Integrated approach to address the temporal changes in Saharan and Arabian aquifers in response to climatic and anthropogenic forces

Mohamed Sultan[1]

Mohamed Ahmed[1], John Wahr[2] & Eugene Yan[3]

1. Western Michigan University
2. University of Colorado at Boulder
3. Argonne National Lab.

GSTM

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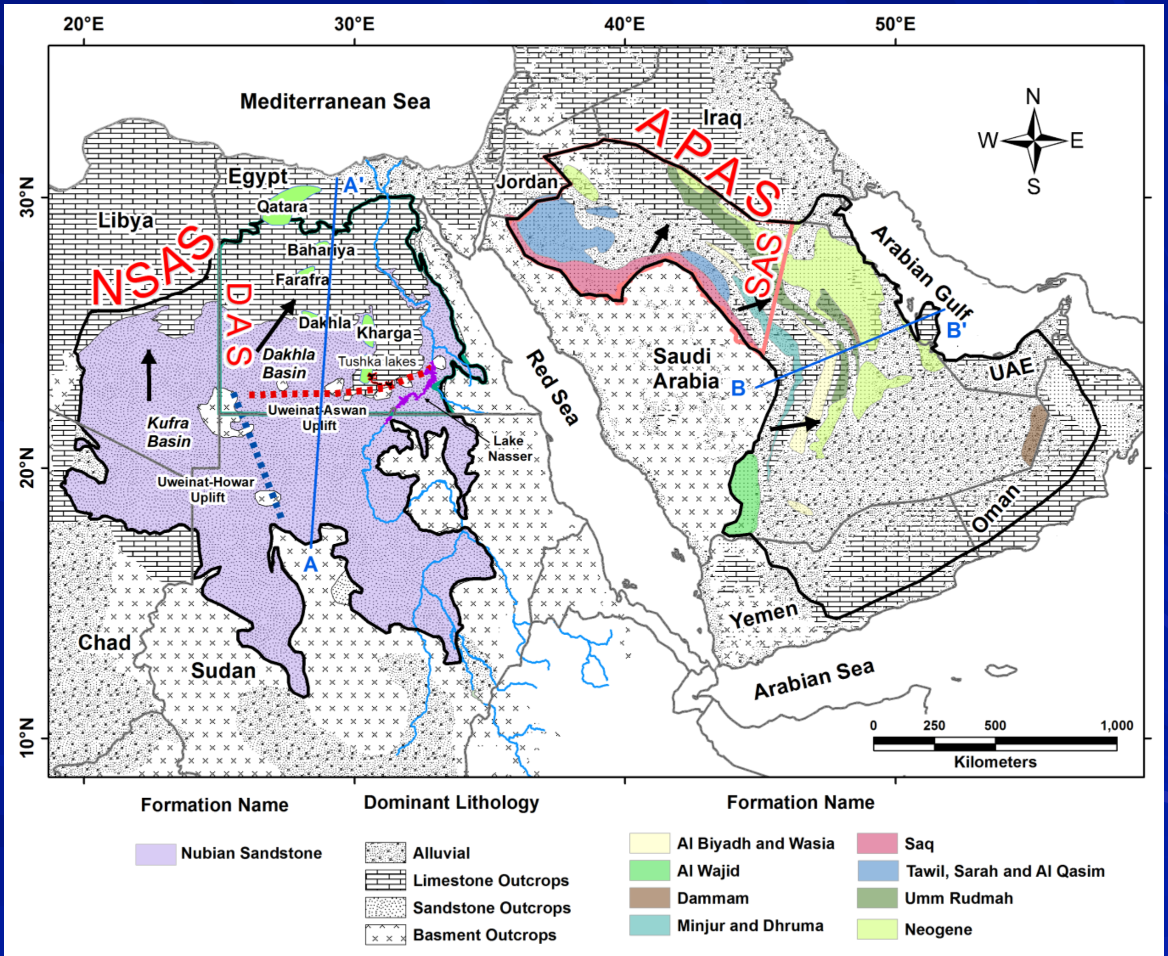
Motivation

- In arid and semi-arid regions (e.g., Saharan Africa & Arabian Peninsula) fresh water resources are limited
- large amounts of fresh water stored in fossil aquifers
- Not well studied given their locations, inaccessibility, difficulties in collecting background information and/or field data, and unavailability of local funding/expertise

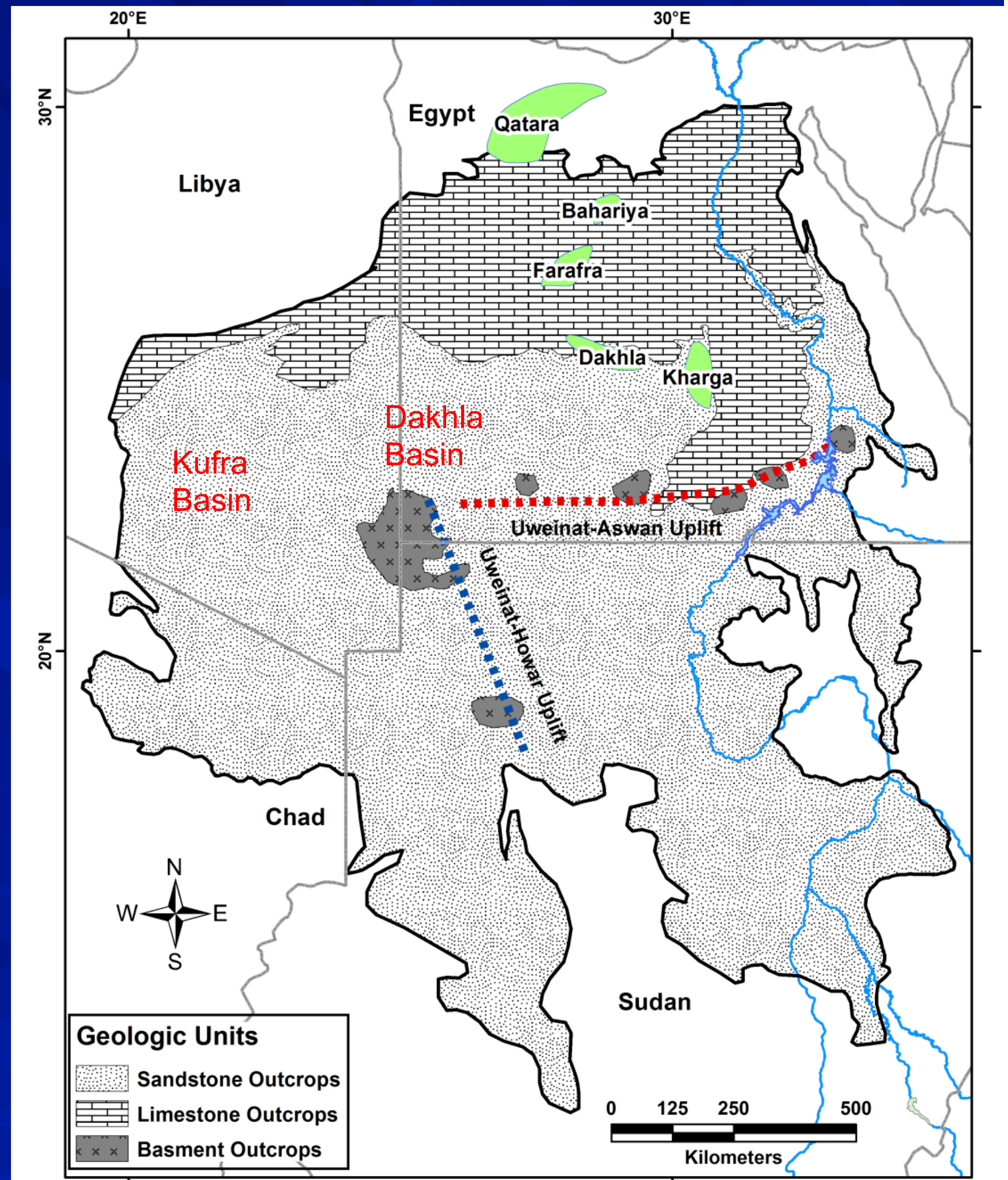
Distribution of Fossil Aquifers

- Red Sea rifting (~25 MA) associated with uplift that brought to surface deeply buried sedimentary sequences, providing opportunities to recharge now-exposed sequences at Red Sea foothills
- These fossil aquifers were largely recharged in previous wet climatic periods tens to hundreds of thousands years ago
- Nubian Sandstone Aquifer System (NSAS) and Arabian Peninsula Aquifer System (APAS)



Nubian Sandstone Aquifer System (NSAS): Geology

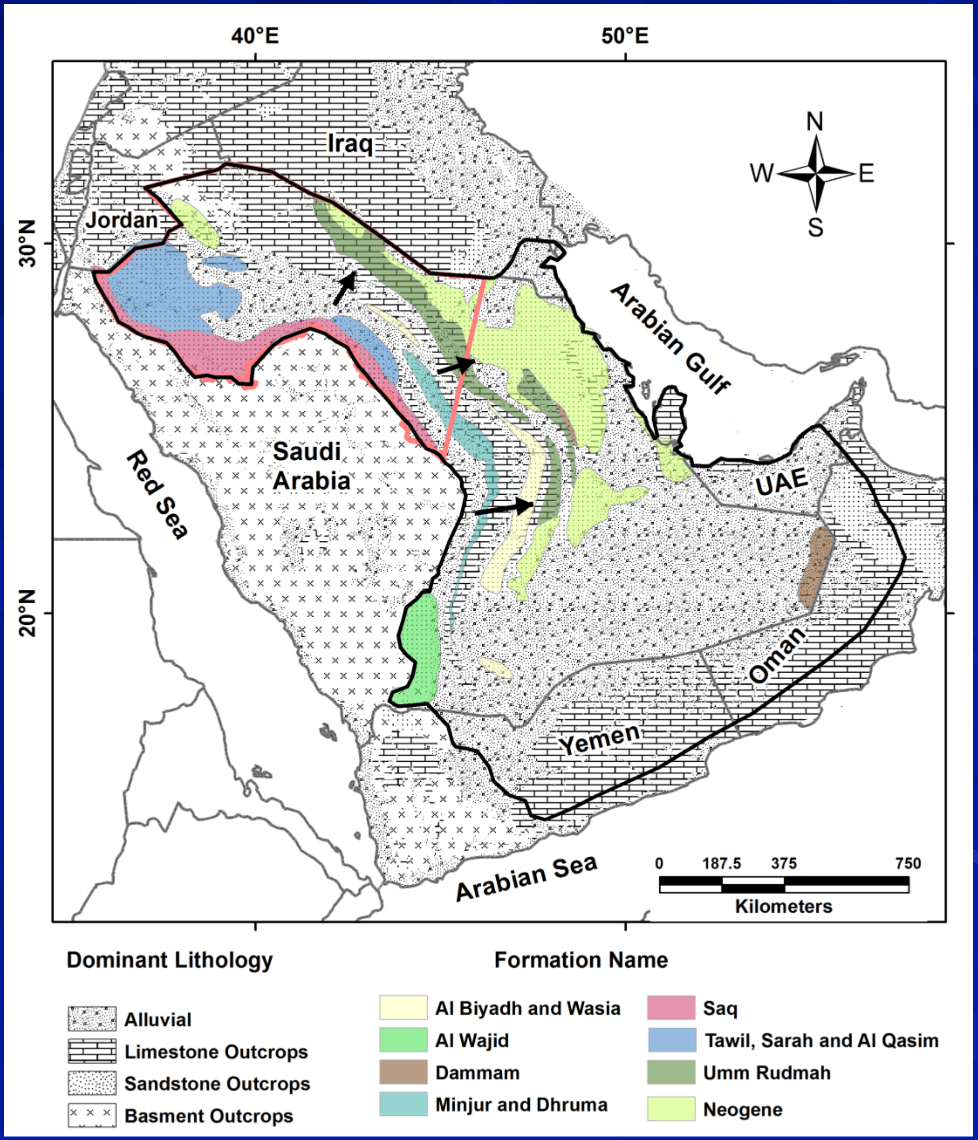
- Shared by four countries: Sudan, Libya, Chad, and Egypt.
- Area: 2×10^6 km^2.
- Cretaceous to recent
- Two major basins: Kufra and Dakhla basins
- Extraction mostly (70%) from the Nubian Cretaceous sandstone; in Egypt Dakhla Aquifer System (DAS)
- Fossil water (age: up to 10^6 yr Bp),
- Thickness of water-bearing DAS is up to 3 km.



