Sustainable coastal groundwater management through innovative governance in a changing climate

Prof. George P. Karatzas
School of Chemical and Environmental Engineering
Technical University of Crete

12th World Congress of EWRA
on Water Resources and Environment
27 June - 1 July 2023, Thessaloniki, Greece
AUTh Research Dissemination Center (KEDEA)

Motivations for Groundwater (GW) management

- The global volume of GW is twice as big as the volume of water stored in icecaps and glaciers (Freeze and Cherry, 1979).

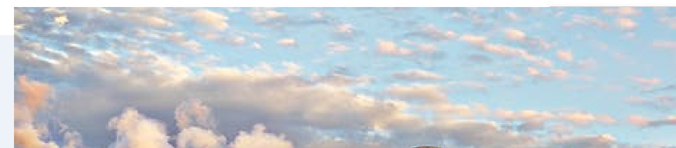
- GW exceeds the volume contained by rivers, lakes and wetlands by a factor of 226 (Gleeson et al., 2015).

- In times of drought GW is the key strategic reserve which provides freshwater for ecosystems (Famiglietti, 2014).

- **Groundwater is the most important natural strategic freshwater reserve in the Mediterranean (MED) region and the only one in the southern MED.**

The MED region

- **The MED sea is a hotspot of species diversity…**Lejeusne et al 2010
- **The MED sea is one of the top tourism destinations in the world, hosting more than 320 million tourists in 2015 (> double of 1995)….**mgi.online
- **The total population of the MED countries is about 500 million, with >50% living in the coastal region….**mgi.online
- **Agriculture depends on irrigation (>80%)….** Hartmann et al 2016



Additional anthropogenic pressures

Population growth (incl. migration)

