Revisiting recharge and sustainability of North-Western Sahara aquifers

Gonçalvès julio, Pr. AMU

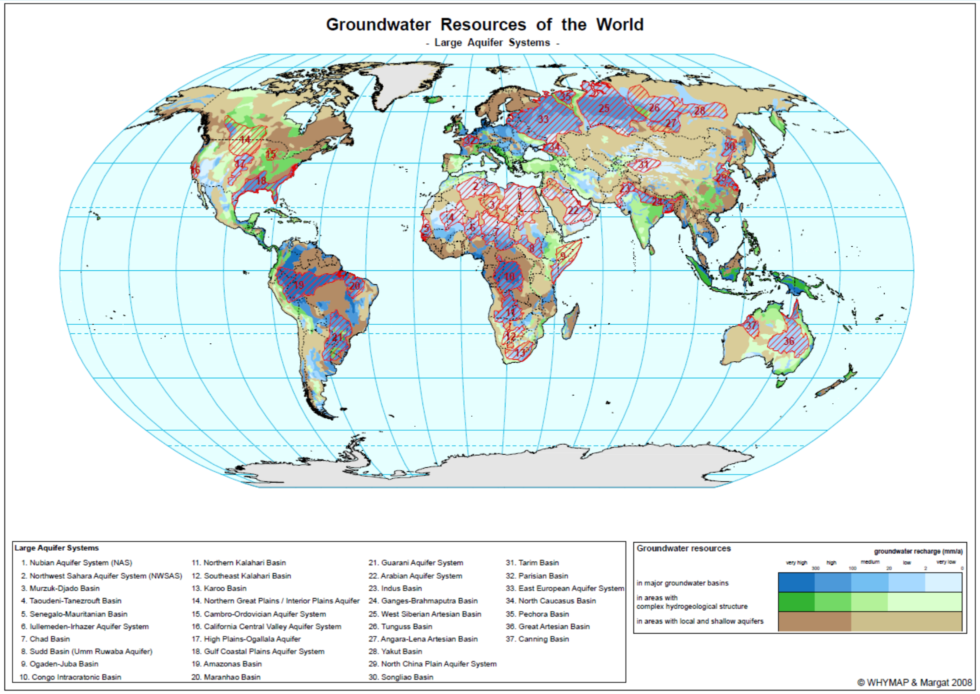
cerege

OT-MED LABEX

A*Midex Initiative d'excellence Aix-Marseille

WHAT KIND OF ENVIRONMENTAL TRANSITION FOR THE MEDITERRANEAN REGION?

OCTOBER 14-16 2019 Marseille Pharo



World-wide **Hy**drogeological **M**apping and **A**ssessment **P**rogram (**WHYMAP**)

Large (Regional) Aquifers in the world (>100000km²)

Key-words in (very) Highly ranked journals: Depletion, Sustainaibility, Resilience

doi:10.1038/nature08238 nature

LETTERS

Satellite-based estimates of groundwater depletion in India

Matthew Rodell[1], Isabella Velicogna[2,3,4] & James S. Famiglietti[2]

2009

LETTER

doi:10.1038/nature11295

Water balance of global aquifers revealed by groundwater footprint

2012

Water Resources Research

RESEARCH ARTICLE
10.1002/2015WR017349

Special Section:
The 50th Anniversary of Water

Quantifying renewable groundwater stress with GRACE

Alexandra S. Richey[1], Brian F. Thomas[2], Min-Hui Lo[3], John T. Reager[2], James S. Famiglietti[1,2,4], Katalyn Voss[5], Sean Swenson[6], and Matthew Rodell[7]

2015

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL076005

Key Points:
- Groundwater sustainability metrics

Global Assessment of Groundwater Sustainability Based On Storage Anomalies

Brian F. Thomas[1], Júlio Caineta[1,2], and Jamiat Nanteza[3]

2017

PNAS

Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data

Bridget R. Scanlon[a,1], Zizhan Zhang[b], Himanshu Save[c], Alexander Y. Sun[a], Hannes Müller Schmied[d,e], Ludovicus P. H. van Beek[f], David N. Wiese[g], Yoshihide Wada[f,h], Di Long[i], Robert C. Reedy[a], Laurent Longuevergne[j], Petra Döll[d,e], and Marc F. P. Bierkens[f]

2018

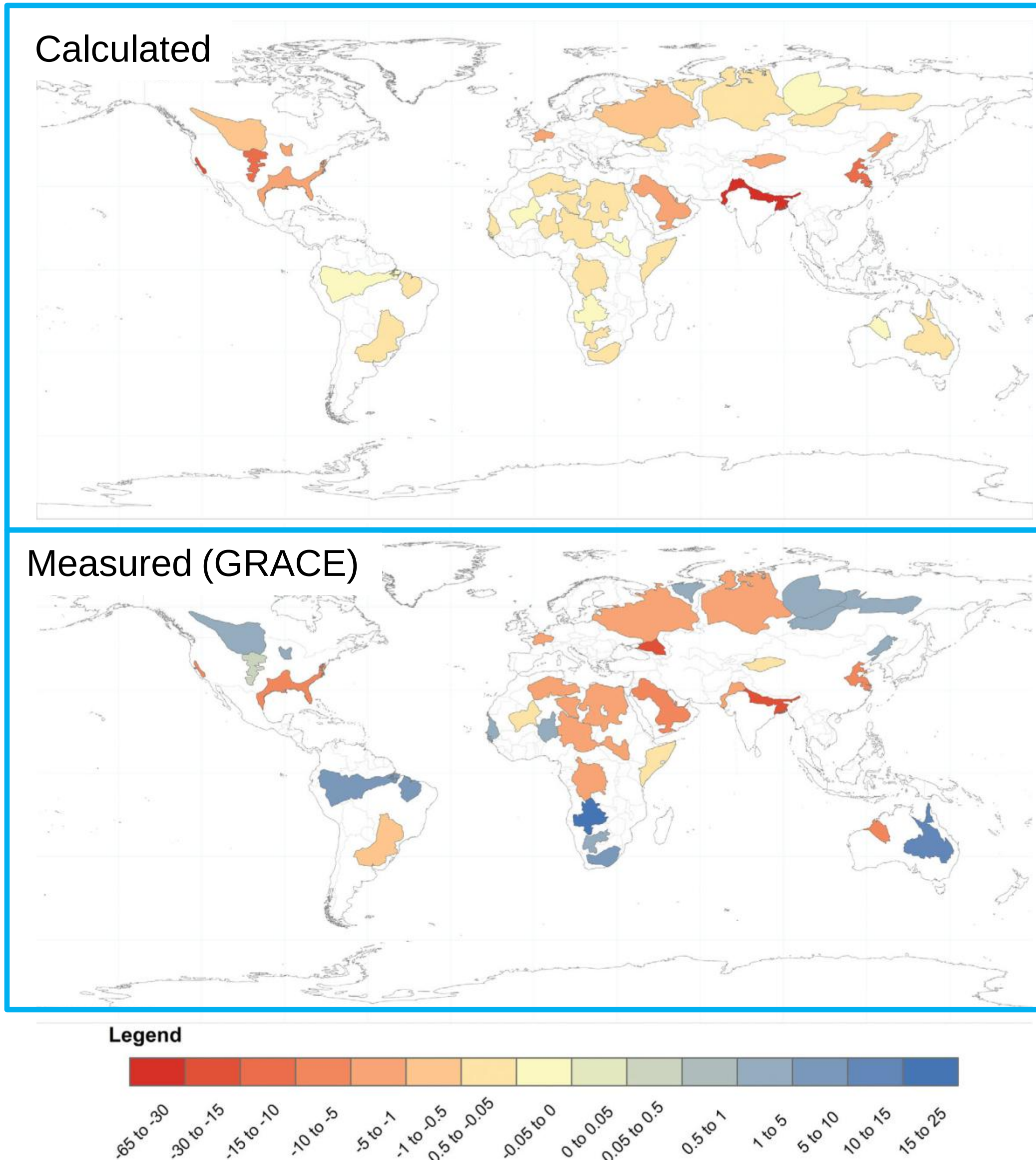
LETTER

https://doi.org/10.1038/s41586-019-1594-4

Environmental flow limits to global groundwater pumping

Inge E. M. de Graaf[1,2,3*], Tom Gleeson[4], L. P. H. (Rens) van Beek[2], Edwin H. Sutanudjaja[2] & Marc F. P. Bierkens[2,5]