Arabian Peninsula Aquifer System (APAS): Geology

- Extends between Saudi Arabia, Iraq and Jordan, Yemen, Oman, UAE
- Area : 1.8×10^6 km^2,
- Cambrian to recent
- Extraction mostly (65%) from the Cambrian Saq

  Aquifer system (SAS);
- Fossil aquifers (age: 22×10^3 - 28×10^3 yr Bp),
- Thickness of water bearing SAS is < 500 m



Questions

Are the NSAS and APAS in steady state or transient conditions?

Are they being depleted? Where & what are the depletion rates?

What are the factors (climatic/anthropogenic) causing these depletions?

What geologic settings are conducive to the observed depletions?

For how long could these aquifers be utilized?

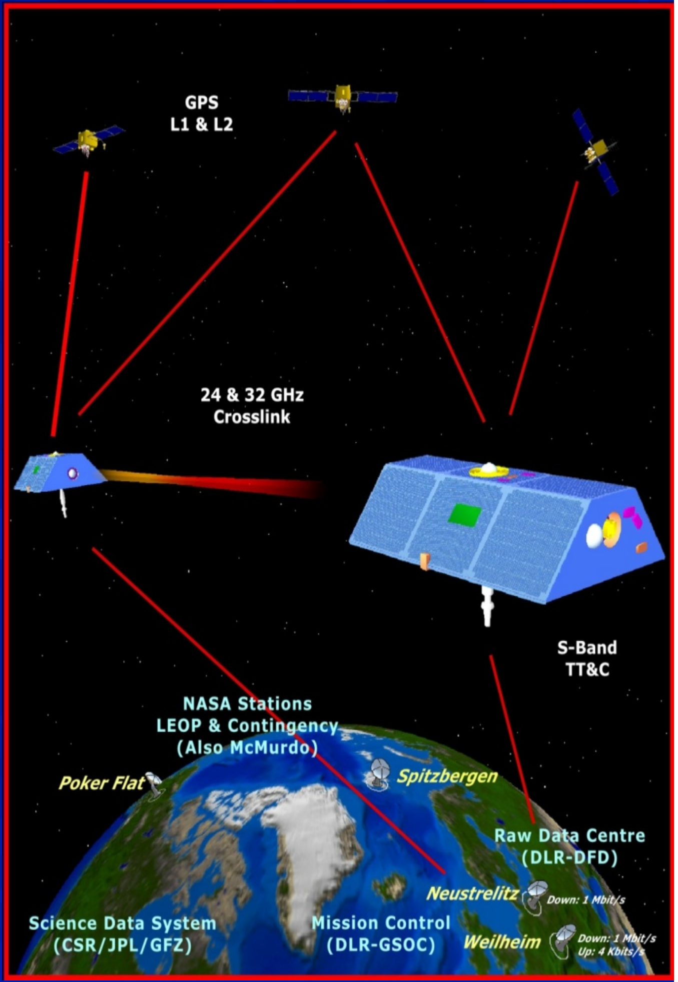
- Calibrated hydrological/groundwater flow models:
  - requires collection of extensive subsurface field data (temporal water levels, hydraulic parameters, etc),
  - such data are not available or difficult to attain for many of the aquifers,
  - uncertainties associated with model parameters.

- GRACE data + other traditional data sets

GRACE Data Processing

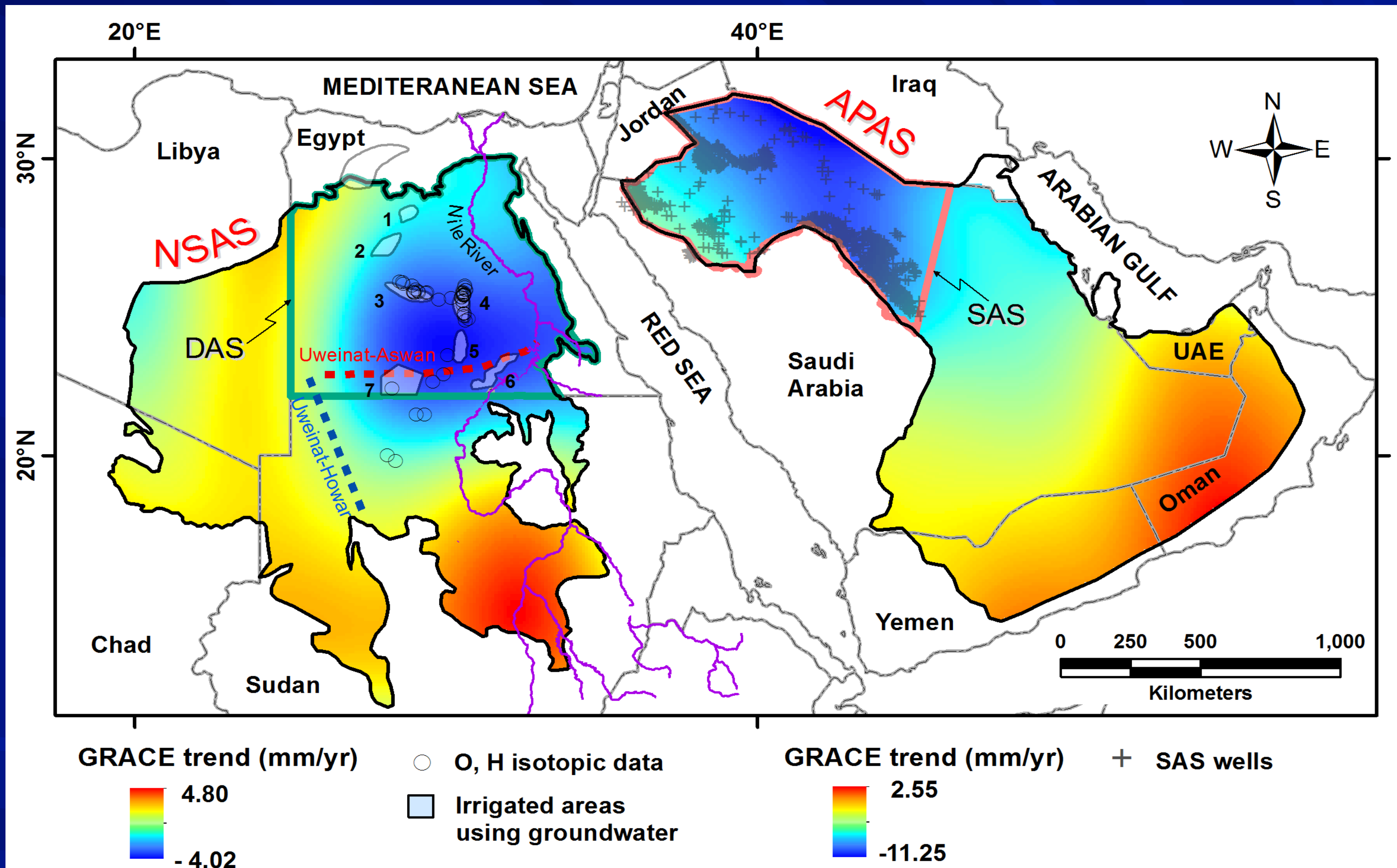
GRACE monthly (CSR; RL05) solutions (01/ 2003 - 09/ 2012) processed as follows:

- Temporal mean was removed;
- Gaussian smoothing function (radius: 350 km) was applied to generate equivalent water thickness grids (0.5ºx0.5º)
- Gaussian smoothing function (radius: 200 km) was applied to generate time series for specific areas (depleted) within the aquifers;
- Time series data were rescaled;
- Trend values where generated by simultaneously fitting a trend and seasonal terms for the generated time series data;
- Trend associated errors were calculated.



GRACE depletion trends

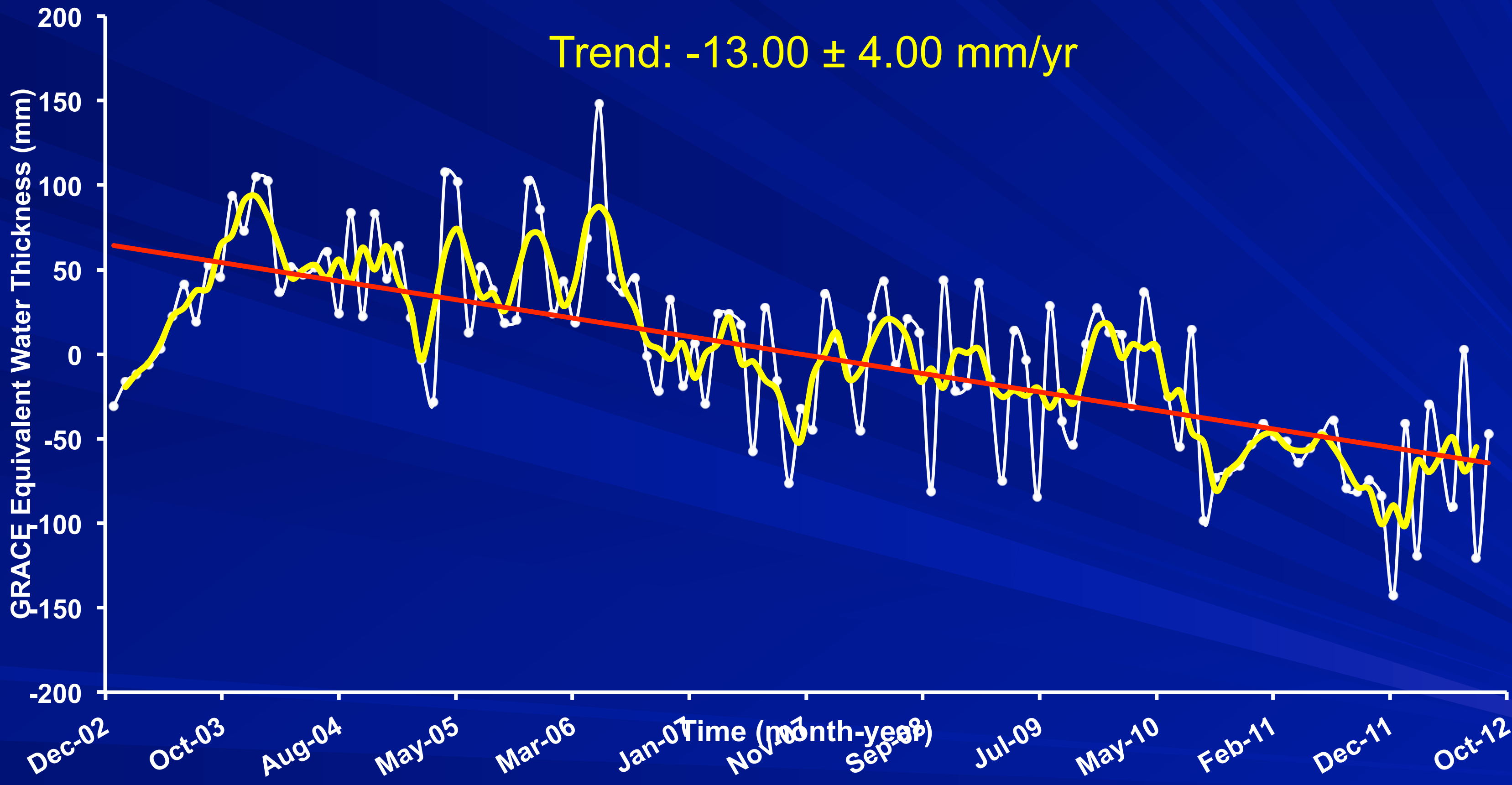
(350 km; Gaussian)