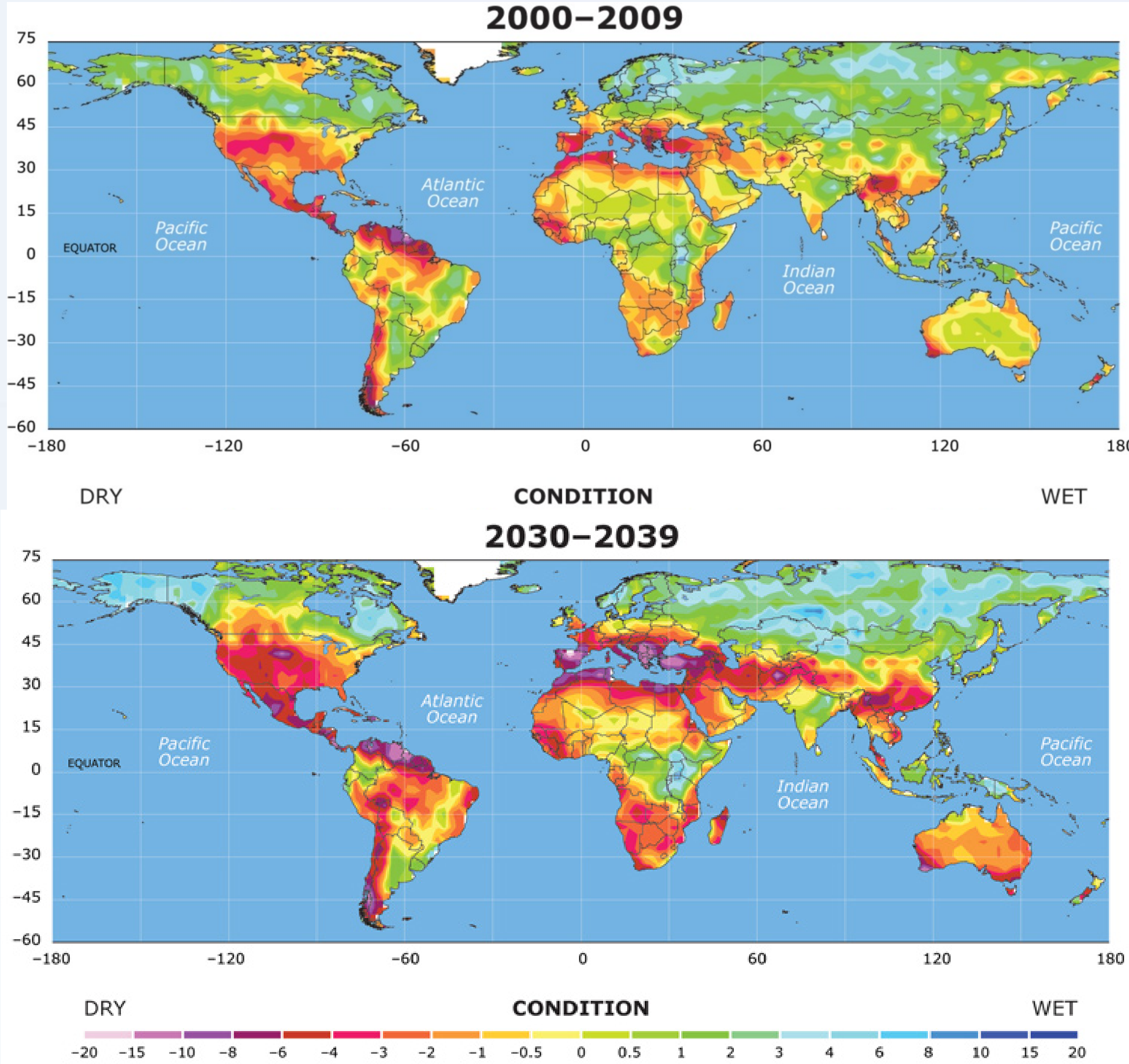
- Increasing **food demand**

- Growth of **urban** and **industrial** areas

- Growing **energy** demand

- Socio-political & environmental changes

Climate change: additional pressure



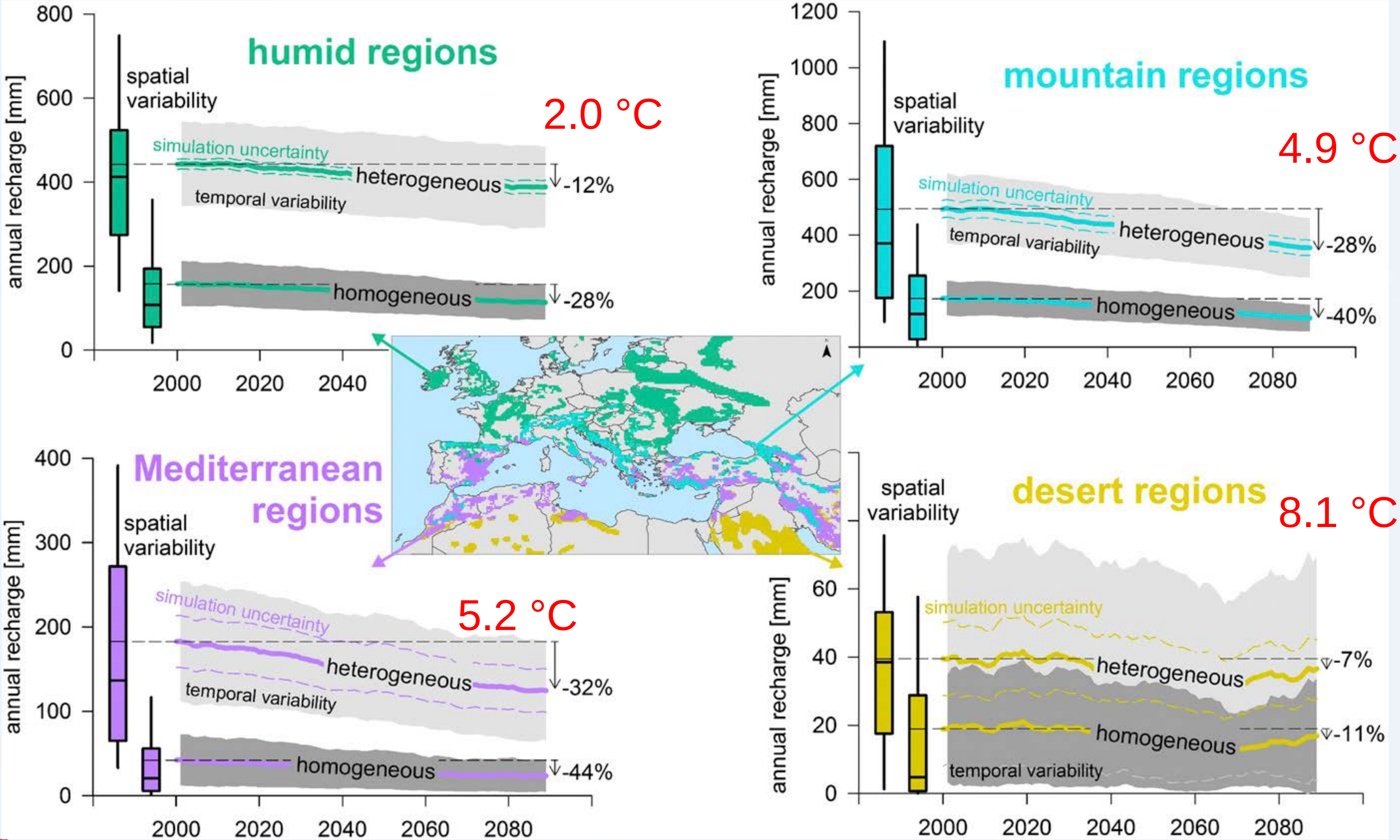
Increasing number & severity of droughts (Palmer Drought Severity Index*)

