.4 mm/yr) yet sustainability could be achieved by reducing annual extraction by 2.8 km^3; and

- The southern sections of MAS (RAKAS) are experiencing low groundwater depletion rates (eastern RAKAS: −1.8 ± 1.4 mm/yr) to steady-state conditions (western RAKAS: −0.73 ± 1.4 mm/yr).

Findings

Analysis of geochemical, field, and RS data over RAK revealed:

- W to E trending buried drainage networks & groundwater flow systems consistent with precipitation source over Red Sea Hills;
- Increasing ^{36}Cl model ages along groundwater flow directions (up to 970,000 years), indicate aquifer recharge in wet Pleistocene periods;
- Progressive depletion in O and H stable isotopic compositions with increasing distance from Red Sea Hills indicate modest recharge in prevailing dry conditions;
- Relatively fresh (TDS: 800 to 2,800 mg/L) & non-radioactive (^{226}Ra + ^{228}Ra < 0.185 Bq/kg) water in western RAKAS; and
- Sustainable agricultural at current extraction rates in western RAKAS