Depletions correlate with the distribution of the DAS & SAS

Groundwater irrigated areas

SAS GRACE Trend



GRACE (200 km; Gaussian) time series over the SAS in Saudi Arabia

Saq Aquifer System (SAS): GRACE Trend

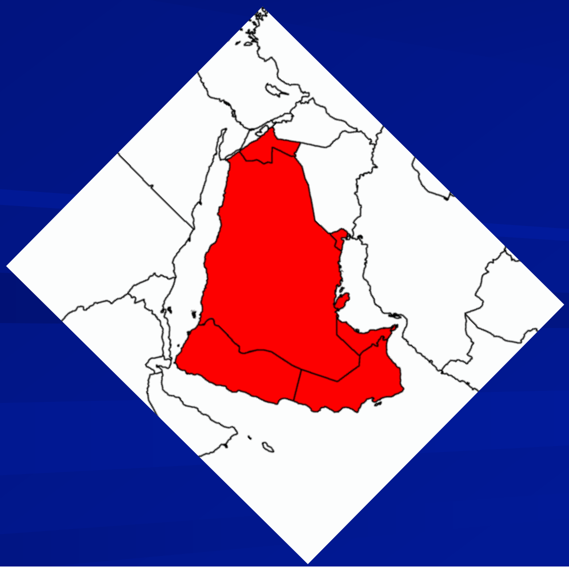
- GRACE Trend: -13.00 ± 4.00 mm/yr
- Terrestrial water storage: Groundwater + Soil moisture; no surface water

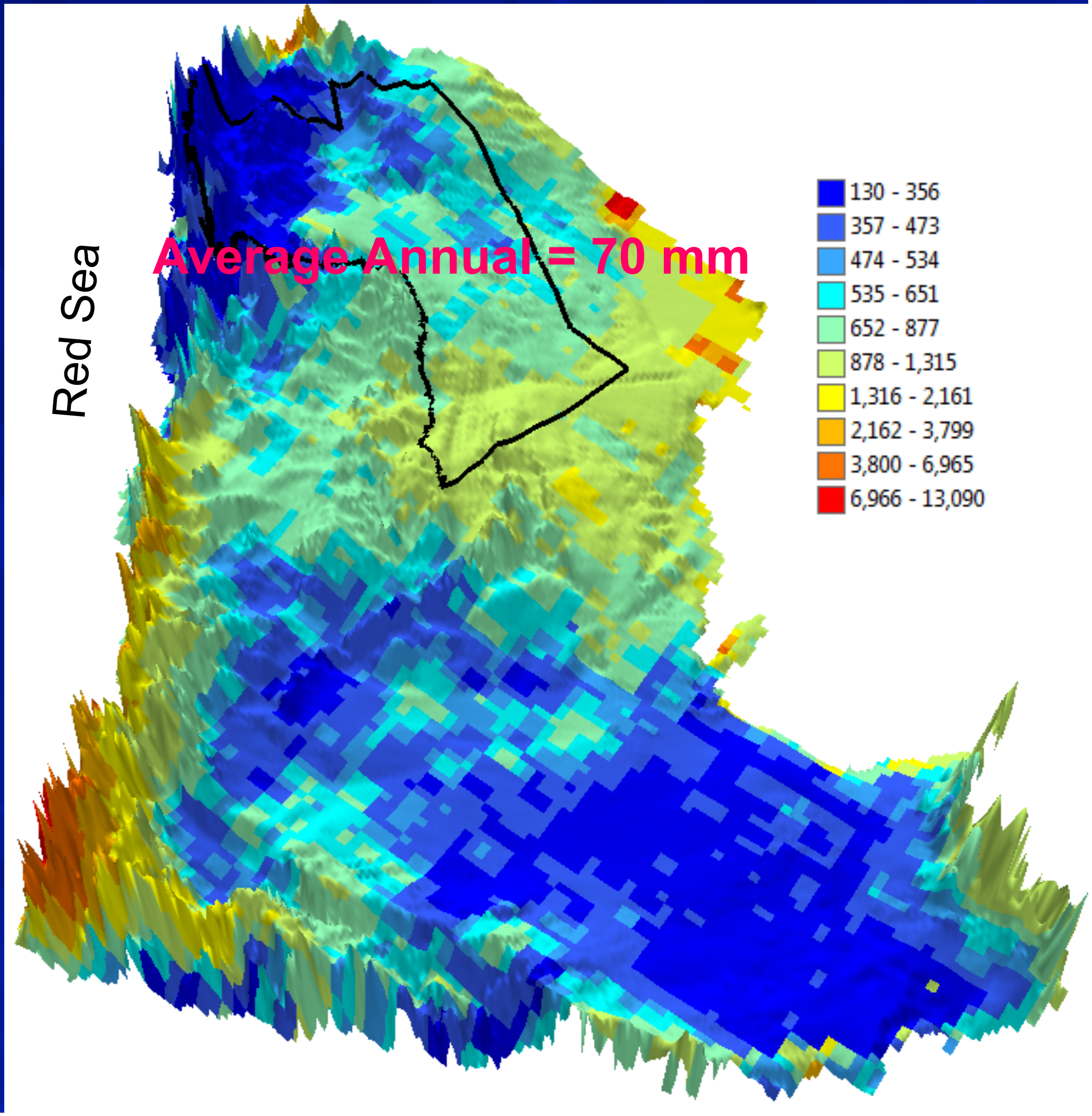
Equivalent to: $-6.11 \pm 1.83 \times 10^{9}$ m^3/yr

Could the observed depletion in GRACE be related to climatic factors causing a decrease in rainfall/soil moisture/recharge?

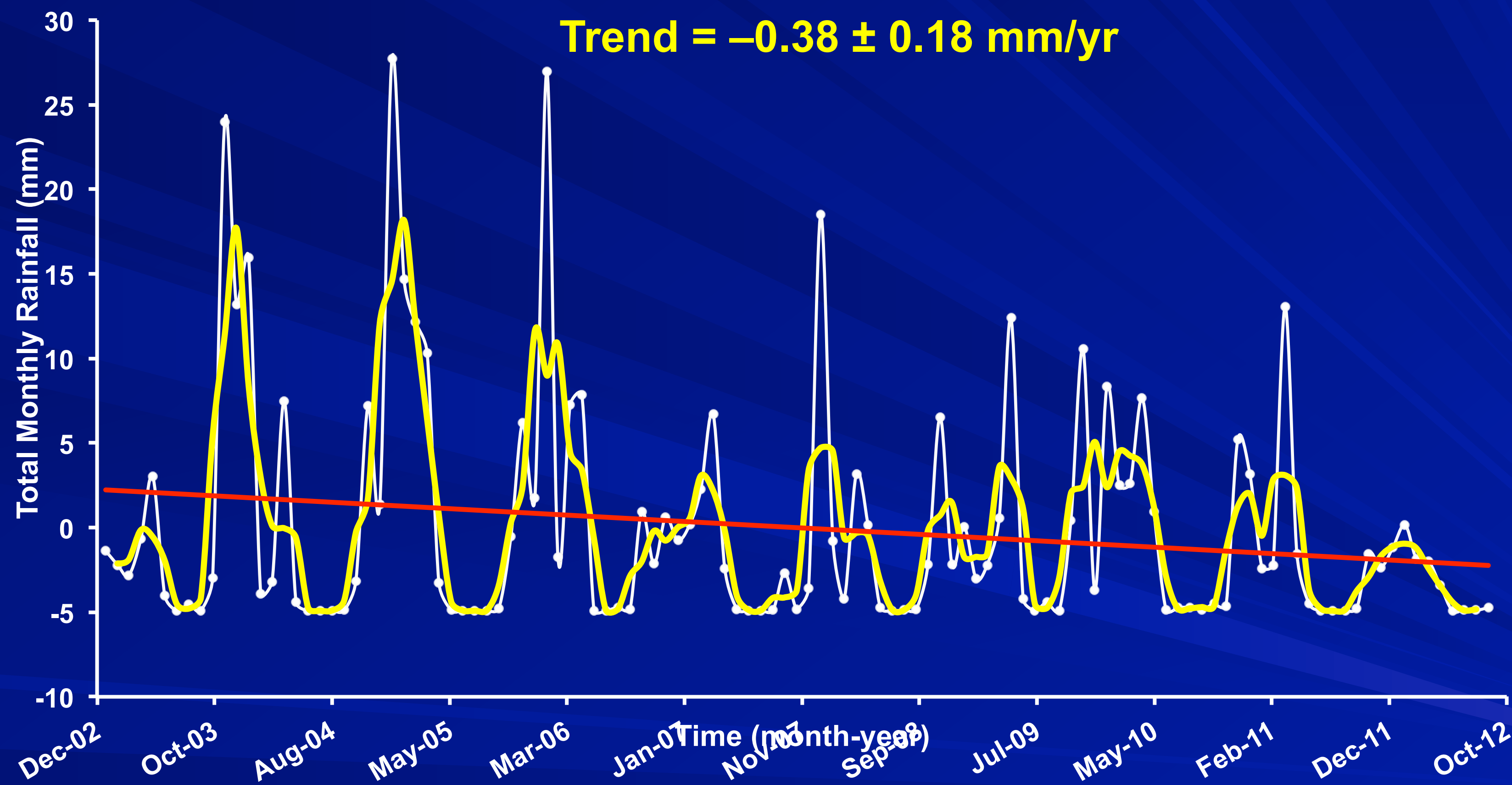
Rainfall over SAS

Cumulative precipitation (mm) from TRMM (3B42 v7A) data (2002 – 2011)