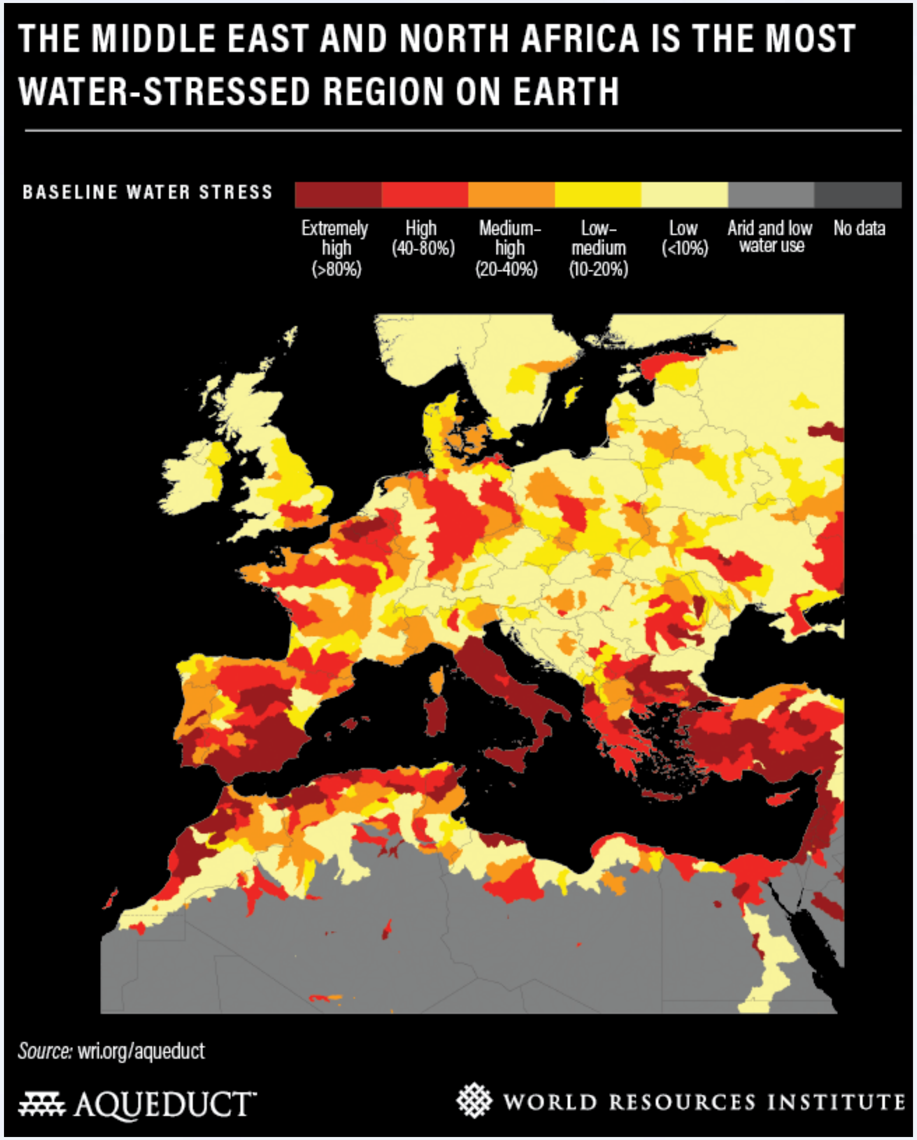
Med region:
Temperature: + 2°C,
Precipitation: - 20% since 1970 (Plan Bleu, 2009),
Decrease in available water resources: up to 50 % by 2100 (EC, 2007),

*** Determines aridity through precipitation and temperature information (part. for long-term prognoses; < -4 = extreme drought)**

Source: NCAR images, 2010

The far future (2080–2099) is more severe!
Reducing recharge rates (Hartmann et al 2016)





According to the World Bank, the MED area is expected to face great economic losses from climate-related water scarcity (~6-14% of GDP by 2050).

wri.org/aqueduc

Therefore, sustainable groundwater management is needed for all the costal aquifers in the MED

Question: What is the approach for sustainable groundwater management for coastal aquifers?

Innovative Water Governance

Pillar 1	Pillar 2	Pillar 3	Pillar 4
Strengthening of coastal water resources management options	**Prevention** of coastal groundwater against pollution	**Active engagement** of the concerned stakeholders in a social learning process	**Reinforcement** of monitoring and communication

Participatory approach, Stakeholder engagement, Living Labs

Pillar 1

Strengthening of desirable coastal water resources management options.

- Detailed site characterization
- Stakeholders' active engagement
- High Resolution Monitoring
- Multi-criteria Decision Support System

Pillar 2

Prevention of coastal groundwater against pollution.