2019



Sustainablility criterion at First order:
$R\text{-}Q_W \geq 0$

Water Resources Research

RESEARCH ARTICLE
10.1002/2015WR017349

Special Section:
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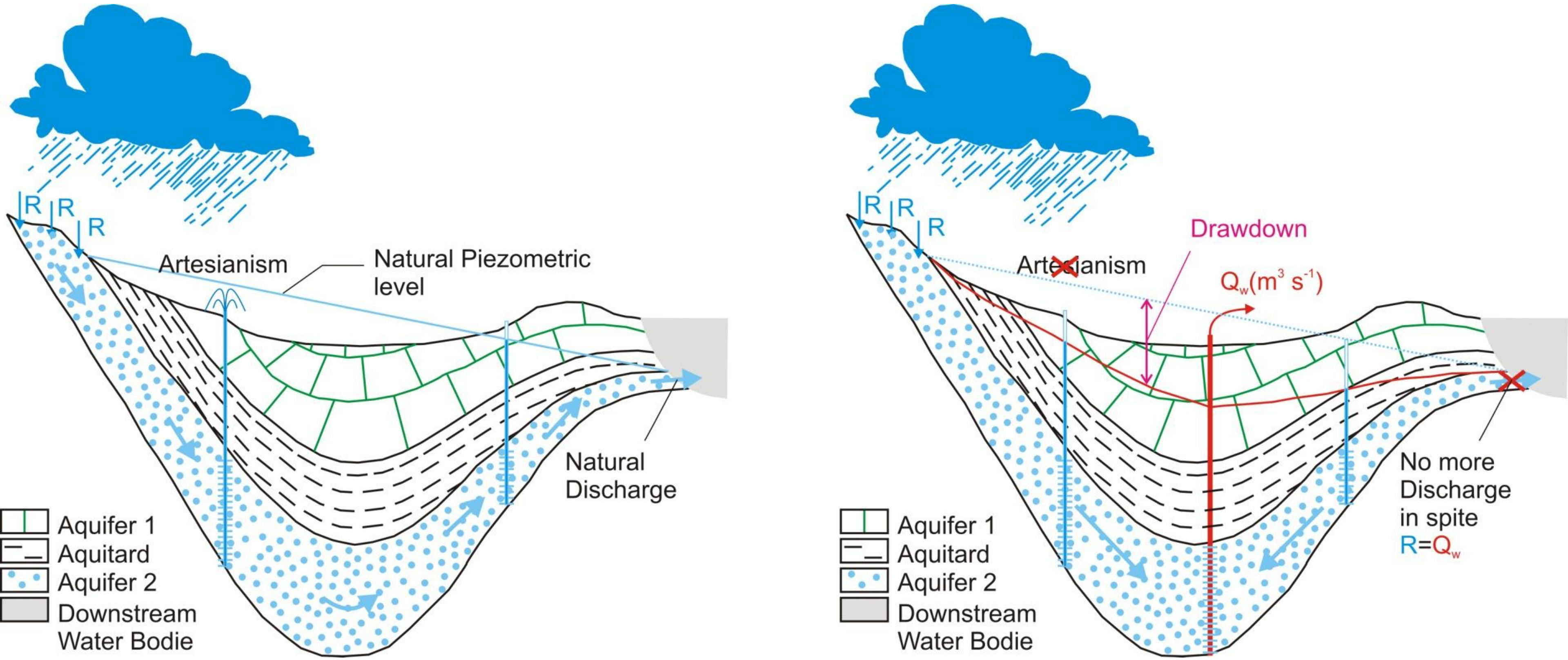
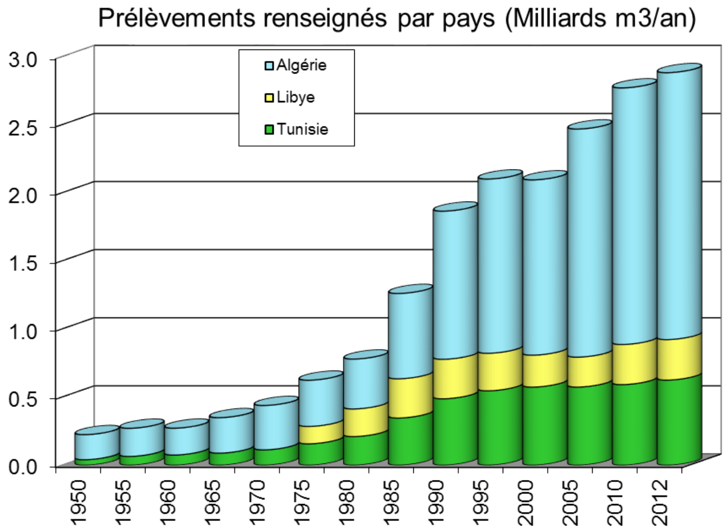
Quantifying renewable groundwater stress with GRACE

Alexandra S. Richey[1], Brian F. Thomas[2], Min-Hui Lo[3], John T. Reager[2], James S. Famiglietti[1,2,4], Katalyn Voss[5], Sean Swenson[6], and Matthew Rodell[7]

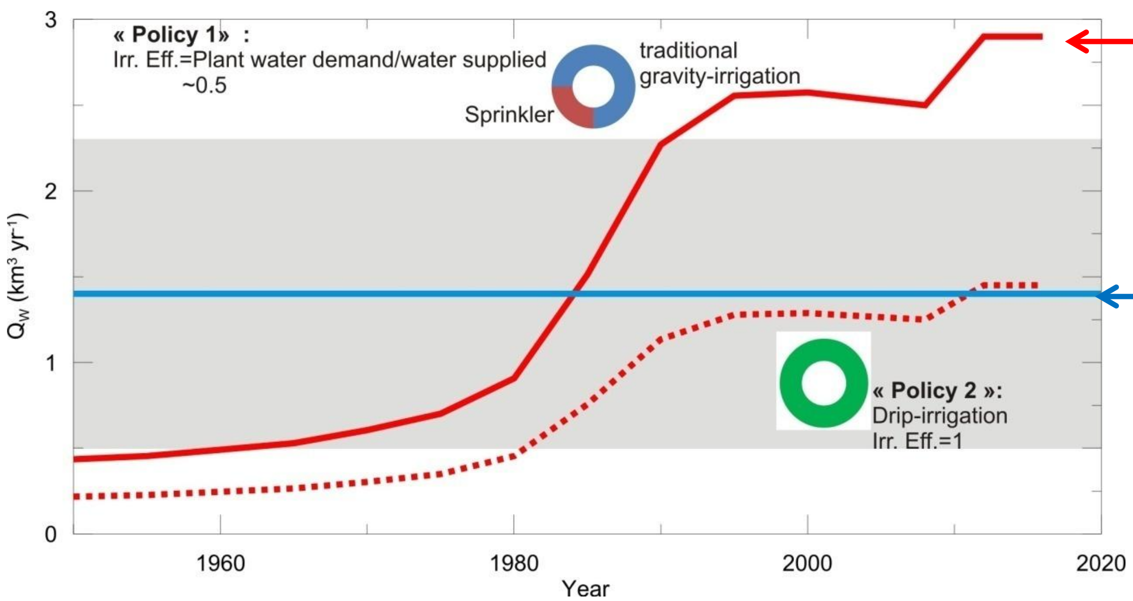
Analyzing sustainable use of groundwater only using R-Q_W is a (over-)simplifying idea

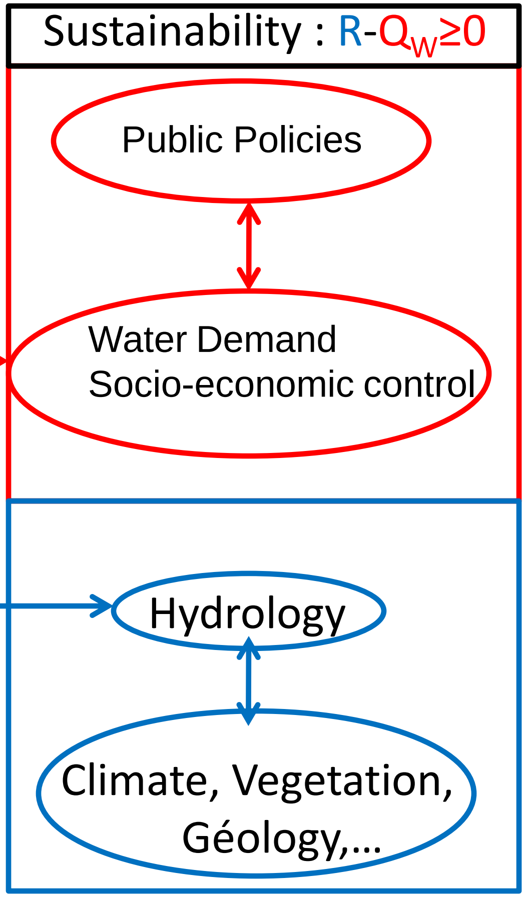
Hidden costs of pumping: We always take water to
somebody or something (ecosystem) downstream. Contrarily to Surface water
Aquifer Withdrawals are more insidious since almost « invisible »!