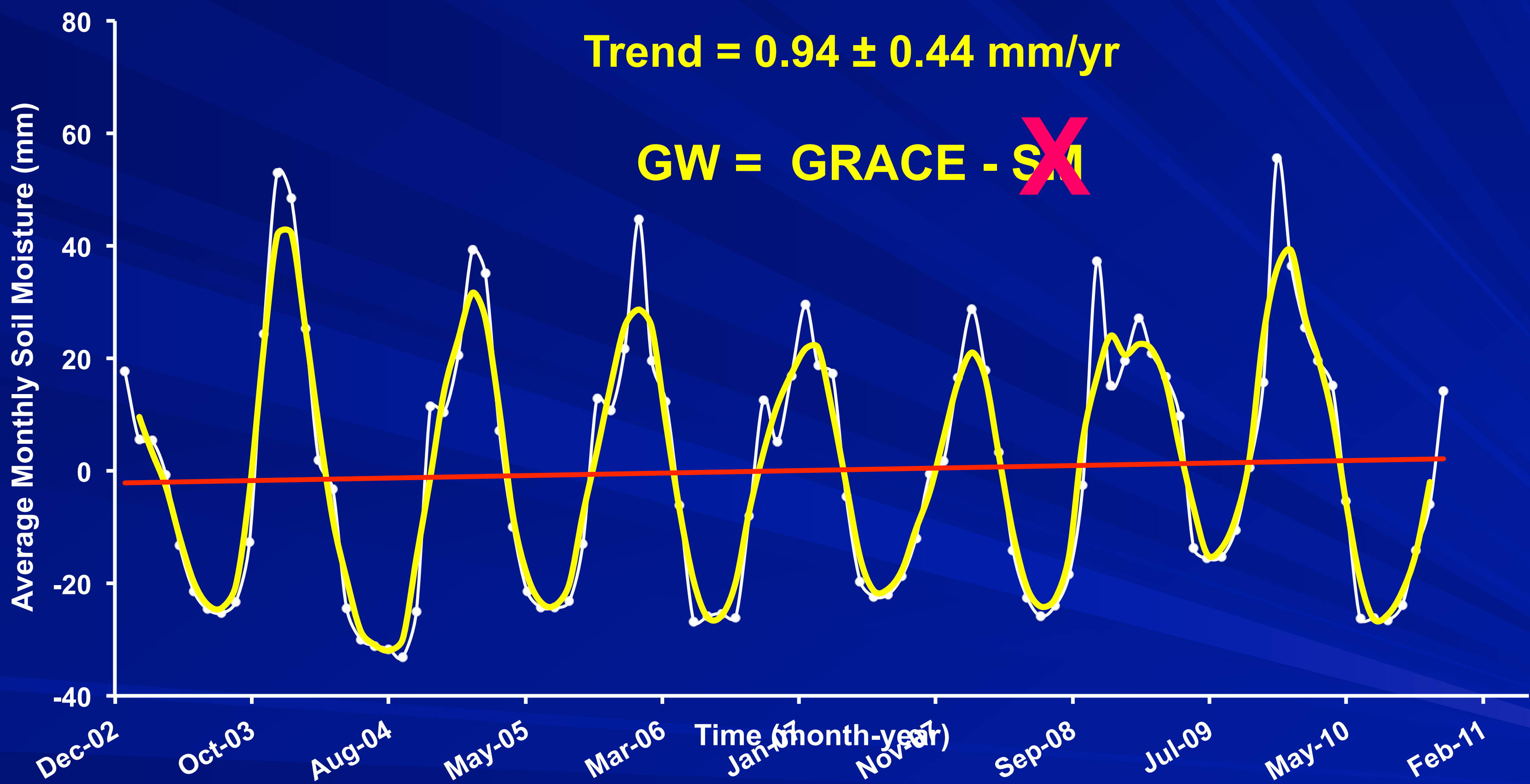


SAS Rainfall Trend



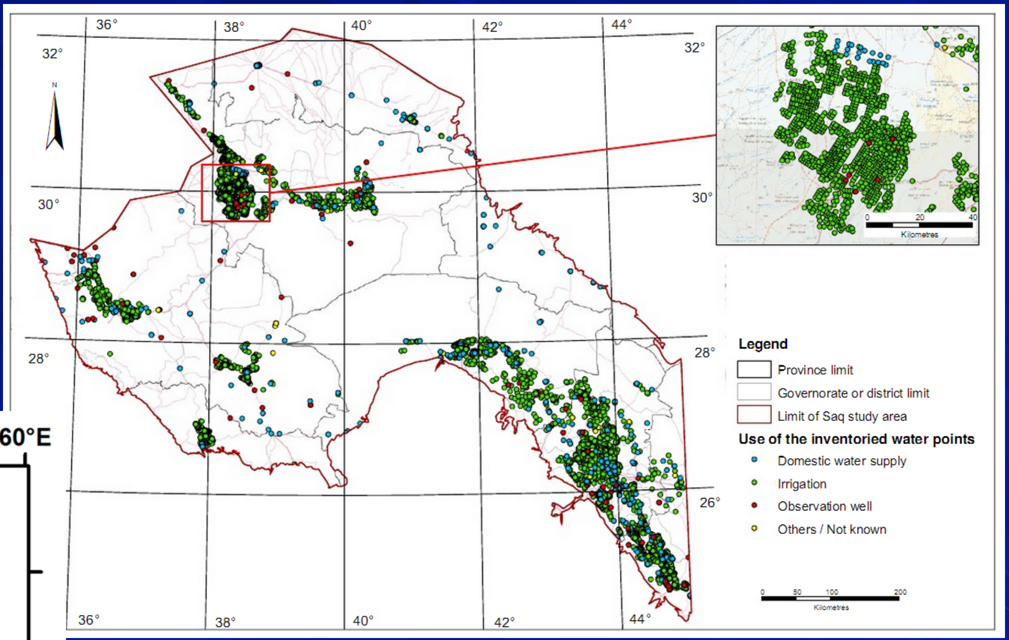
Rainfall time series over the SAS in Saudi Arabia

SAS Soil Moisture Trend

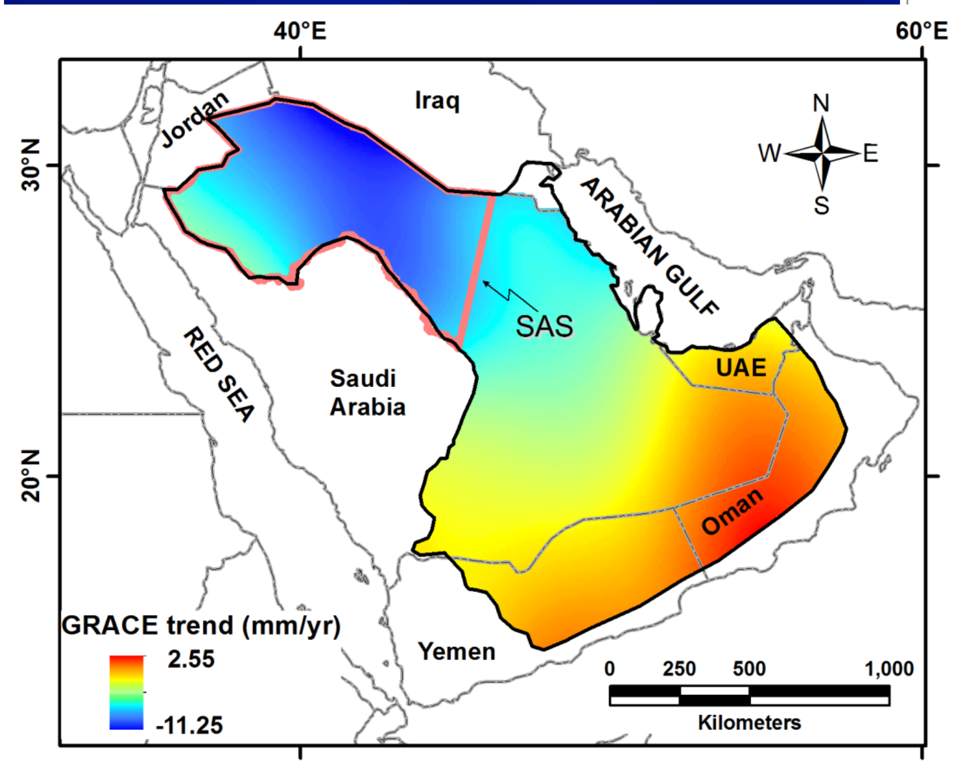


Soil Moisture time series (ESA-Essential Climate Variable project) over the SAS in Saudi Arabia