- Learning process involving "main identified polluters"
- "4R principle: Reduce; Recycle; Reuse & Recover"
- Flow & pollution plume transport prediction using numerical models

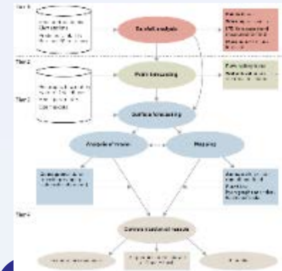
Pillar 3
Active engagement of the concerned stakeholders in a social learning process.

- Raising awareness on water management
- Interactive living labs & workshops to create new social learning spaces
- Digital ICT approaches, smart, adapted and visualized web apps attractive to new generation

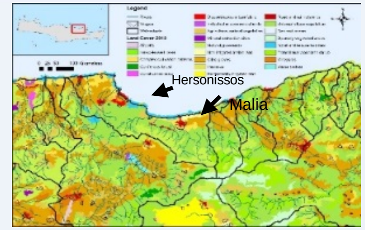
Pillar 4
Reinforcement of monitoring and communication.

- Integration of international clusters and initiatives
- Cross-country interactive dissemination strategy

The Overall Approach



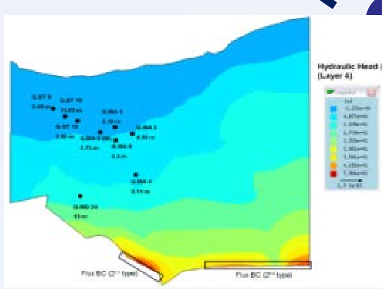
Site characterization



Living Labs

High-resolution monitoring

Smart modeling



Socio-economic assessment & innovative governance

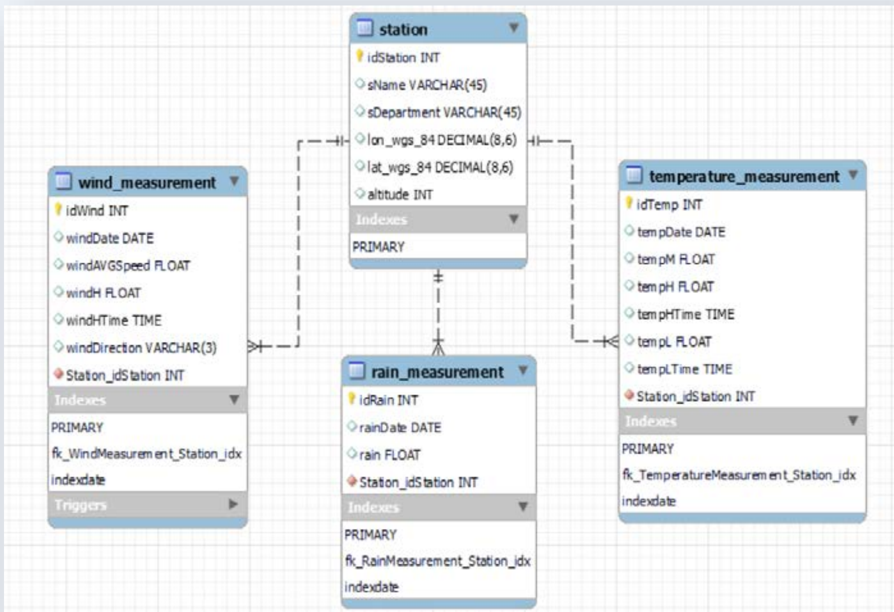
Decision support system

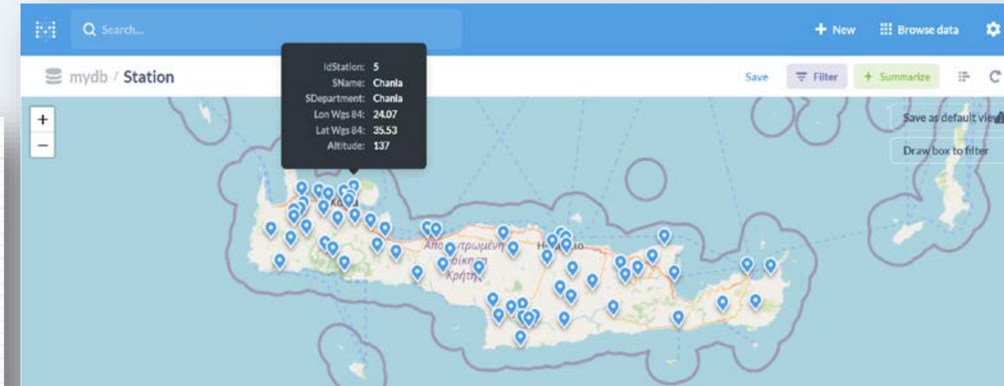
Site Characterization

- Surface water Data
- Groundwater Data
- Water Quality Data
- Governance System Description
- Identification of Sectors that Require Attention & Specific Challenges