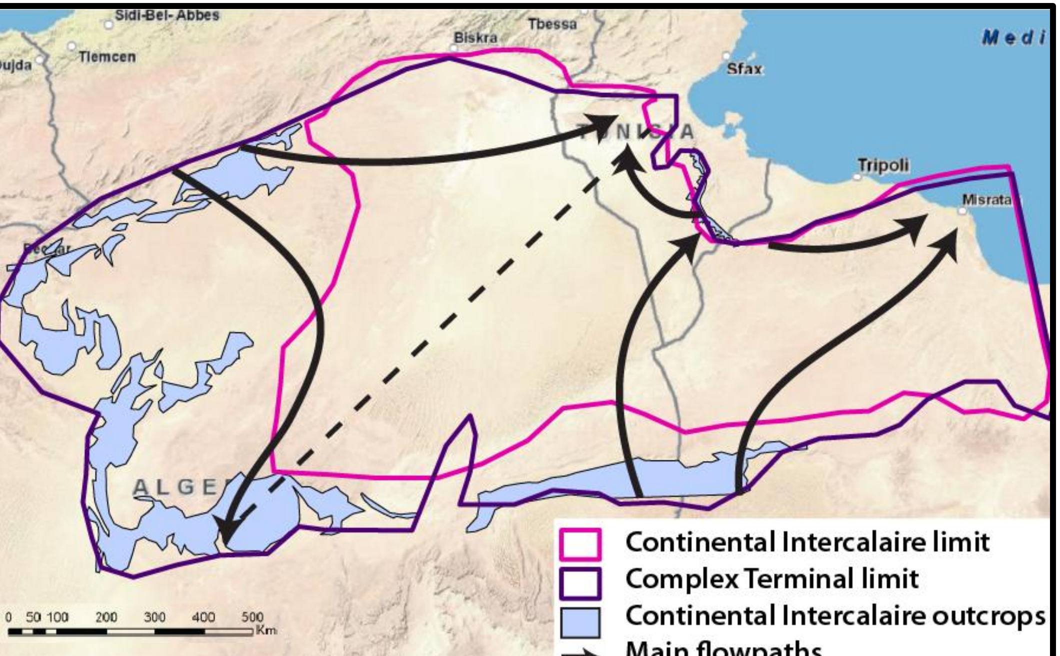


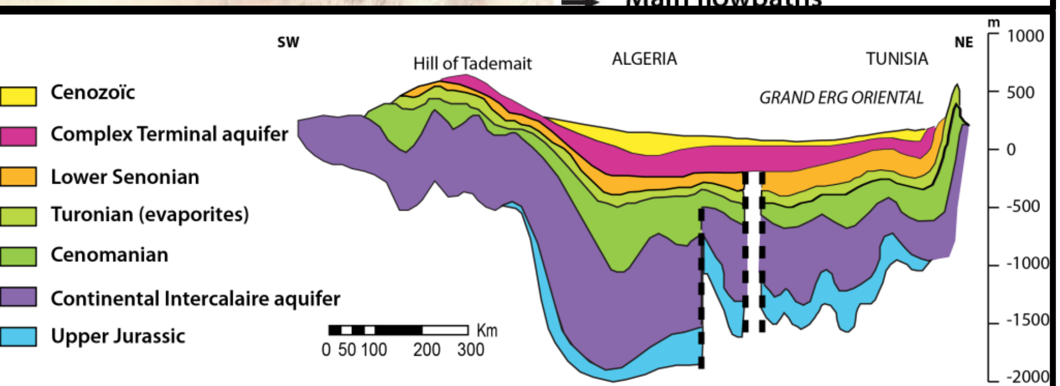


(Observatoire du Sahara et du Sahel)
Sahara and Sahel Observatory



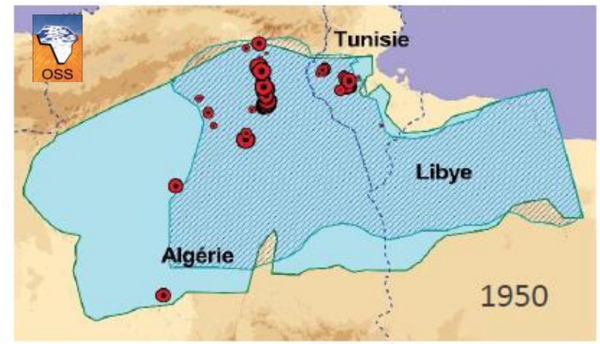




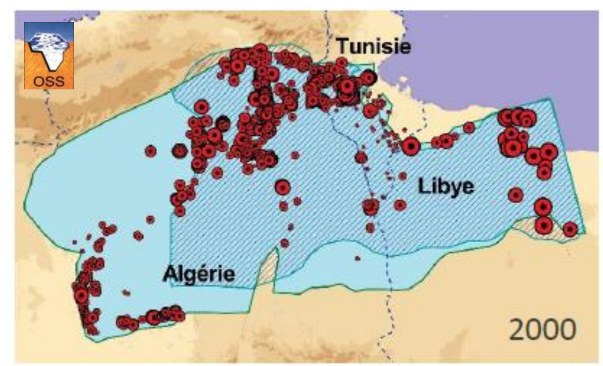


North-Western Sahara Aquifer System (NWSAS): Multi-layered system over 10^6 km^2 , estimated reserves: 31 000 km^3 (Baba Sy, 2005)

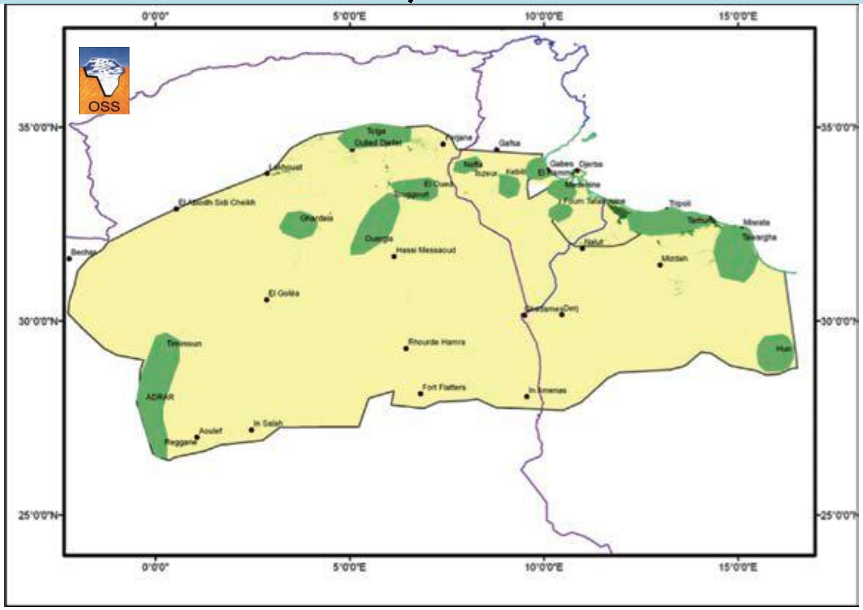
1950 ~2000 Boreholes Q_W=0.5 km^3/yr...

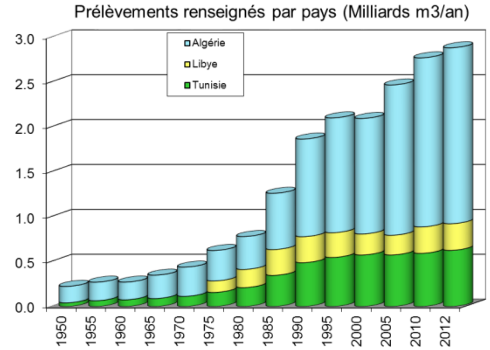


… 9000 boreholes in 2000 QW=2.5 km3/yr



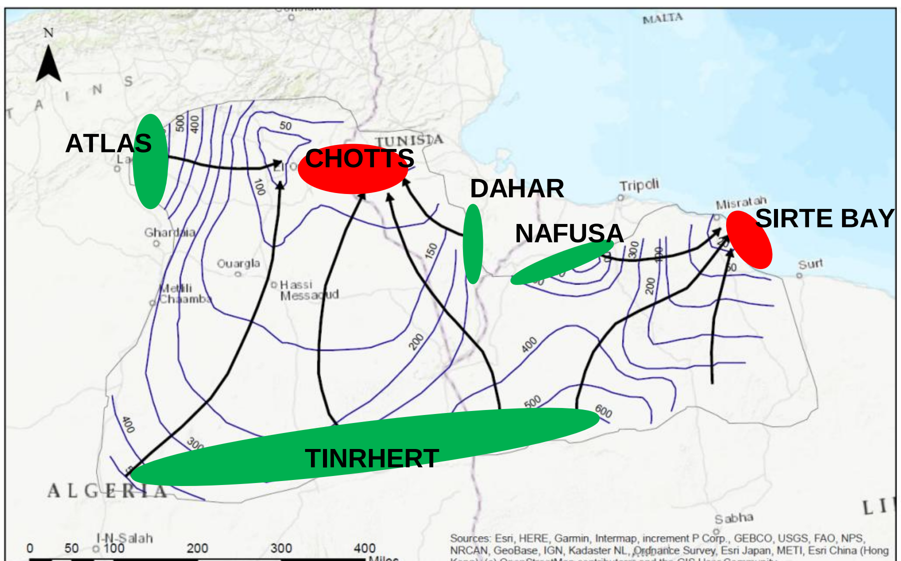
Mean piezometric drawdown : 20m CT 30 m CI between 1950 & 2000



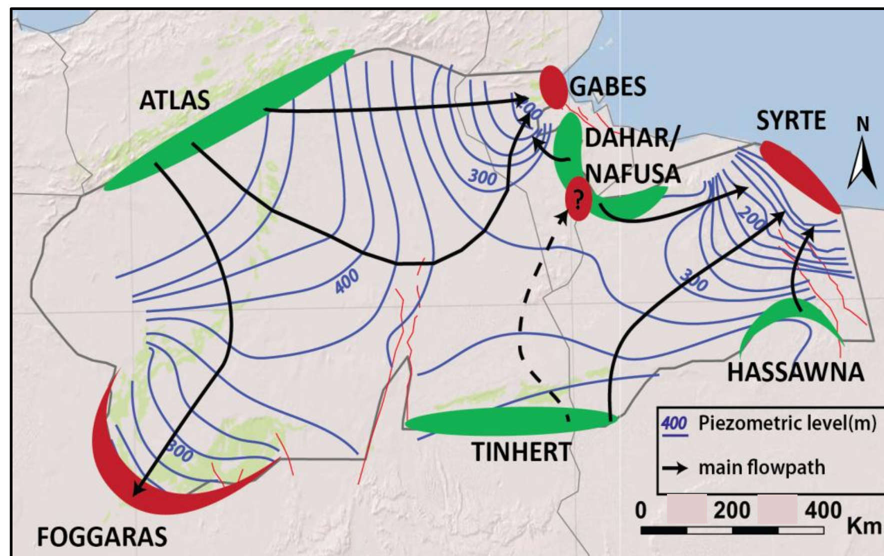


80 to 85% of withdrawals for agriculture (irrigation)
Oasis (« Socio economic aspects of the Irrigation in the SASS basin », OSS (2014)

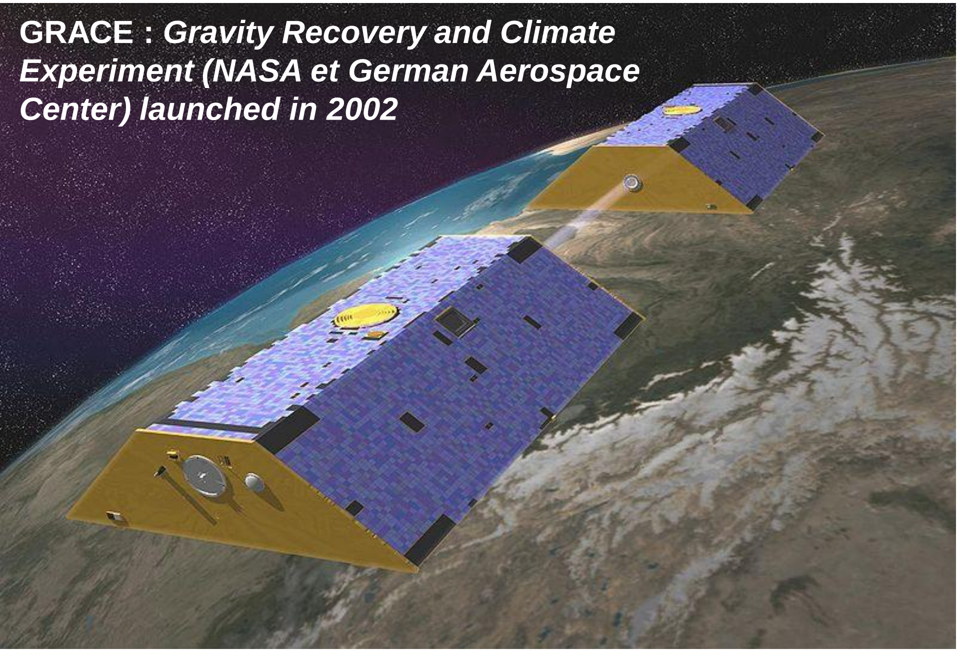
Hydrodynamics at steady-state (natural, 1950) of the NWSAS Recharge/discharge areas