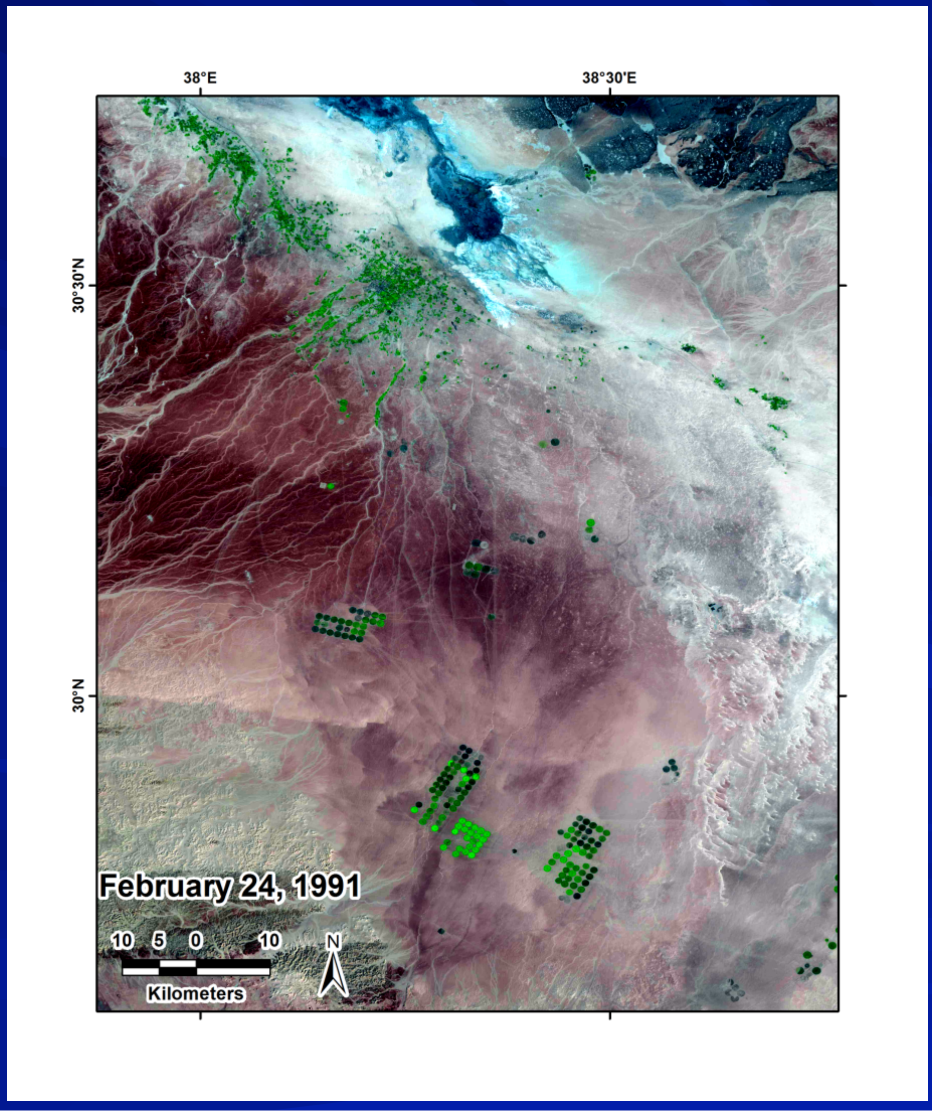
SAS Irrigation Activities

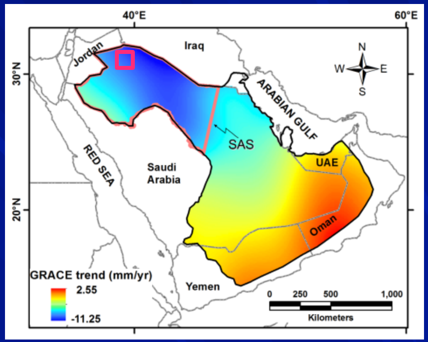


Wells distribution



Saq Aquifer System (SAS): Irrigation Activities





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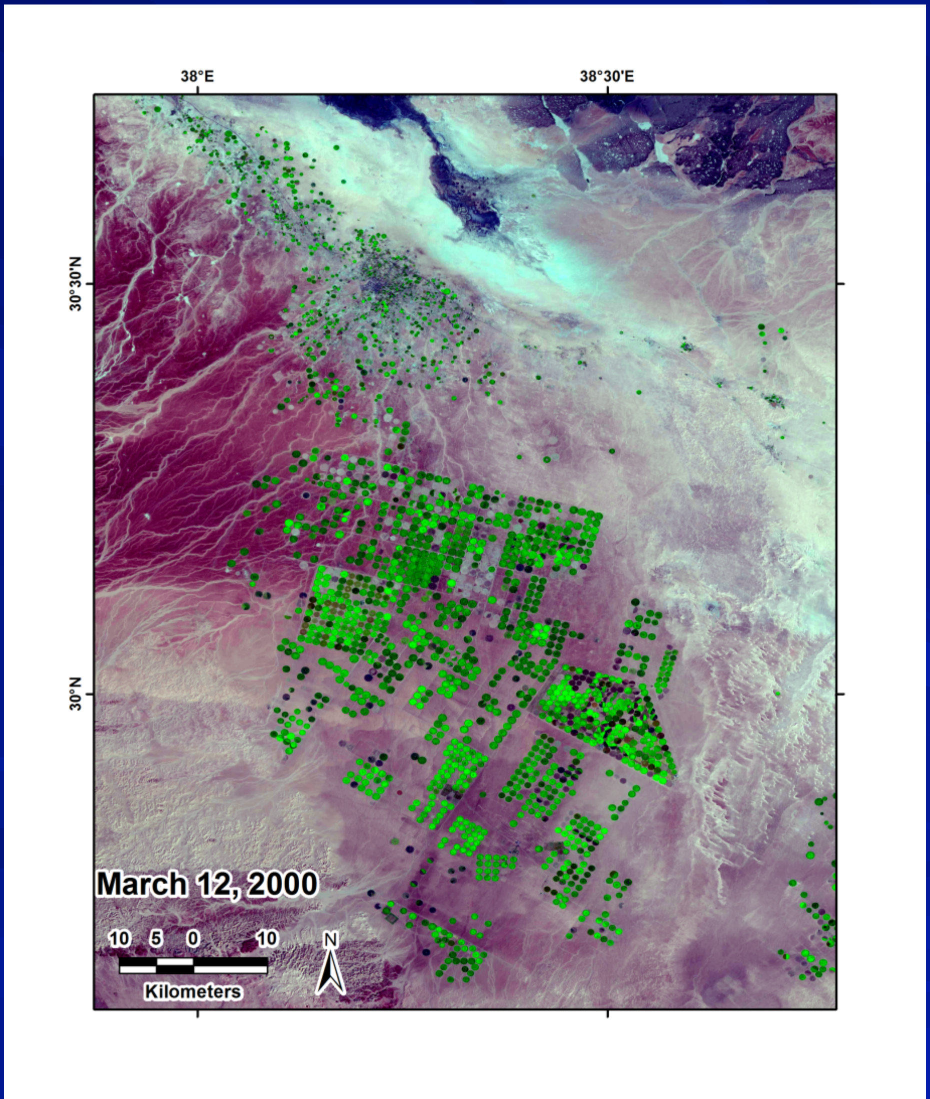
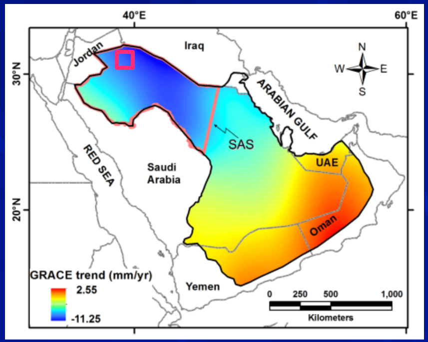
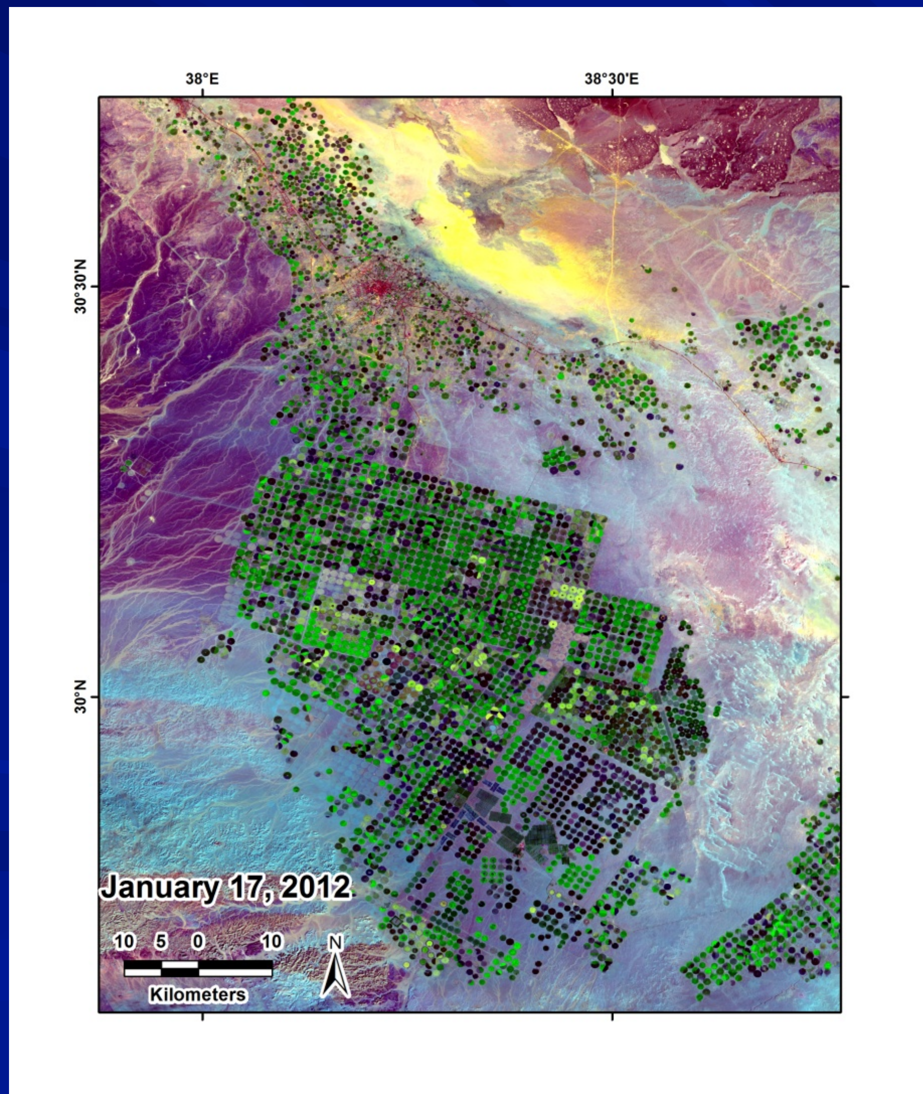
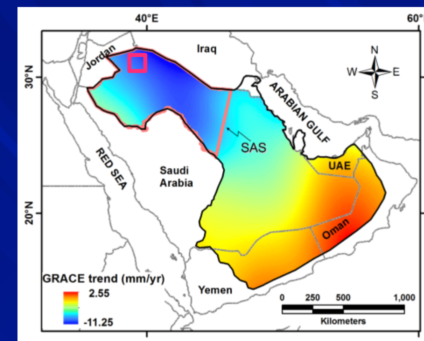
Saq Aquifer System (SAS): Irrigation Activities





Saq Aquifer System (SAS): Irrigation Activities





GRACE data *vs* Field data

- From before: GRACE depletion rate:

  $-6.11 \pm 1.83 \times 10^9$ m^3/yr

- The extraction increases with time

(BRGM, 2008)

  – 1960 → 0.1×10^9 m^3

  – 1984 → 2×10^9 m^3

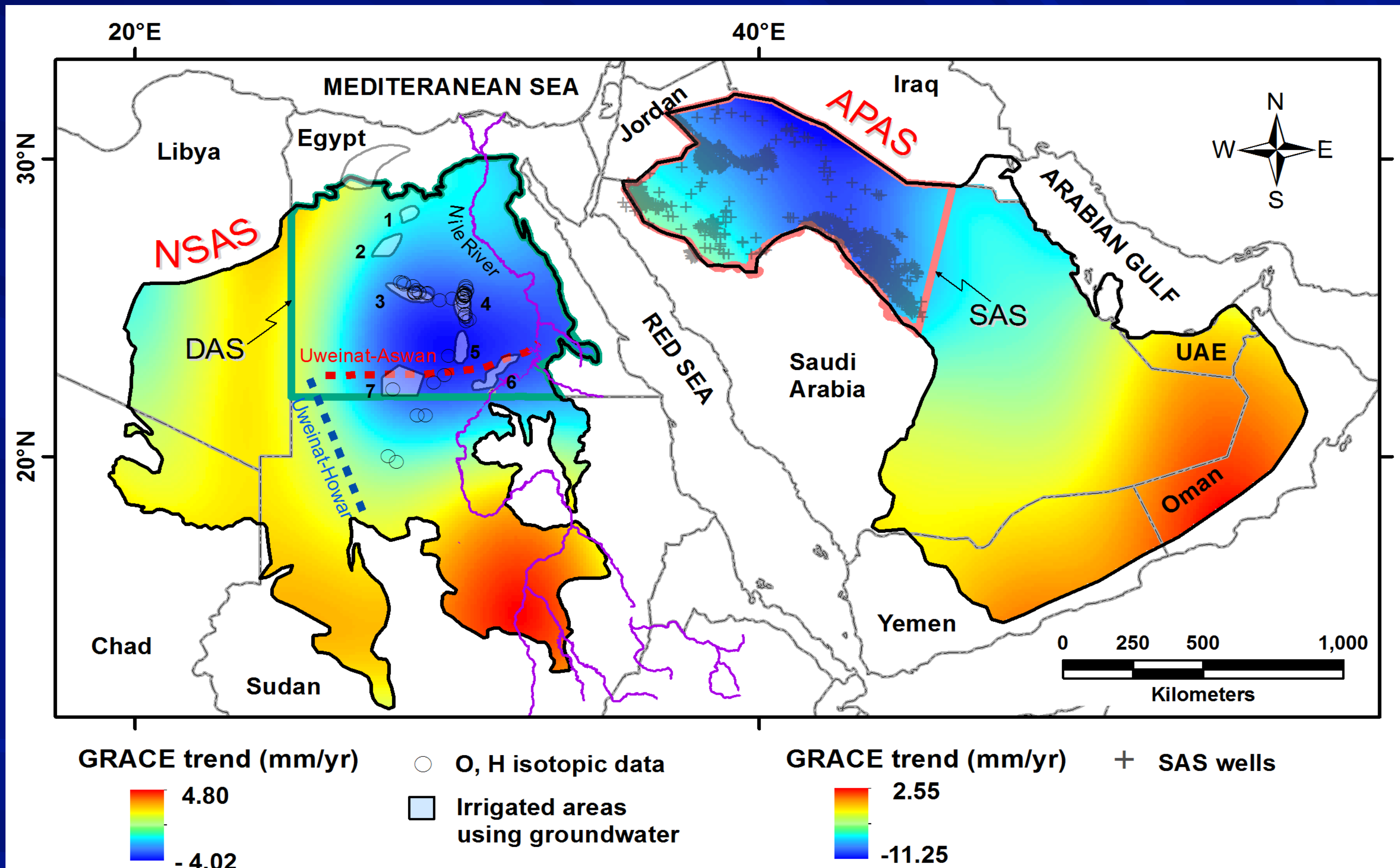
  – 2005 → 8.7×10^9 m^3

SAS Management Scenarios

- The SAS available reserves range from 430×10^9 m^3 to $1{,}000 \times 10^9$ m^3 [FAO, 2009];
- SAS could be mined for 70 to 160 years at the present GRACE-derived extraction and depletion rates.

GRACE depletion trends

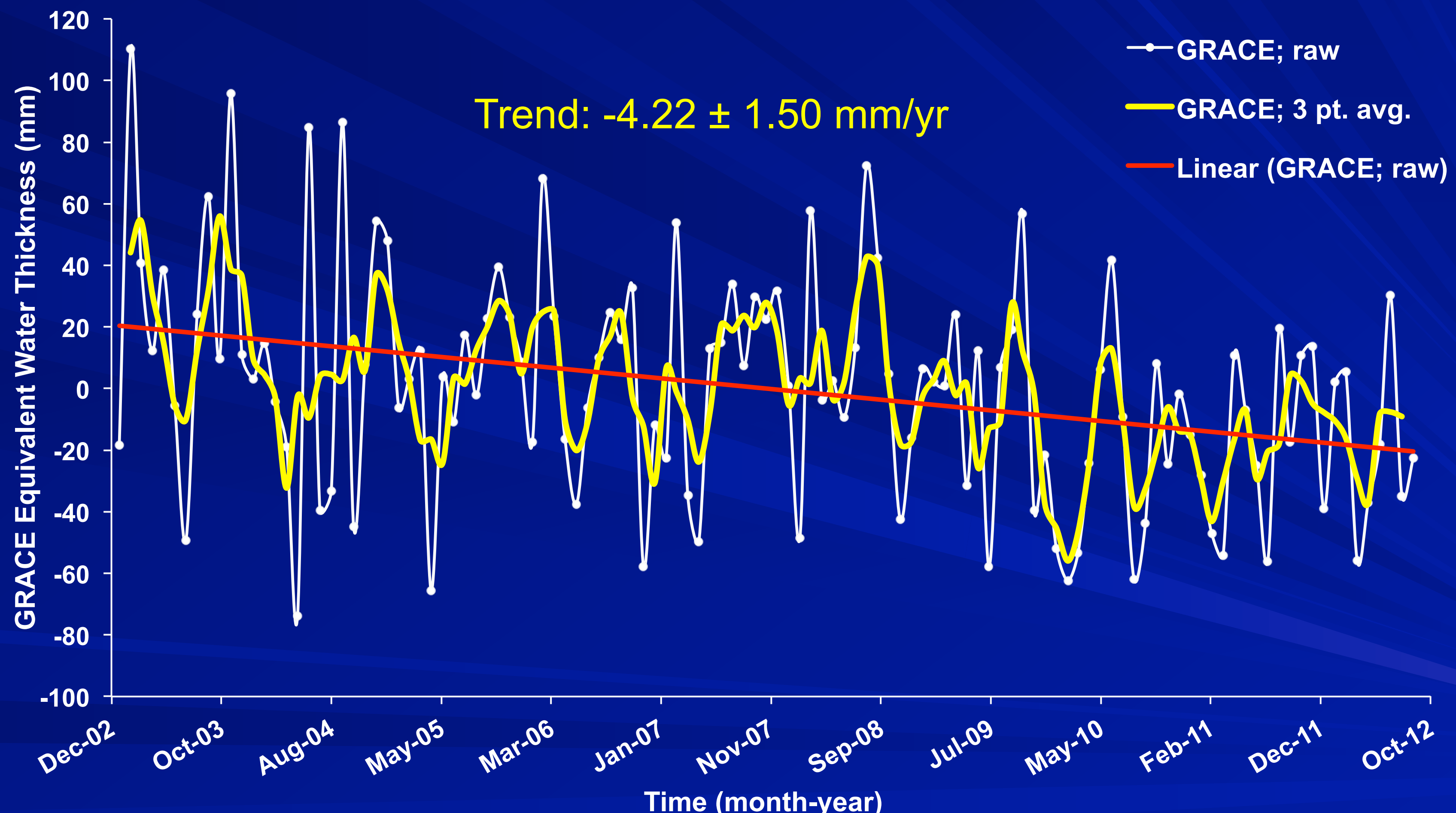
(350 km; Gaussian)