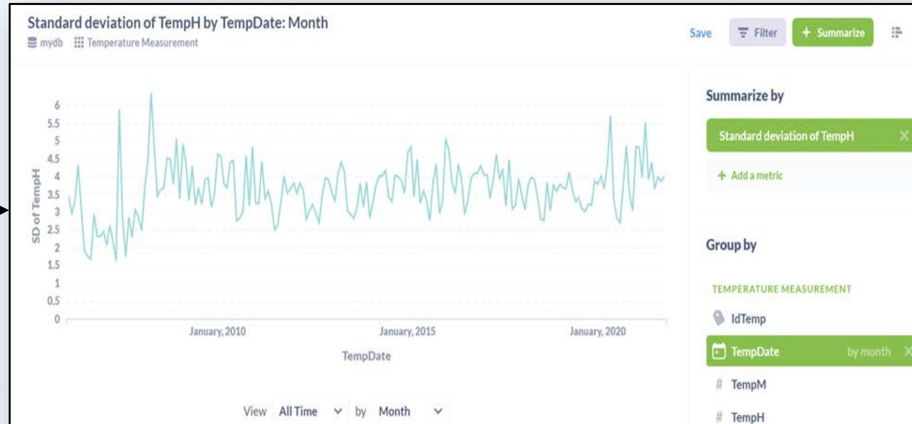
Database development

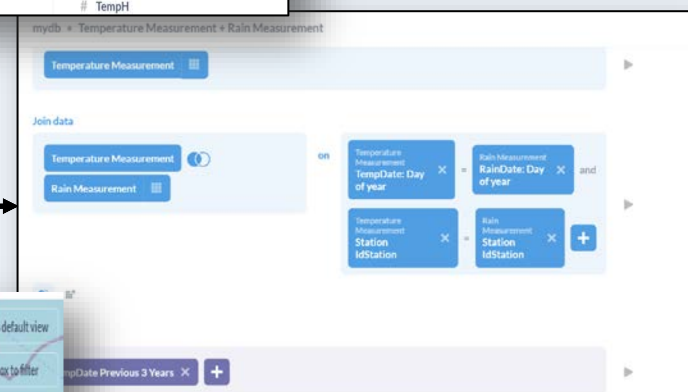
A unified, open source, SQL(**Structured Query Language)** database for the management of meteorological data from multitude monitoring stations alongside with the development of an infrastructure with a user interface.