CT at steady state 1950 (Q_W~0)



CI at steady state 1950 (Q_W~0)



Monitoring of the gravity field g (1°×1° Africa) by twin Satellites

Basic hypothesis:

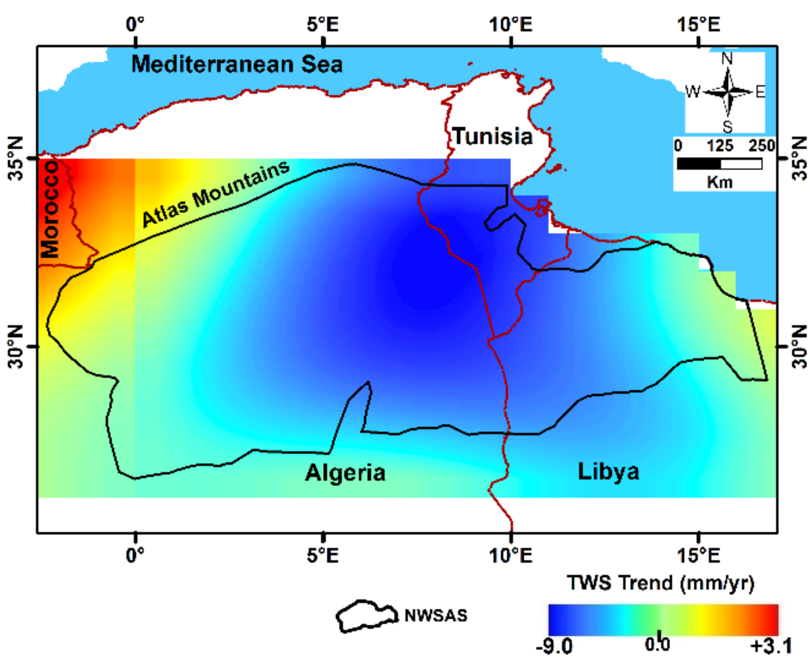
$\Delta g \Leftrightarrow \Delta M$ mass variations of continental water bodies including groundwater (Groundwater Storage GWS)

Monthly values of g expressed in « water height anomalies » (value minus long term mean) =**Terrestrial water storage (TWS)**

(water mass: 2.25 cm water height ⇔ 1µGal)

« Satellite Hydrology » :

Monitoring of aquifers seasonality; water balances for large hydro(geol)logical basins



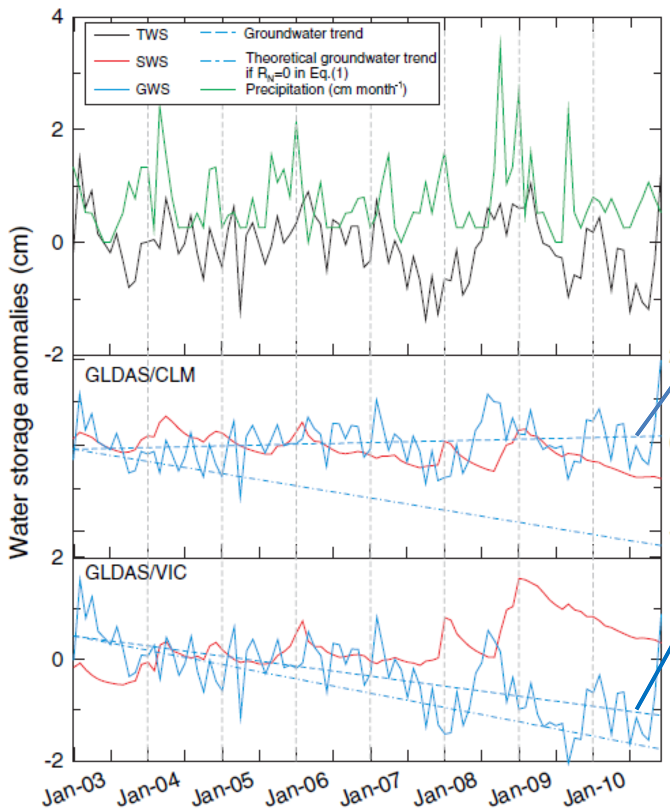
Example: TWS variation (mm/yr) between 2002 and 2016 For the NWSAS ⇔ water fluxes (depletion or replenishment) of water bodies (here aquifers+soil)

Mohamed A. & Gonçalvès J., Submitted, J. Hydrol.

Application to the whole NWSAS domain: for each monthly map of TWS the NWSAS surface area averaged value is calculated yielding a TWS time-series

TWS=GWS+SWS+S_uWS
SWS (Soil water storage) obtained from GLDAS
SuWS (Surface Water Storage) ~0 in NWSAS

GWS=TWS-SWS



Gonçalvès et al. (2013)

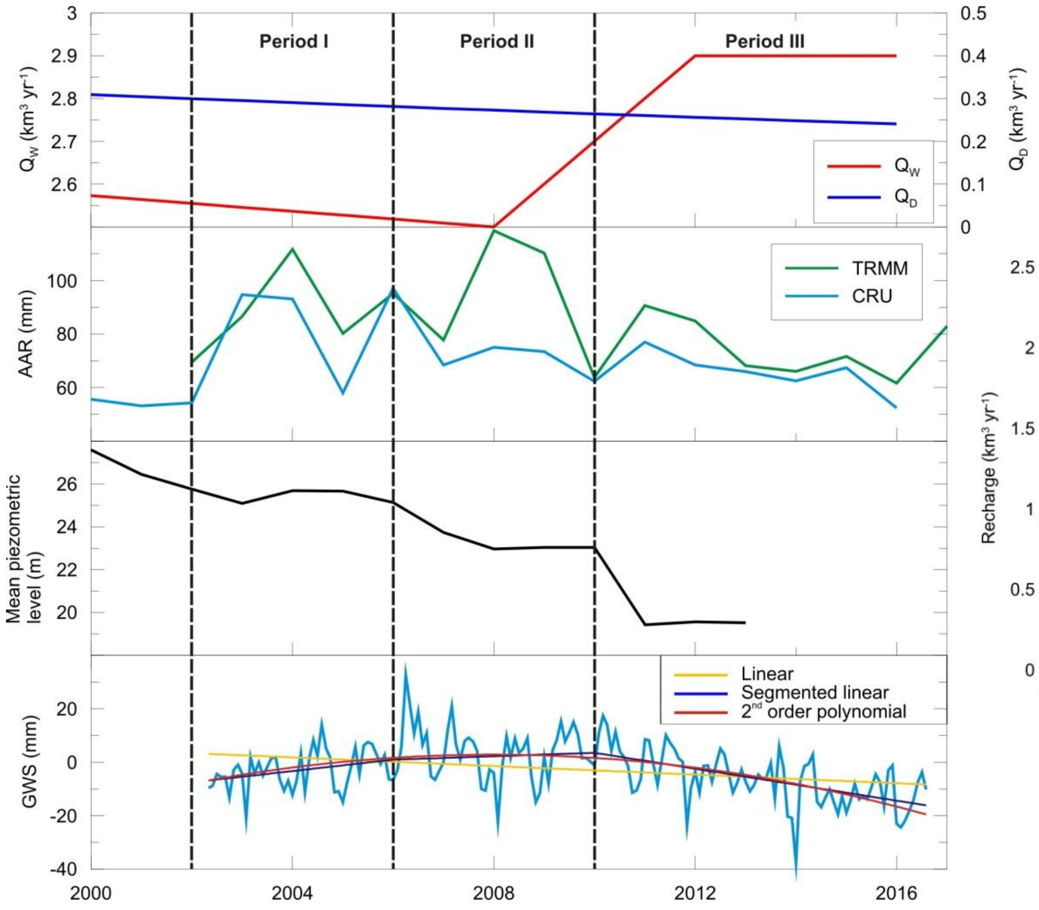
$\Delta GWS = -Q_W - Q_D + R_{Ir} + R_N$

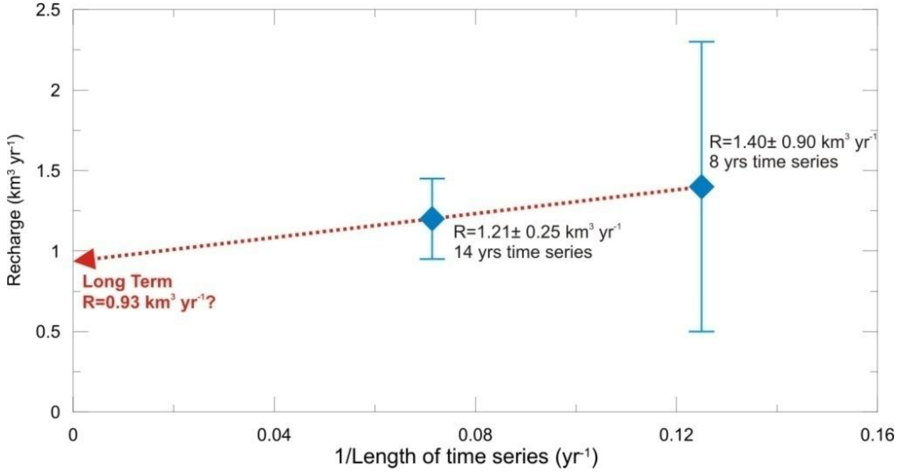
Q_W(pumpings), Q_D (discharge) , R_{Ir} (irrigation) are known
Budget closure using GRACE Solutions:

Natural modern Recharge R_N ~2.2 ±1.4 mm/yr or 1.4 ± 0.9 km³/yr → ~40% of the pumpings (2.75 km³/yr)

NWSAS is not strictly fossil!