Depletions correlate with the distribution of the DAS & SAS

Groundwater irrigated areas

Dakhla Aquifer System (DAS): GRACE Trend



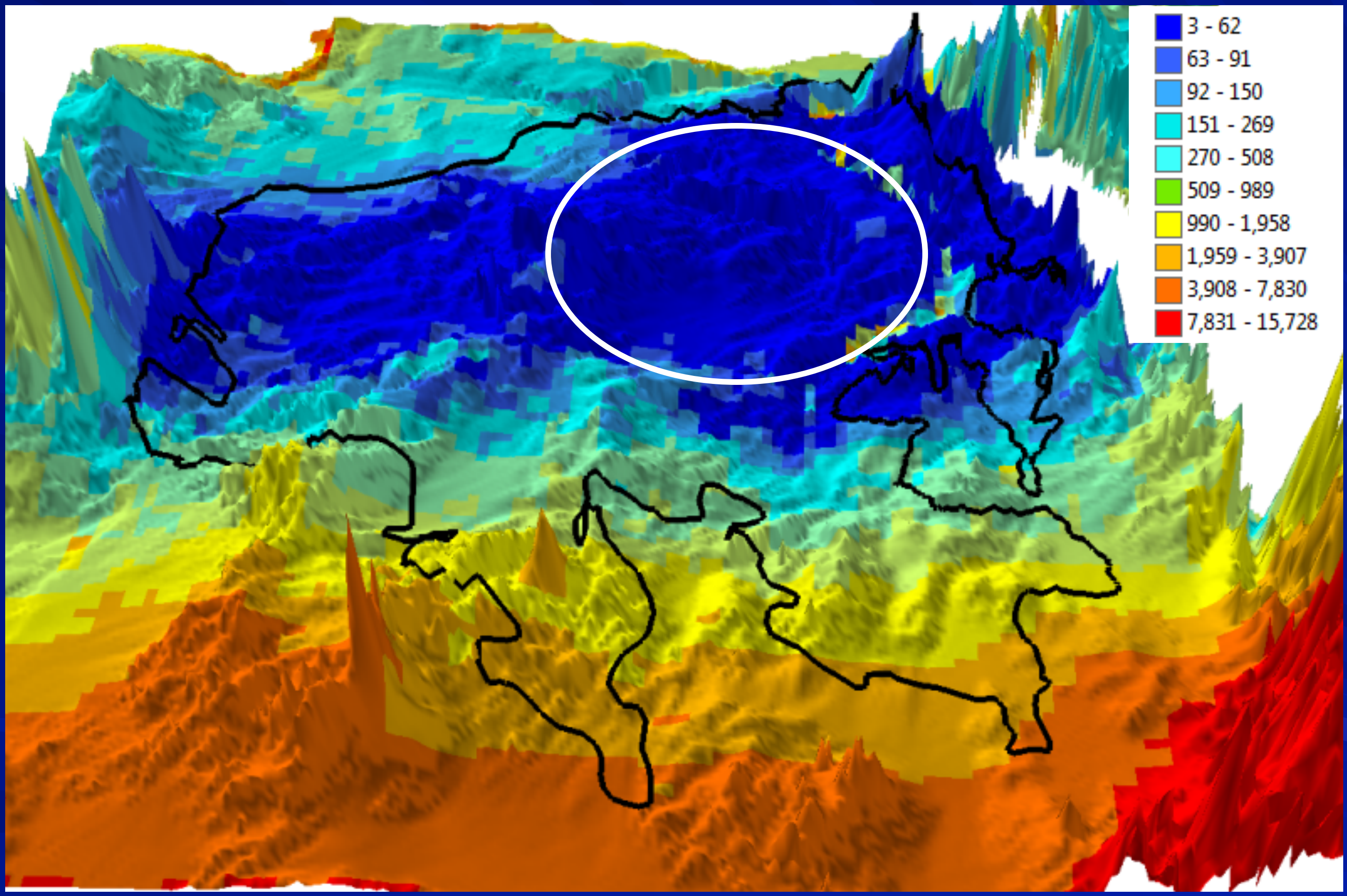
GRACE (200 km; Gaussian) time series over the DAS in Egypt

DAS GRACE Trend

GRACE Trend = -4.22 ± 1.50 mm/yr

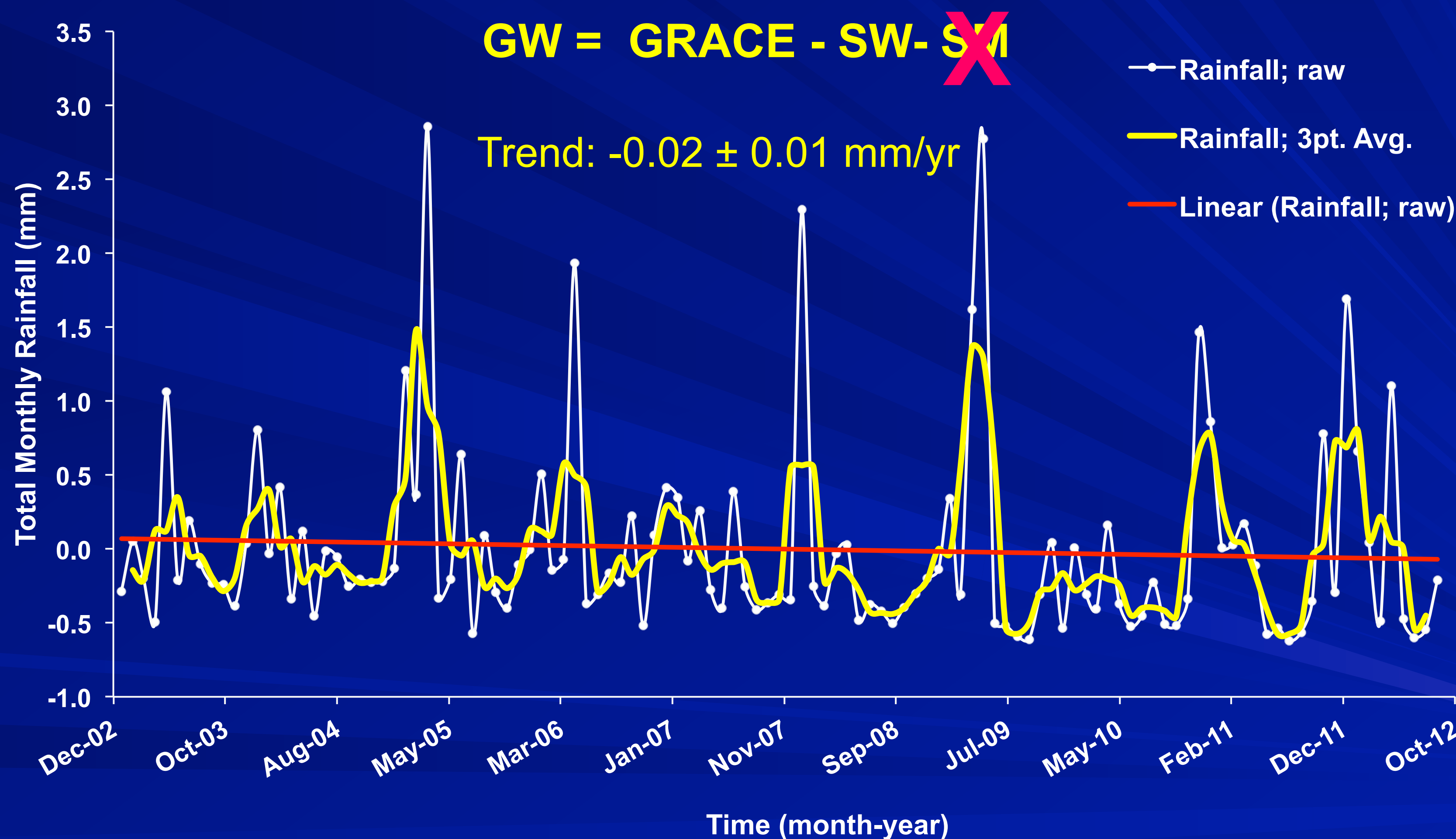
Could the observed depletion in GRACE be related to climatic factors causing a decrease in rainfall/soil moisture/recharge)?

Nubian Sandstone Aquifer System (NSAS): Rainfall



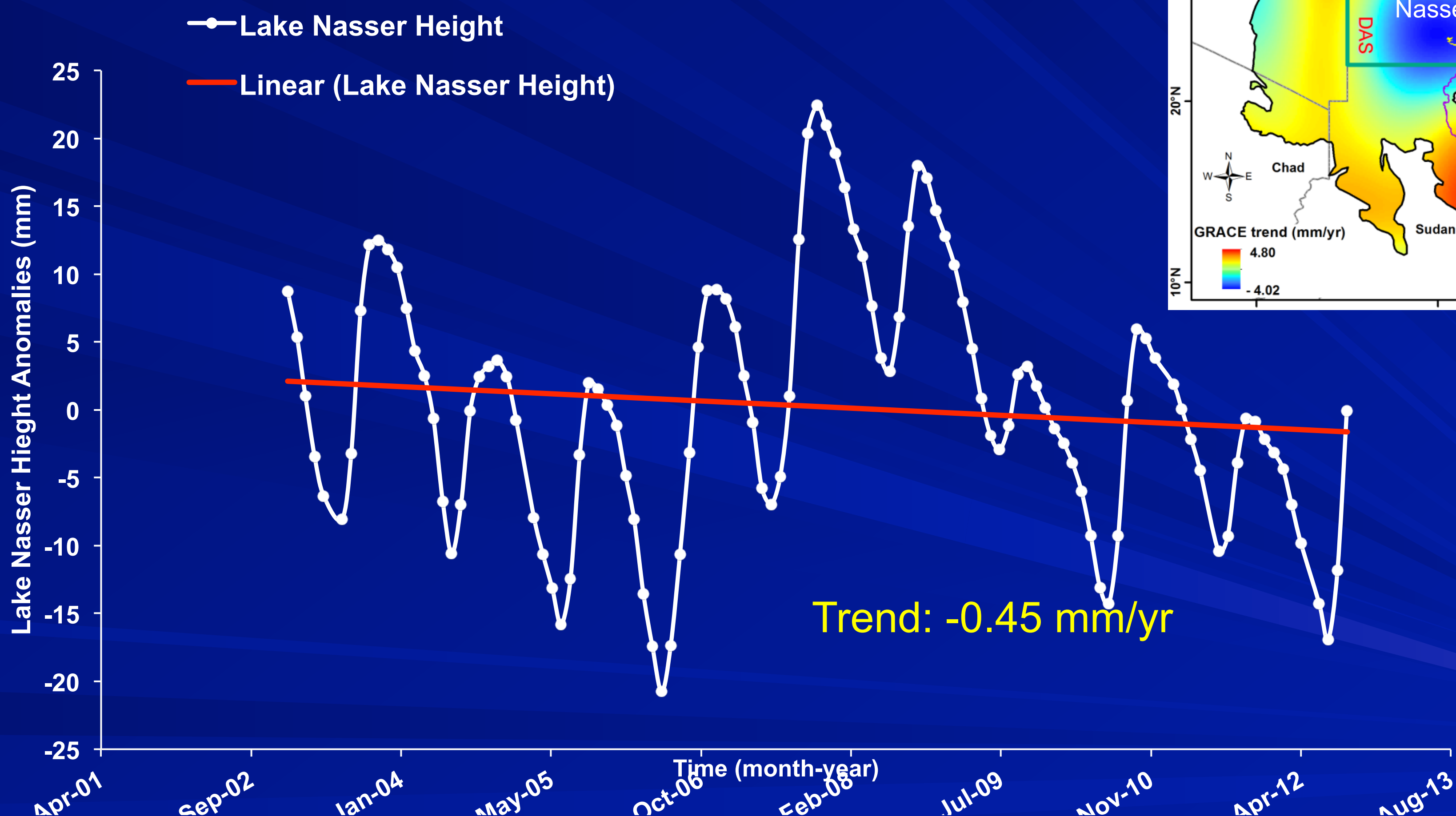
Cumulative precipitation (mm) from
Tropical Rainfall Measuring Mission (TRMM; 3B42 v7A) data (2002 – 2011)