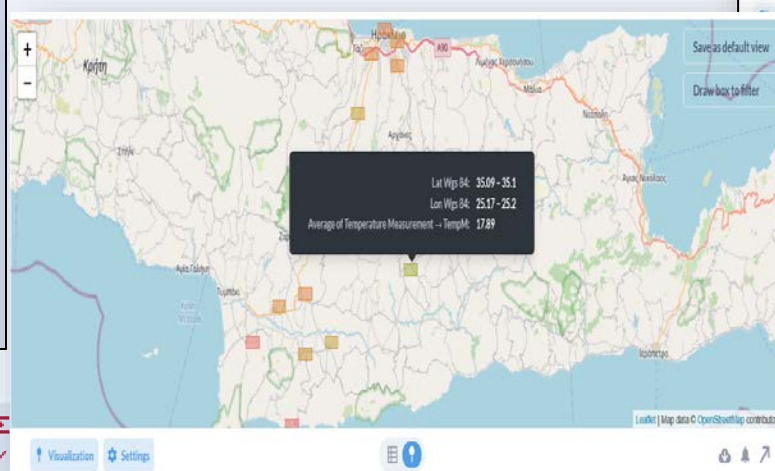




Database development







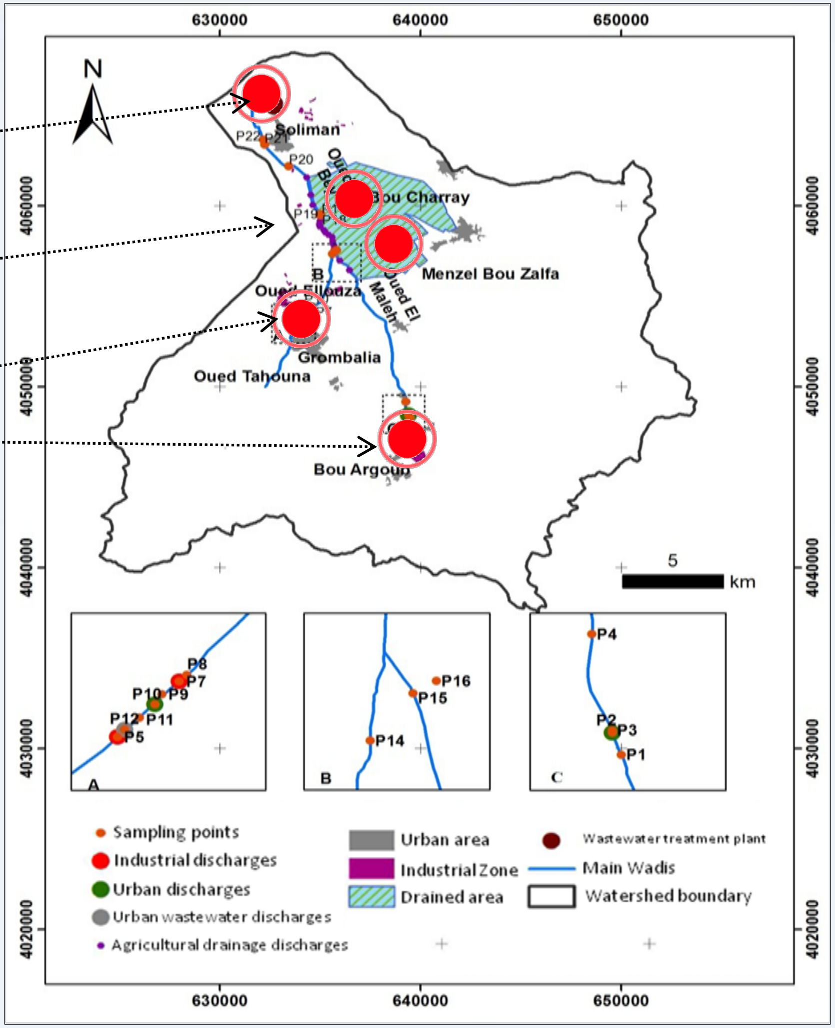
Asking Questions

1. **Simple question mode**: lets the user filter, summarize and visualize data.
2. **Custom question mode**: gives the user a powerful notebook-style editor to create more complex questions that require joins, multiple stages of filtering and aggregating or custom columns.
3. **The SQL/native query editor**.

ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ
TECHNICAL UNIVERSITY OF CRETE

Identify Hotspots

- Watershed outlet
- Drain area – Agricultural
- Industrial area / discharges



Ben Salem et al., 2019

Identify major problems

Surface water	Groundwater
High **N** & **COD** levels	**Over exploitation**
High **salinity**	High **N** concentrations
	High **salinity**

Living Labs

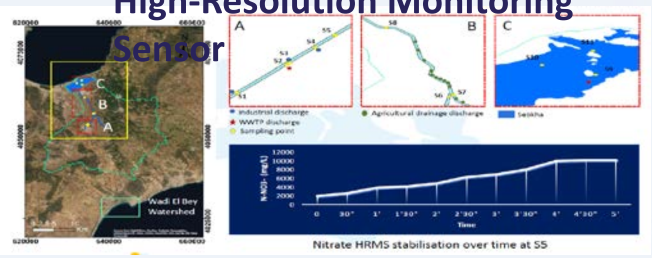
- Stakeholders representing different sectors of the civil society and administration should get involved in each aquifer management area.
- Participatory tools such as play games and a future oriented approach which supports thinking and dialogue are used during these Living Labs.
- **At the end of the process a series of recommendations on innovative governance options and approach will be produced to better orient and inform policies and water management interventions**.

High-resolution monitoring

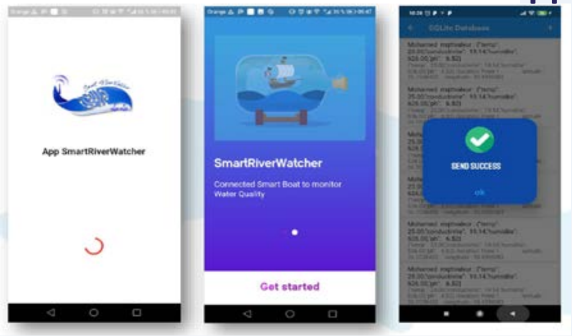
Assess parameters of interest in terms of spatial and temporal dynamics

Use of integrated High-Resolution Monitoring Approach (HRMA)