Approach using GRACE recently extended (2002-2016)…





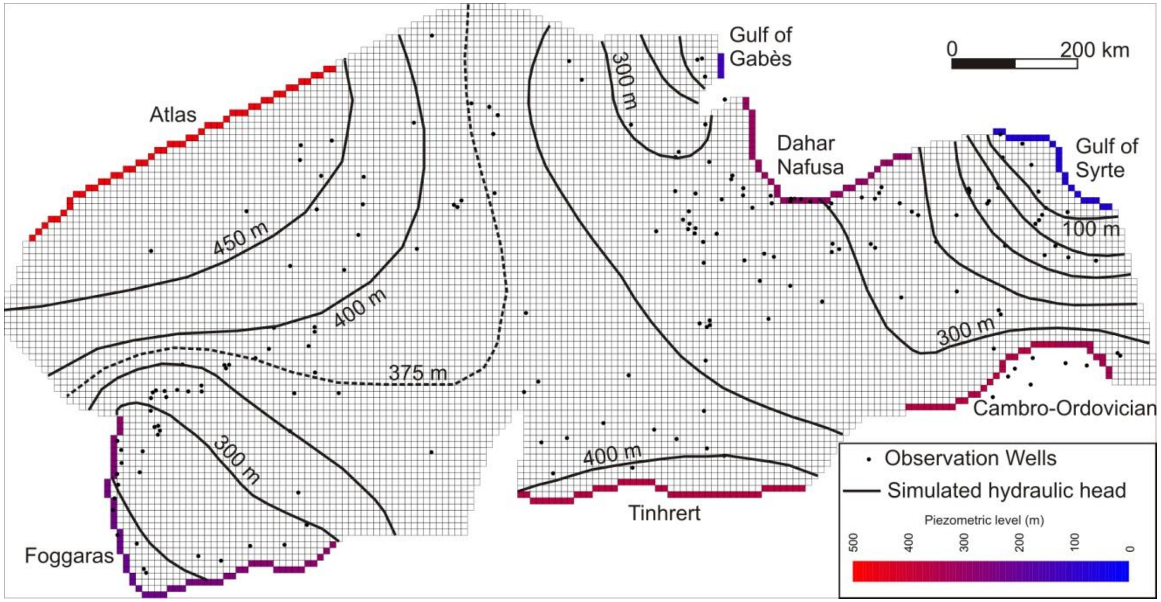
Long term value??? GRACE ended in 2018…

..yielding a R=1.21±0.25 km3 yr^{-1}

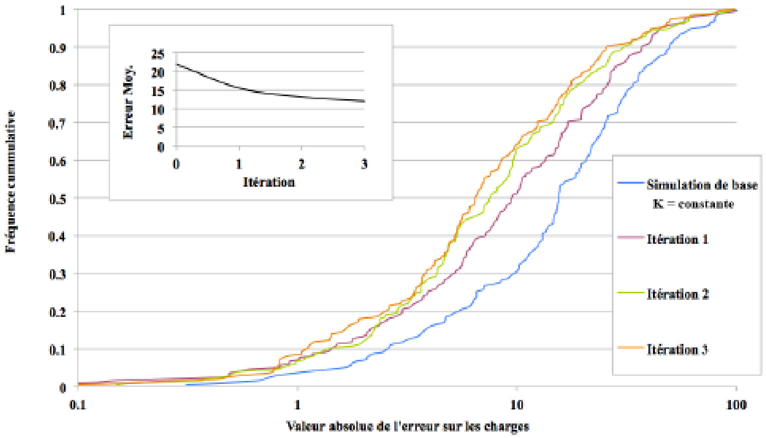
(Mohamed A. & Gonçalvès J., Sub.)

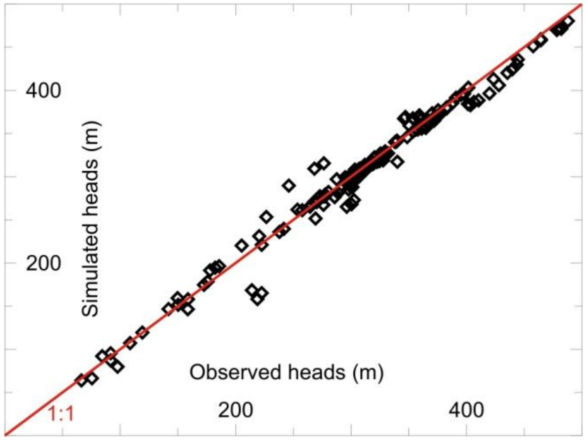
Hydrogeological model (Petersen, 2014) of the CI at steady-state (~1950) PMWIN (Modflow)
Using the geometry from the last complete model by Baba Sy (2005)

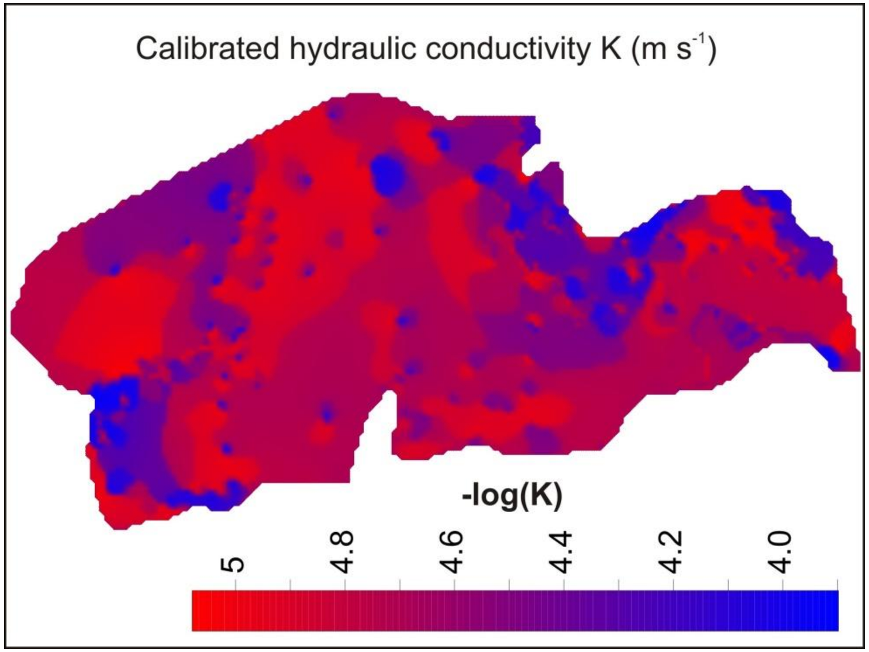
10 previous models CI→R_{CI}=0.36±0.15 km³ yr⁻¹; 2 CI+CT→R_{CT}=0.66±0.12 km³ yr⁻¹

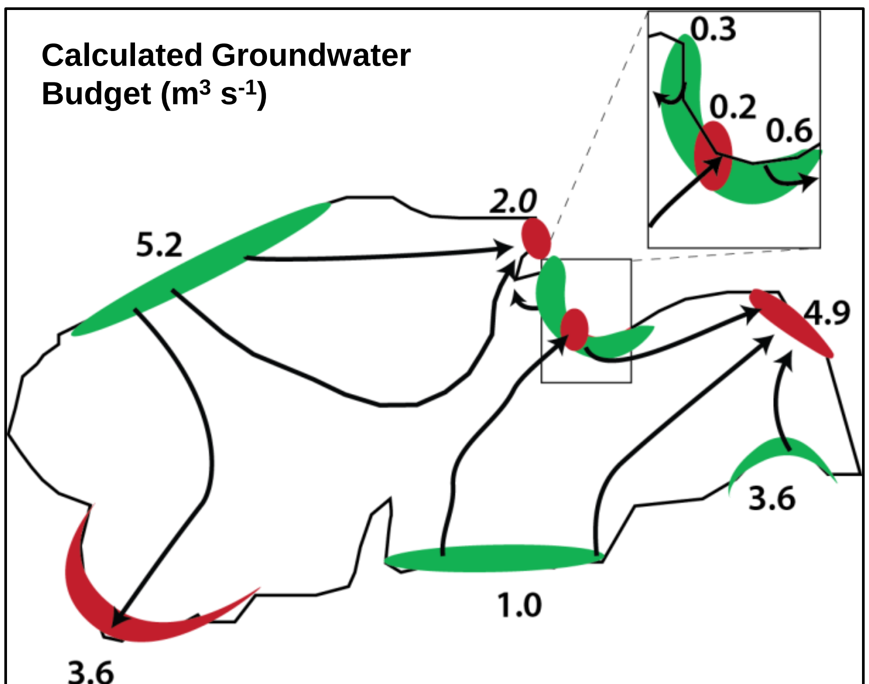


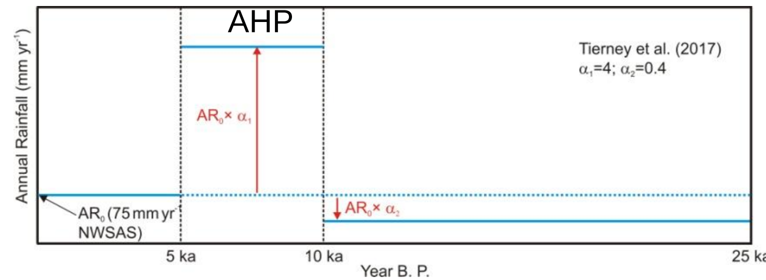
Automatic calibration (Gradient method)











Validity of the postulated Steady-state in 1950 while the end of the African Humid Period (AHP) is at -5ka?