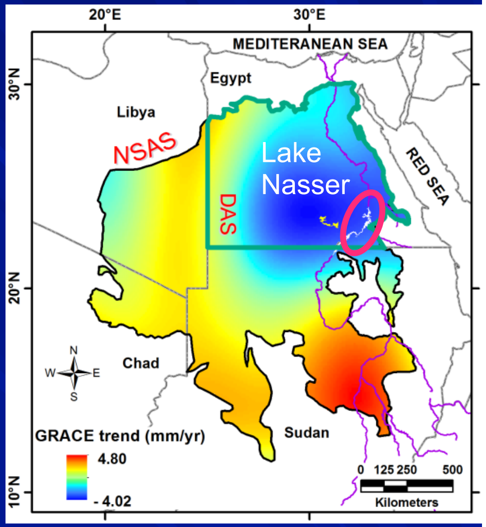
DAS Rainfall Trend



Rainfall time series over the DAS in Egypt

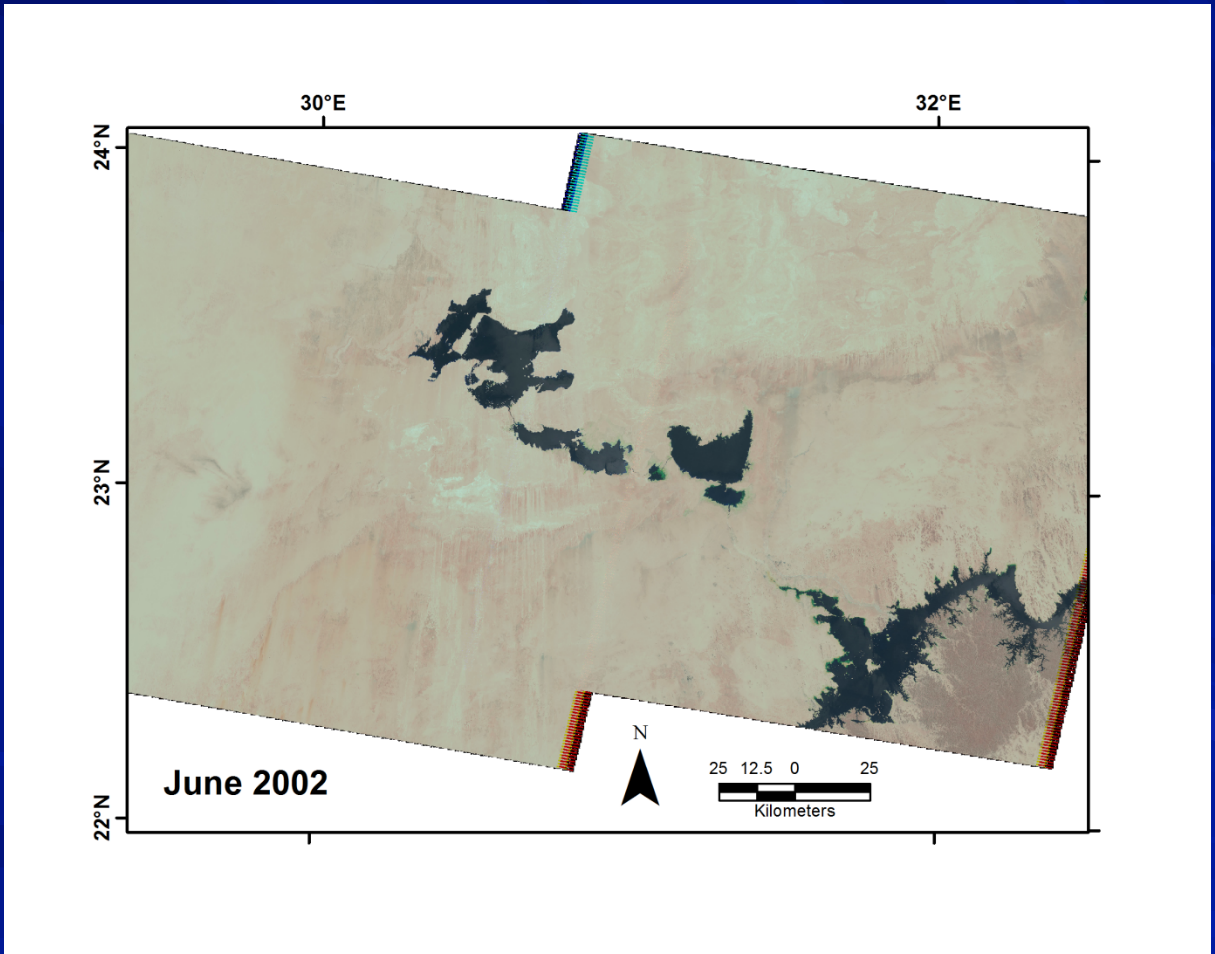
DAS Surface Water: (1) Lake Nasser





Lake Nasser height anomalies (01/2003 – 09/2012) (SH; 200km, Gaussian)

DAS Surface Water: (2) Tushka lakes



Tushka Lakes – Temporal Variations

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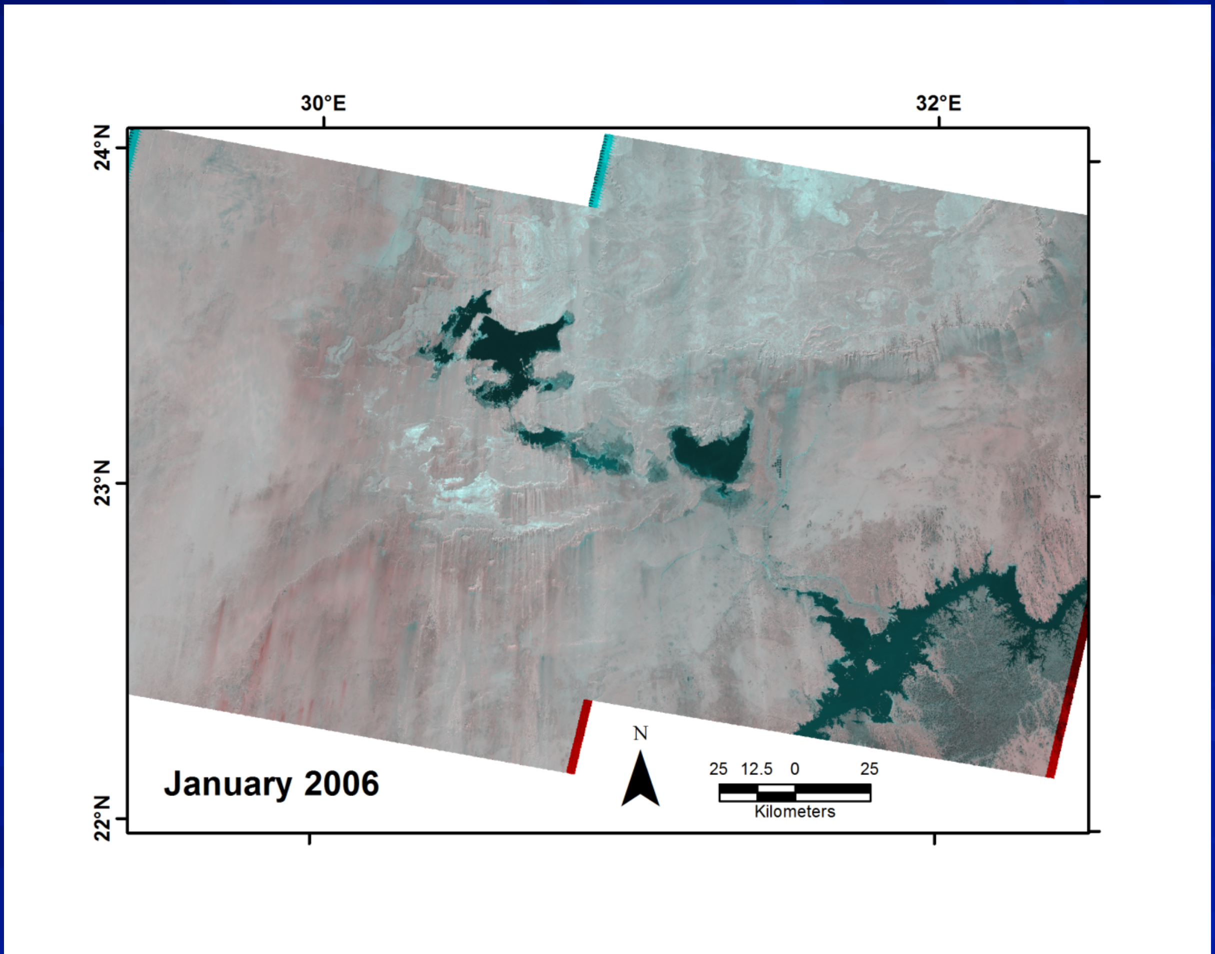

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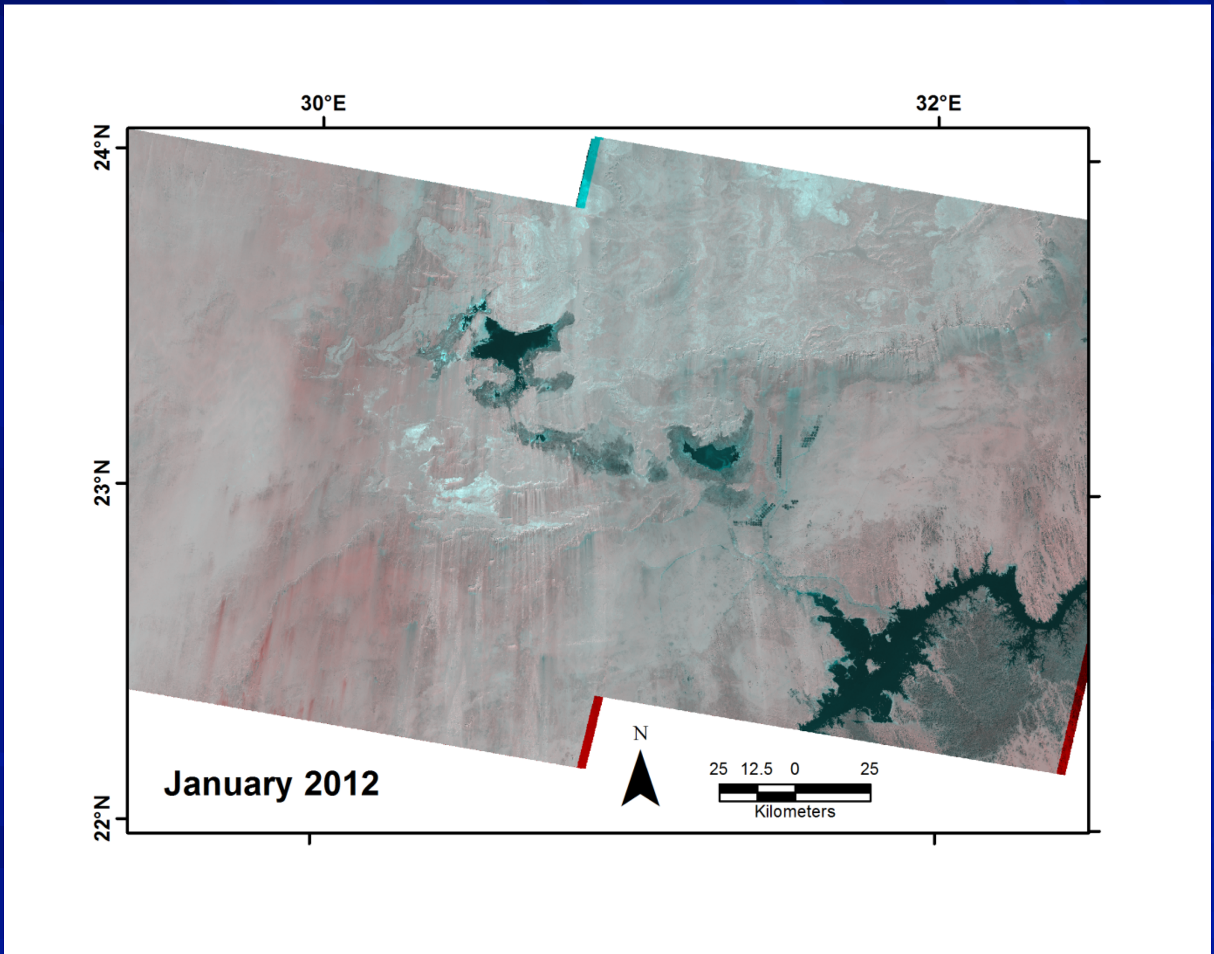