High-Resolution Monitoring Sensor



RiverWatcher Mob App

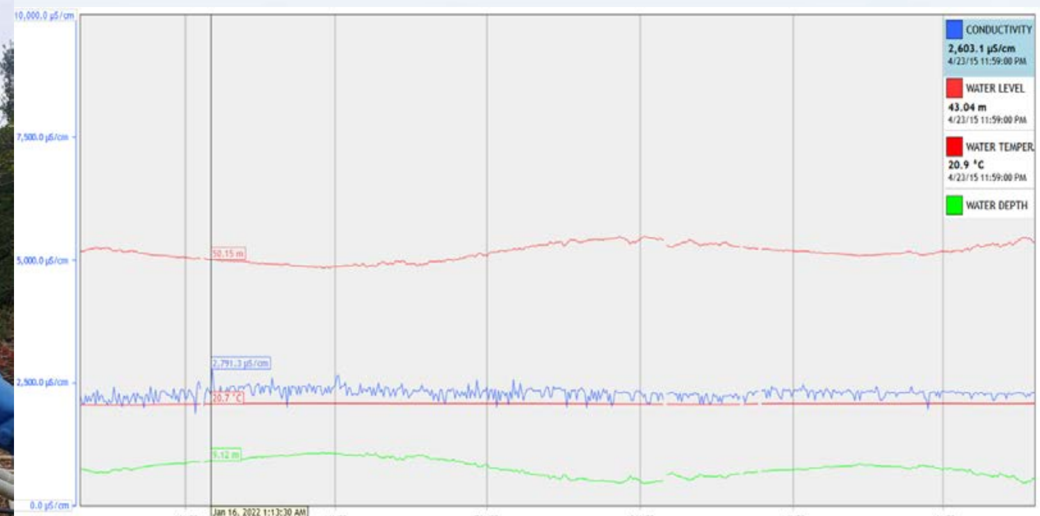


Tech low-cost Sensors: Smart River Watcher

3D printed boat

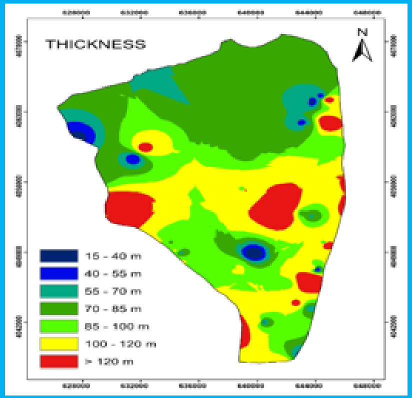
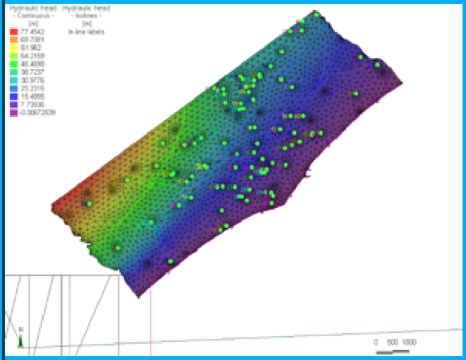
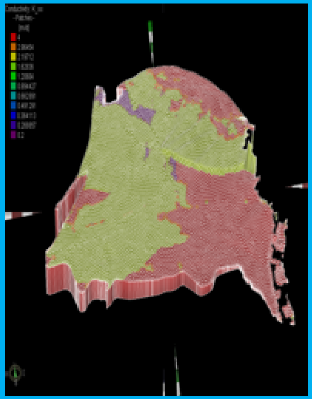
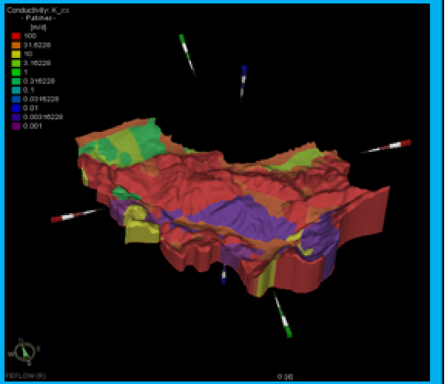
High-resolution monitoring using sensors