●**K_m=4 10^{-5} m s^{-1}** + Cl average thickness of 350m **T=1.2 10^{-2} m^2 s^{-1}**

Equilibration time (**Resilience!**) T_E~3τ (characteristic time) with $\tau=L^2/(T/S)$

S: storativity 10^{-3}

L: dimension of the system (recharge-discharge distance) ~500 km

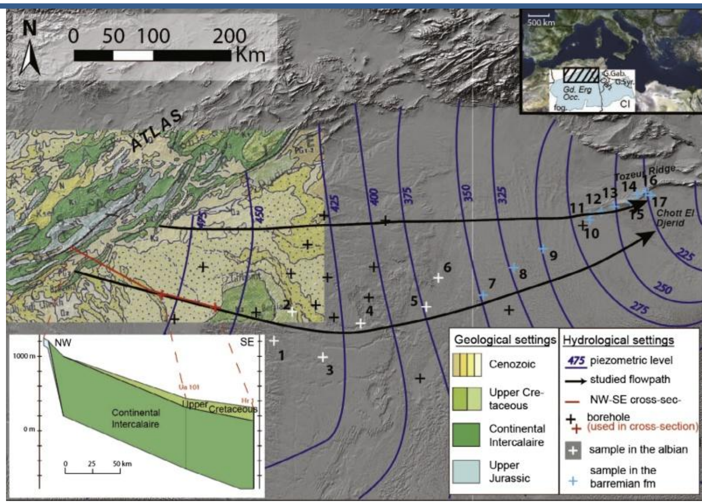
⇔T_E=2ky

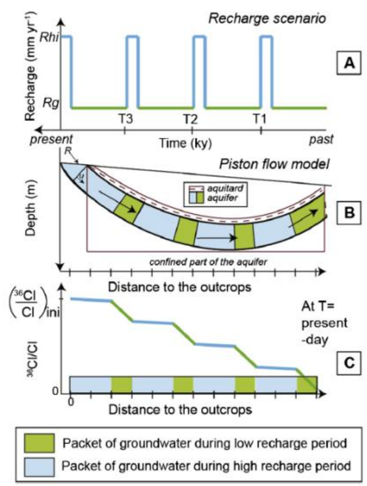
●**R_{Cl}=0.22 km^3 yr^{-1}**

Atlas ~75% of this value

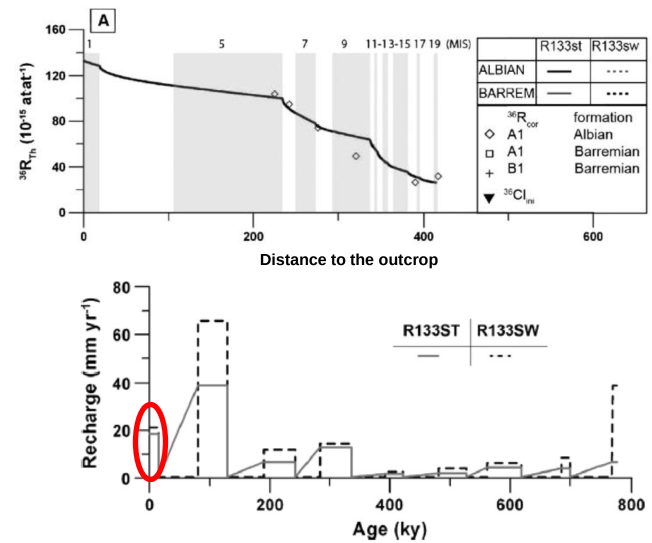
Gonçalvès et al. (In Rev.) REEC

Recharge using cosmogenic radio-isotopes : example ^{36}Cl in the Cont. Intercalaire





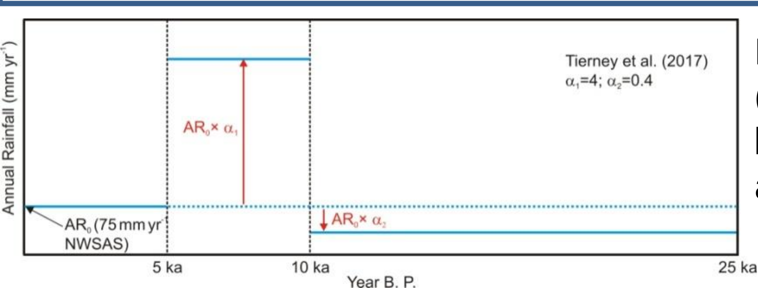
Petersen et al. (2014)



Field sampling along streamlines

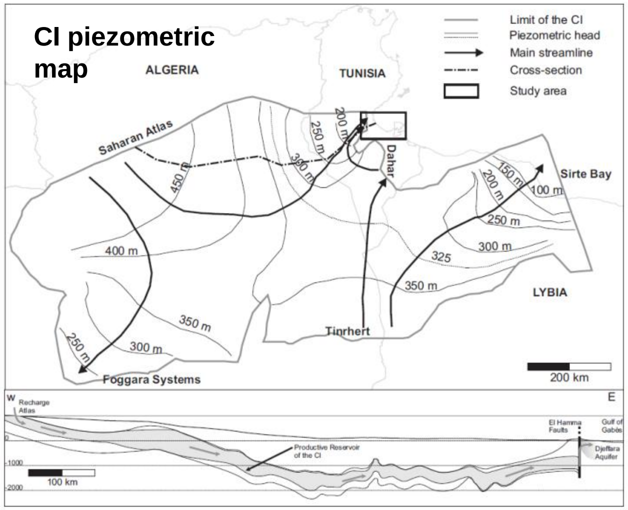
Piston Flow model

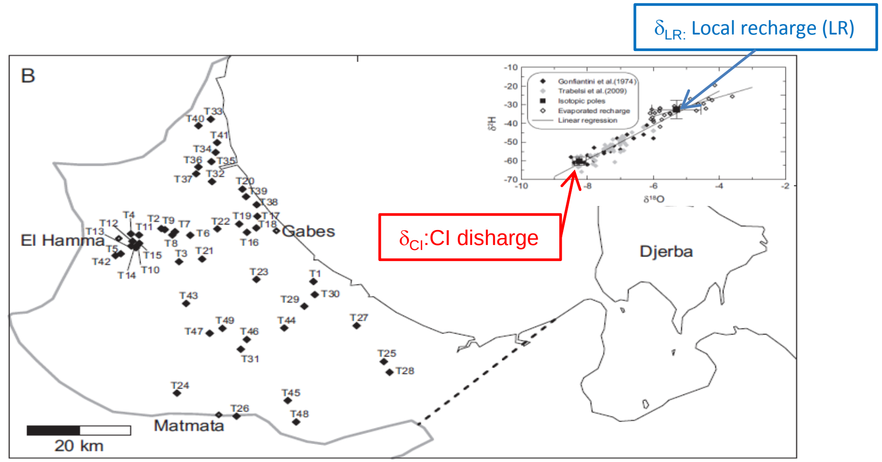
Calibration of recharge (0-800ky)



Noting that 20 mm yr^{-1} is the mean recharge value (0-15 ky BP), assuming i) square-wave climatic scenario, ii) linearity R-AR, iii) a_1=5±2.3 (model + proxy reconstructions) a_2~0 and the 25000 km² outcrop CI Atlas → **R_{CI}^{Atlas}=0.25±0.1 km³ yr^{-1}**

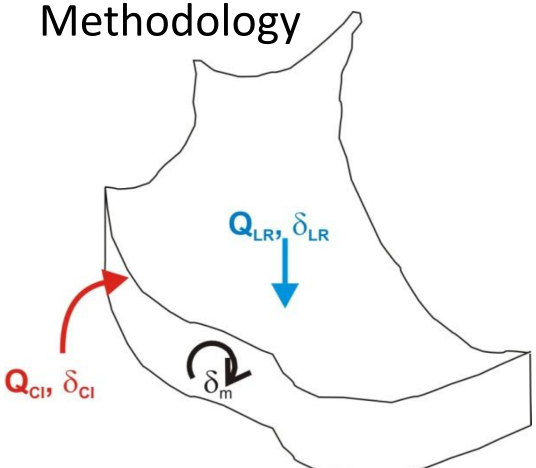
Beyond sustainability, "ecosystem" damages: example of the Djeffara plain





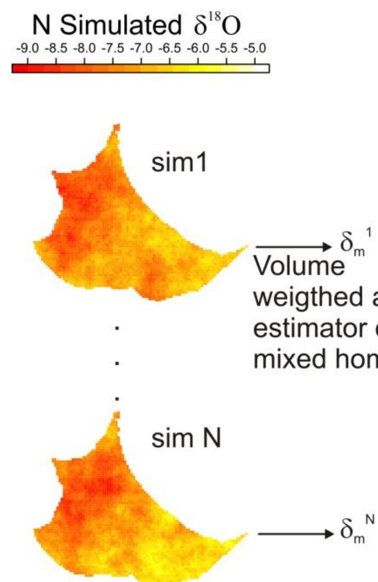
Objective : using Isotopic data; end-members identification and a simple mixing model **to Identify Q_{CI}**

Methodology



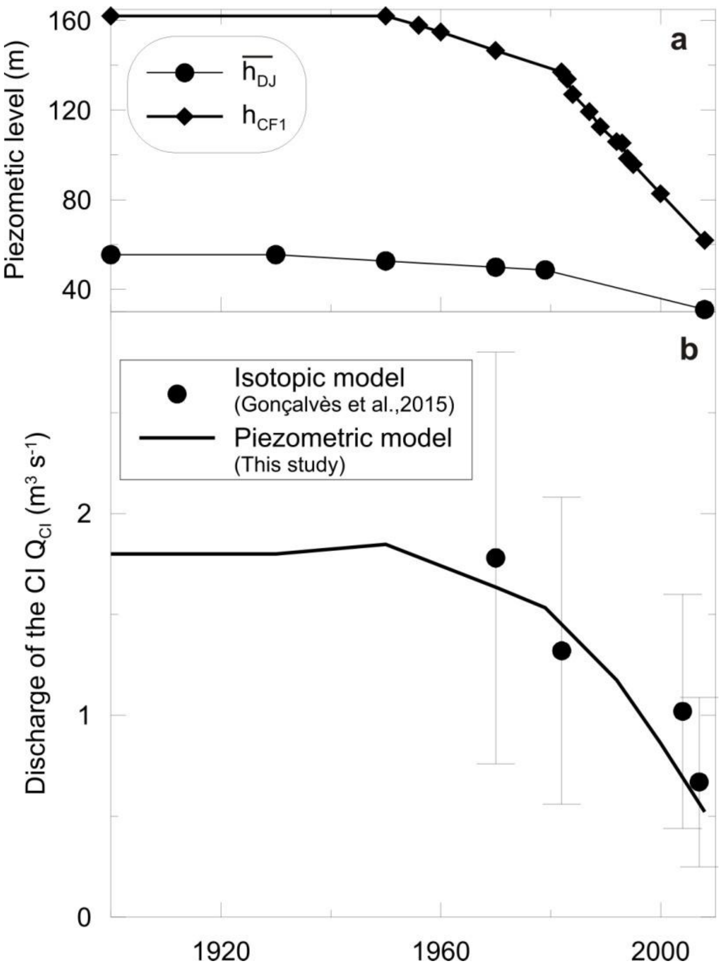
Homogeneous mixing reservoir model : $Q_{CI}=Q_{LR}\times(\delta_{LR}-\delta_m)/(\delta_{LR}-\delta_{CI})$