Tushka Lakes – Temporal Variations

DAS Surface Water: (2) Tushka lakes

- Knowing surface water levels at years 2003 and 2012 and having a DEM that pre-dated the Tushka lakes we calculated the average annual decline in volume of water (-0.68 mm/yr).

DAS GRACE Trend

$$GW = GRACE - SW$$

- GRACE Trend = -4.22 ± 1.5 mm/yr
- Surface Water Trend = -0.45 (lake Nasser) -0.68 (Tushka Lakes) = -1.13 mm/yr
- Groundwater = 3.08 ± 1.5 mm/yr = -2.04 ± 0.99 × 10^9 m^3/yr

GRACE *vs.* Field Data

- GRACE-derived groundwater depletion rates is estimated at $2.04 \pm 0.99 \times 10^9$ m^3/yr.

- The reported extraction rates from DAS are estimated at:
  - 0.5×10^9 m^3 → 1979 (Amer et al., 1979),
  - 1.1×10^9 m^3 → 2003 (Ebraheem et al., 2003),
  - Predicted to be 2.8×10^9 m^3 → 2070 (Heinl and Brinkmann, 1989).

DAS Management Scenarios

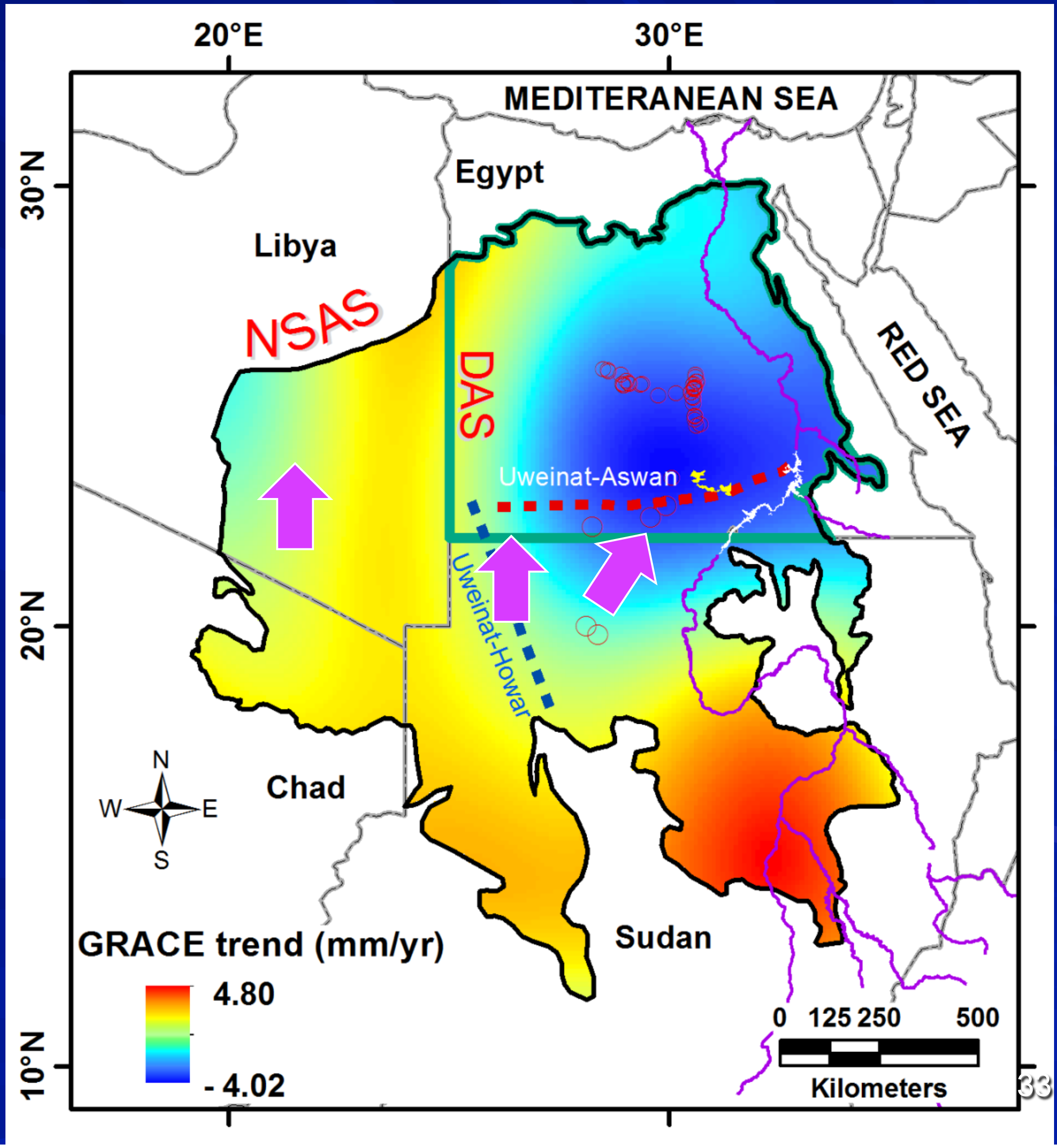
DAS recoverable groundwater volume: $5{,}180 \times 10^9$ m^3 (Bakhbakhi 2006).

- Scenario I: Assuming current GRACE depletion rate ($2.04 \pm 0.99 \times 10^9$ m^3/yr)
  - DAS will last for 2500 years
- Scenario II: Assuming projected depletion rate (2.8×10^9 m^3 in year 2070; model dependant)
  - DAS will last for 1500 years
- Scenario III: Assuming depletion rate will double every 50 years (extraction doubled from 1980-2003)
  - DAS will last for 300 years

Why are GRACE depletions observed in Dakhla but not in Kufra?

South to north groundwater flow impeded by E-W uplift

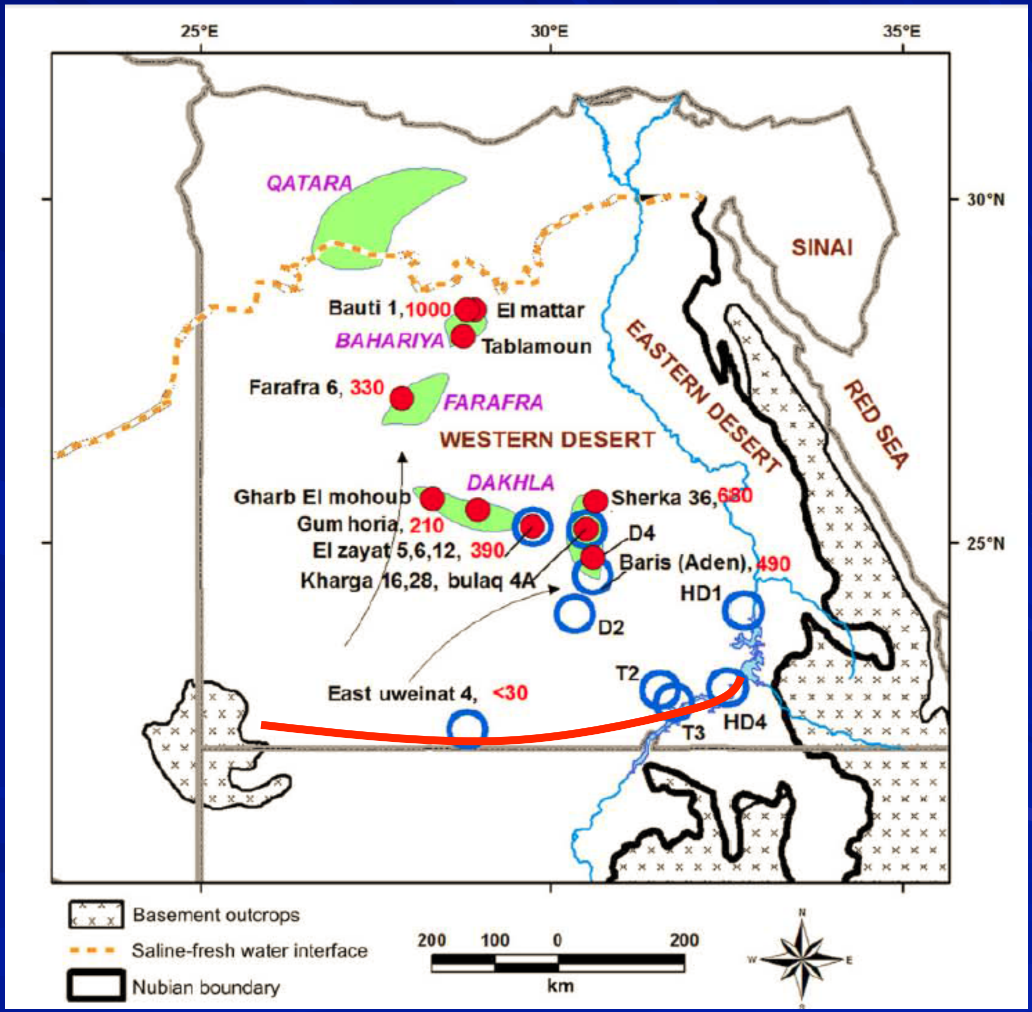
- North of uplift (average isotopic composition $\delta^{18}O$: –10.7‰ ± 0.9‰);
- South of uplift (average isotopic composition $\delta^{18}O$: –8.6‰ ± 1.4‰).



Groundwater ages

South to north groundwater flow impeded by E-W uplift

- Groundwater ages increase from the SW to NE within DAS.



Conclusions

- Observed depletions over the DAS and the SAS and their absence across the remaining regions of the NSAS and the APAS indicate the aquifers are largely at near-steady conditions, yet the DAS and SAS are not.
- Excessive groundwater extraction, not climatic changes, is responsible for the TWS depletion over the DAS and the SAS
- DAS in Egypt shows a groundwater depletion rates of $2.04 \pm 0.99 \times 10^9$ m^3/yr.
- Uweinat Aswan uplift is impeding replenishment of DAS by groundwater flow from the south
- SAS in Saudi Arabia shows a groundwater depletion rates of $6.11 \pm 1.83 \times 10^9$ m^3/yr
- First order management scenarios could be formulated

- *Sultan, M., Ahmed, M., Wahr, J., Yan, E., Emil, M.K., 2013, Monitoring Aquifer Depletion from Space: Case Studies from the Saharan and Arabian Aquifers, Chapman Remote Sensing AGU monograph, In Press.*