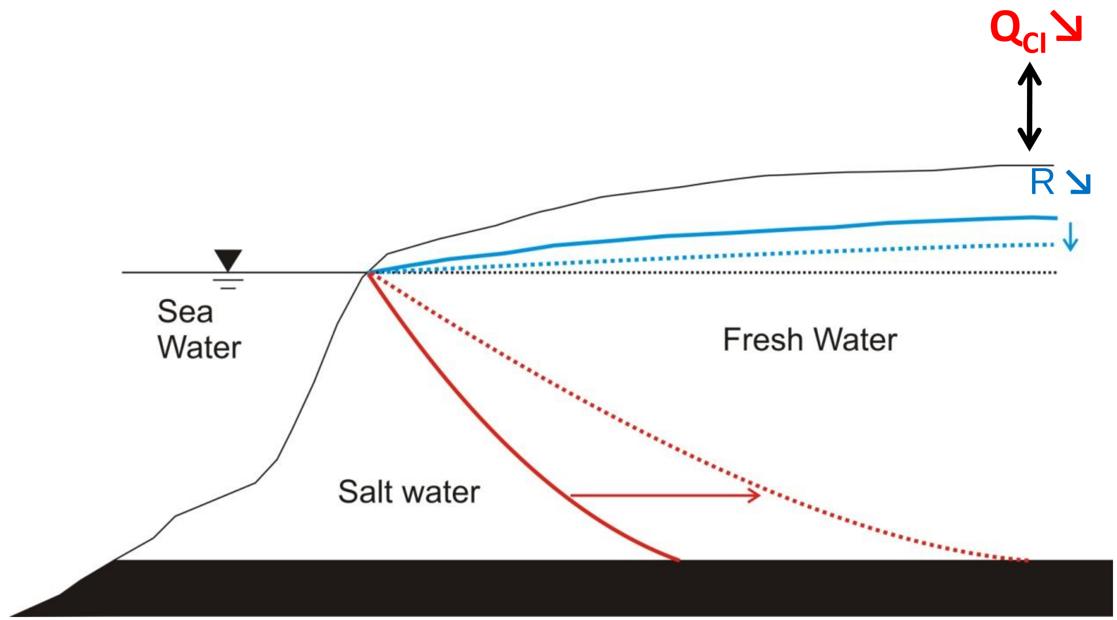
δ_m? Geosatistical approach



Volume weigthed average of the grid: estimator or the well mixed homogeneous res.

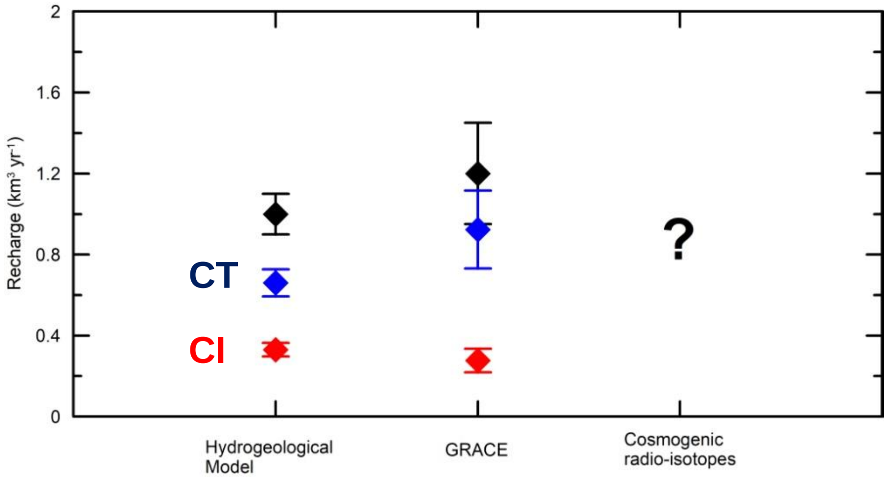
δ_m (mean and Std deviation)





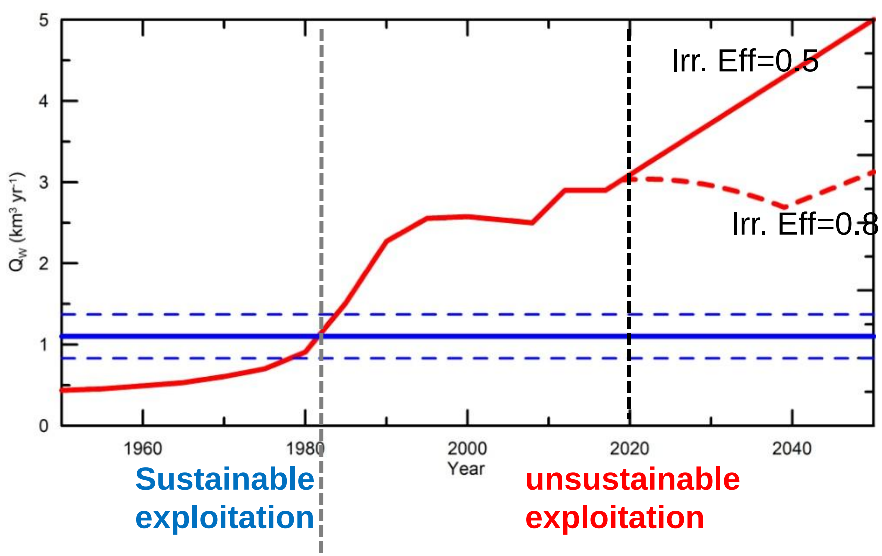
Q_{CI}=1.78±1.00 $m^3\ s^{-1}$ in 1970
and Q_{CI}=0.67±0.42 $m^3\ s^{-1}$ in 2007
vs Q_{LR}=0.67±0.23 $m^3\ s^{-1}$

Gonçalvès et al. (2015);
Gonçalvès et al. (In Rev.) REEC



- Consistency between Model-derived (1.02±0.27) And GRACE derived values **R=1.1±0.27 km^3 yr^{-1}**
- Values proposed here are domain averaged

For future hydrogeological modeling need for regionalization

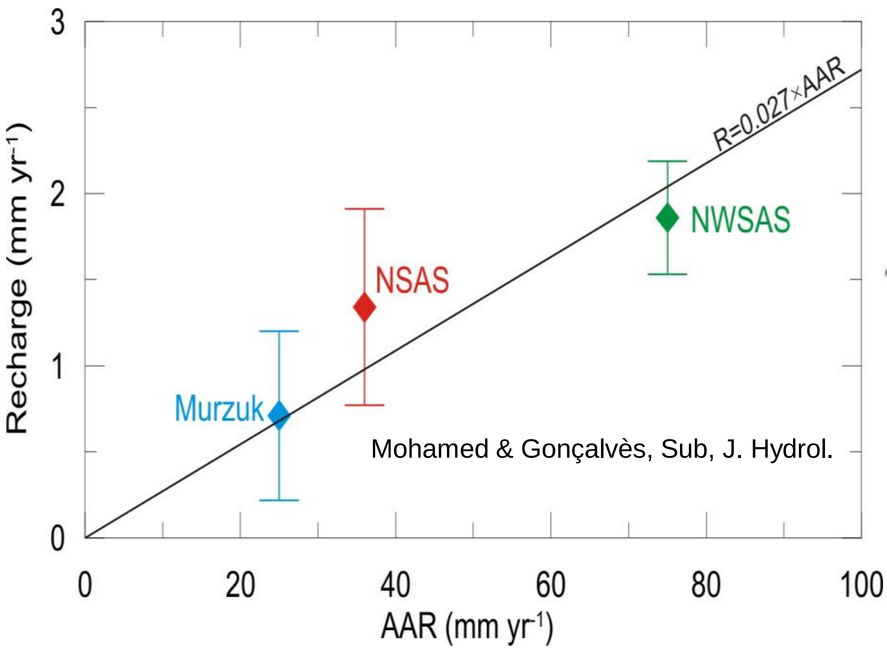


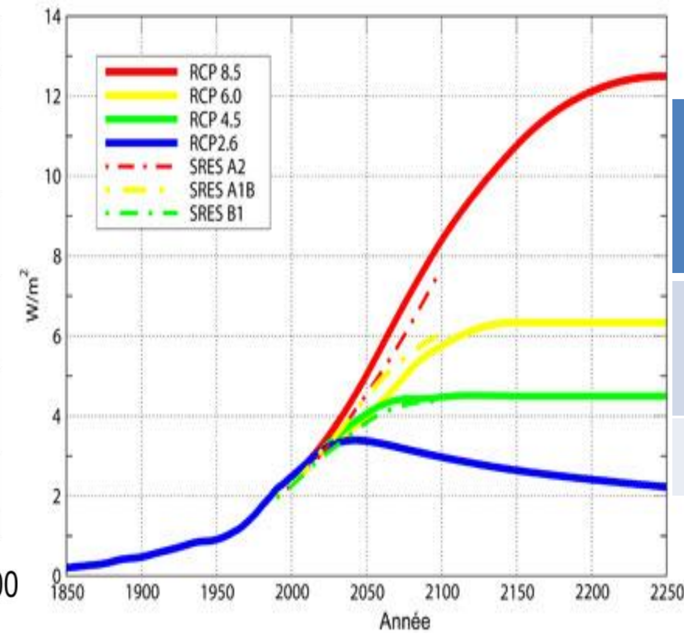
- Unsustainability since ~1980
- Regarding pumping projections

system increasingly unsustainable … Ineluctable Groundwater is the only resource!

Only Irrigation practices improvement can limit the phenomenon

Relative importance of climate and withdrawals in future projections?





% Variation/ average rainfall 1986-2005	2050	2100
RGP 2.6	+1%	+2.5%
RGP 8.5	-5%	-15%

ΔQ_W=15% (0,45 km^3 yr^{-1})

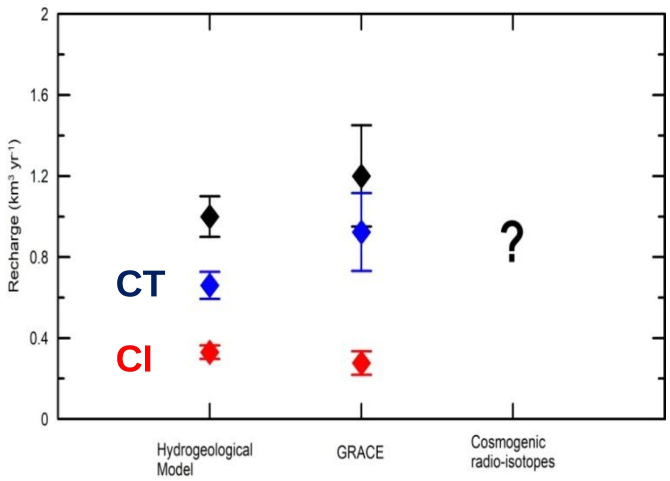
$\Delta GWS = R_N + R_A - Q_W - Q_D$

ΔAAR=15%→0,15*0,027 ΔR=0,4%
(0,004 km3 yr-1)

Main concern is water demand→ parsimonious irrigation methods promoted by OSS (Pilot experiments, SASS III)

Prospects

●A more extensive use of cosmogenic radio-isotopes?



A lot of unexploited Cosmogenic data (14C, 36Cl)
Draw a even more convincing picture of regional recharge and regionalization of the recharge (data for different streamlines and AAR) →future hydro-economic model

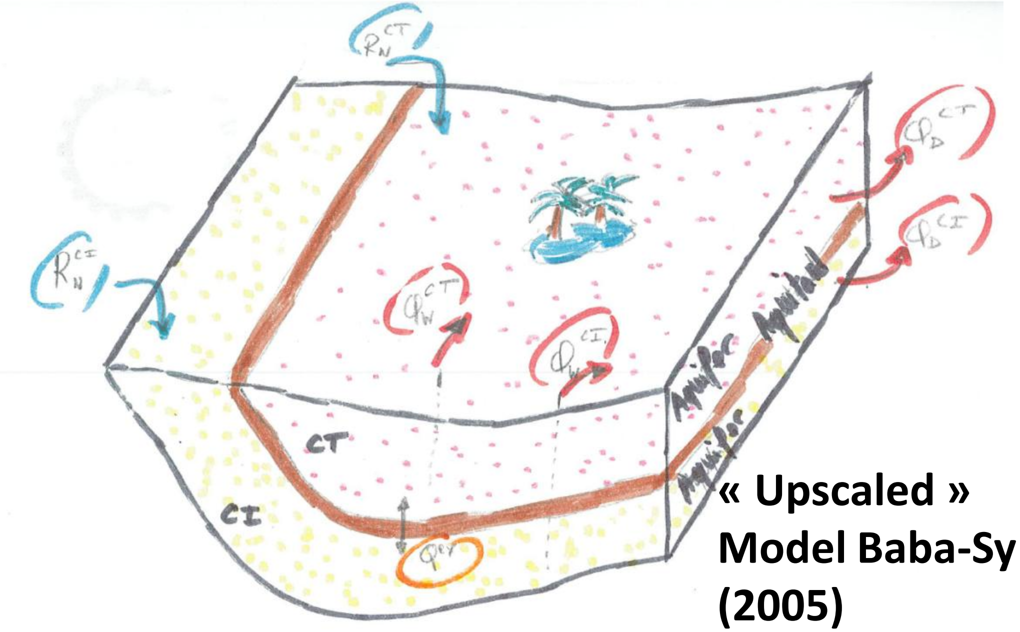
●Hydro-economic modeling (PhD A. Chekireb ; 2018-..)
Coupling of hydrogeological model (first global then distributed (?)) with an economic model to analyze optimal groundwater use demand/price/cost/mitigation CT-CI

Coll. CEREGE & AMSE (Aix-Marseille School of Economics)

Current work building of a global hydro-economic model (two homogeneous reservoirs)

Our simplified two reservoirs vision of the NWSAS

Simplified economic vision of the NWSAS!!

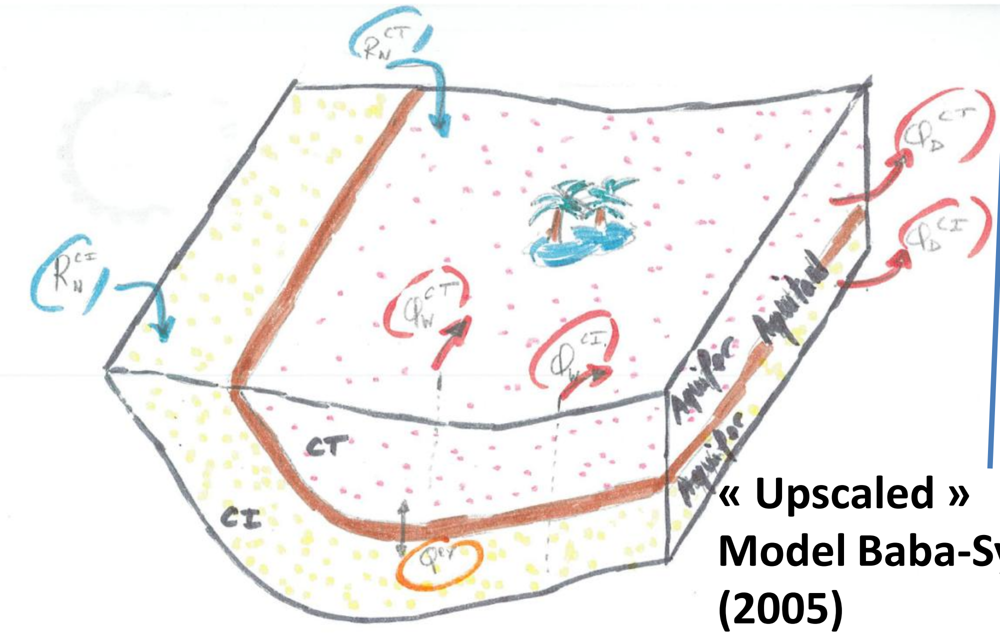


« Upscaled » Model Baba-Sy (2005)

First step: building methodological concepts, first results mitigation CI/CT→need for a regionalization of the Hydrogeological model?

Current work building of a global hydro-economic model (two homogeneous reservoirs)

Our simplified two reservoirs vision of the NWSAS



« Upscaled » Model Baba-Sy (2005)

Simplified economic vision of the NWSAS!!

- The dynamics of the Intercalary Continental

$$\dot{H}_T = \frac{\rho_T R - Q_T(t)}{s A_T} \quad (1)$$

- The dynamics of the Terminal Complex

$$\dot{H}_I = \frac{\rho_I R - Q_I(t)}{s A_I} \quad (2)$$

3.2 The exploitation of the resources

Based on the standard modeling, we have

- A global linear water demand for irrigated agriculture: $Q(t) = \frac{a_0}{a_1} - \frac{p(t)}{a_1}$, with $a_0, a_1 > 0$.
- $p(t)$ the water price per unit of water
- $Q = Q_T + Q_I$
- The farmer revenues: $\int_0^{Q_T+Q_I} p(x)dx = a_0 (Q_T + Q_I) - \frac{a_1}{2} (Q_T + Q_I)^2$
- the marginal pumping cost: $c(H_T) = \gamma_T(\bar{H} - H_T)$ for pumping in the Terminal Complex, and $\chi(H_T) = \gamma_I(\bar{H} - H_I)$ for pumping in the Intercalary Continental, with $\bar{H}$ the land surface elevation above the seal level, and $\gamma_T, \gamma_I > 0$ the marginal cost of extracting one cubic meter of water from the ground.

All together, we deduce the net benefit as follows:[1]

$$NB(t) = a_0 (Q_T(t) + Q_I(t)) - \frac{a_1}{2} (Q_T(t) + Q_I(t))^2 - \gamma_T(\bar{H} - H_T(t))Q_T(t) - \gamma_I(\bar{H} - H_I(t))Q_I(t) \quad (3)$$

First step: building methodological concepts, first results mitigation CI/CT→need for a regionalization of the Hydrogeological model?

Collaborative work :

CEREGE : Pierre Deschamps, B. Hamelin, C. Vallet Coulomb &Aster Team
Geosciences Rennes: Luc Aquilina
GEOPS, Univ. Paris-Sud : Jean-Luc Michelot, M. Massault
LSCE : Elise Fourré, Arnaud Dapoigny
AMSE: Agnès Tomini, Hubert Stahn
University of Blida (Algeria): Amid Gendouz
LRAE (ENIS), Sfax (Tunisia) : Kamel Zouari
OSS : O. Baba-Sy, Maxime Thibon,…
Assiut University (Egypt): Ahmed Mohamed

PhD: Jade Petersen (2010-2014), Amine Chekireb (2018-)

With valuable Support

State of the Art Hydrodynamics, water balance of the NWSAS

First historical program ERES **E**tudes des **R**esources en **E**aux du **S**ahara Septentrional (UNESCO, 1972)

Characterization of the Recharge:

●**Geochemistry** : Mostly Qualitative (presence of tritium, $\delta^{18}O$,$\delta^{2}H$ signal of modern rainfall in groundwater) and rarely quantitative results **1 Recharge value 1.3 mm/yr** by CMB at Tozeur (Tunisia) and **a net discharge (R<0)** at Beni Abès (Algeria) ; Pore velocity (Not R) in the Atlasian part of the NWSAS using ^{36}Cl

● **Hydrogeological model :** 10 models developed for the CI, 2 for the CI+CT. Upon calibration, they lead to an overall groundwater balance at steady state (natural) with a cumulated regional **$R=1.02\pm0.2$ km^3 yr^{-1}** .

●**Geophysical approaches? NO**