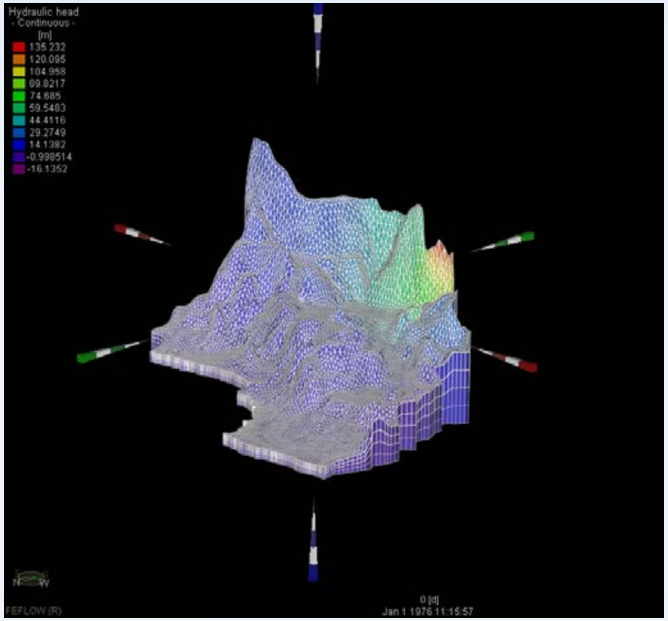
Installation of sensors

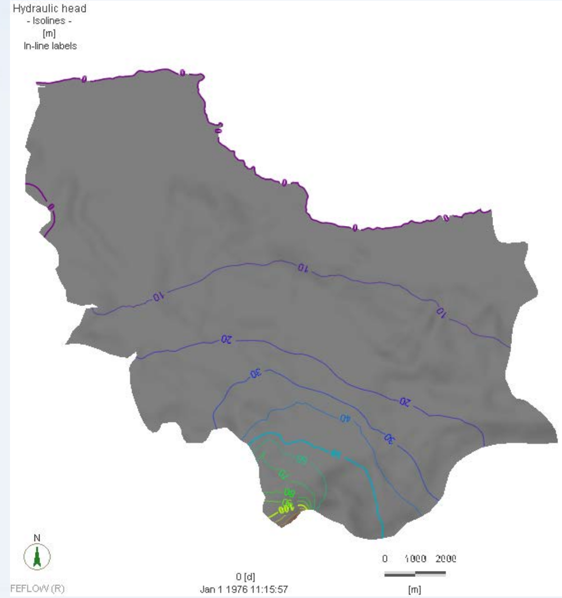


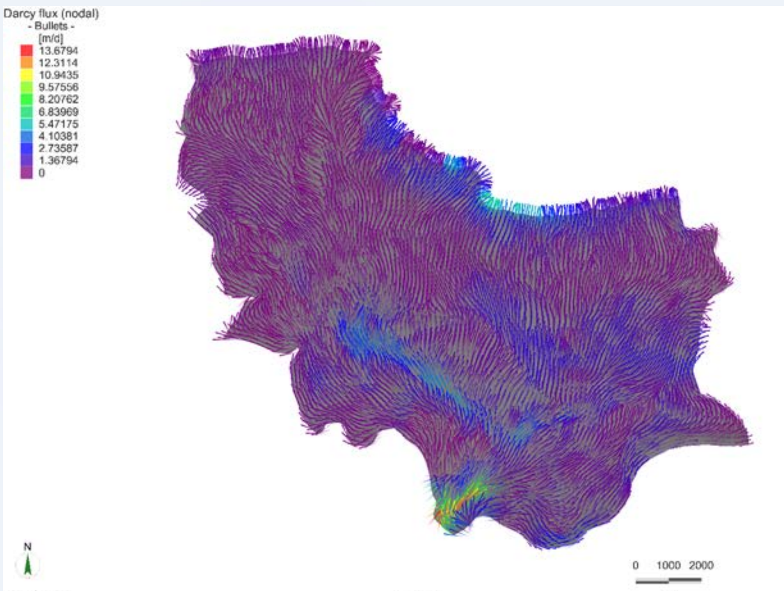
Smart modeling

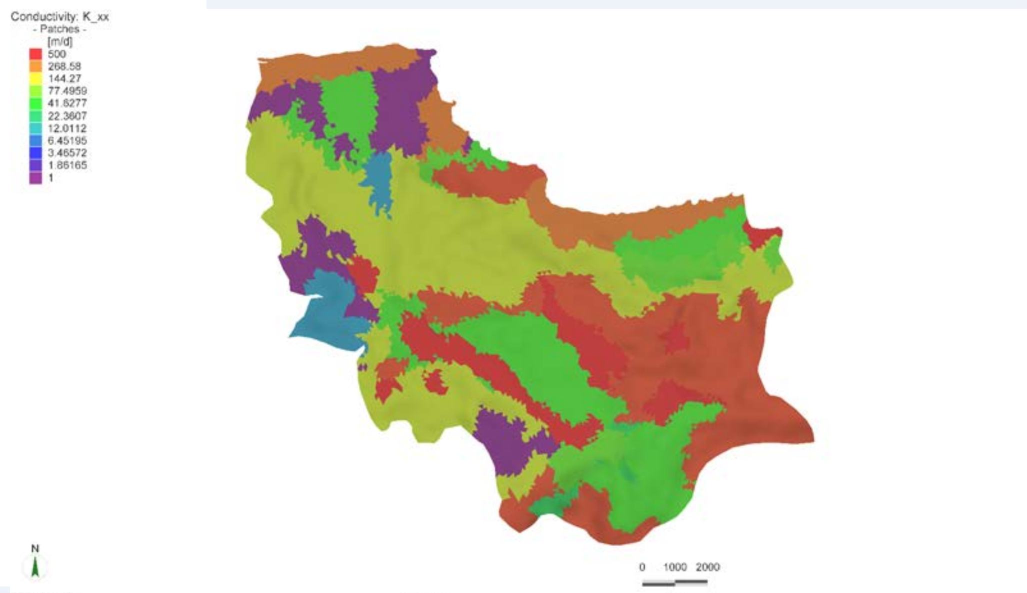
To predict the effects of stakeholder-suggested prevention and mitigation options and to test **climate change scenarios**

Wadi El Bey – TUNISIA	Erdemli – TURKEY	Arborea – ITALY	Malia - GREECE
			

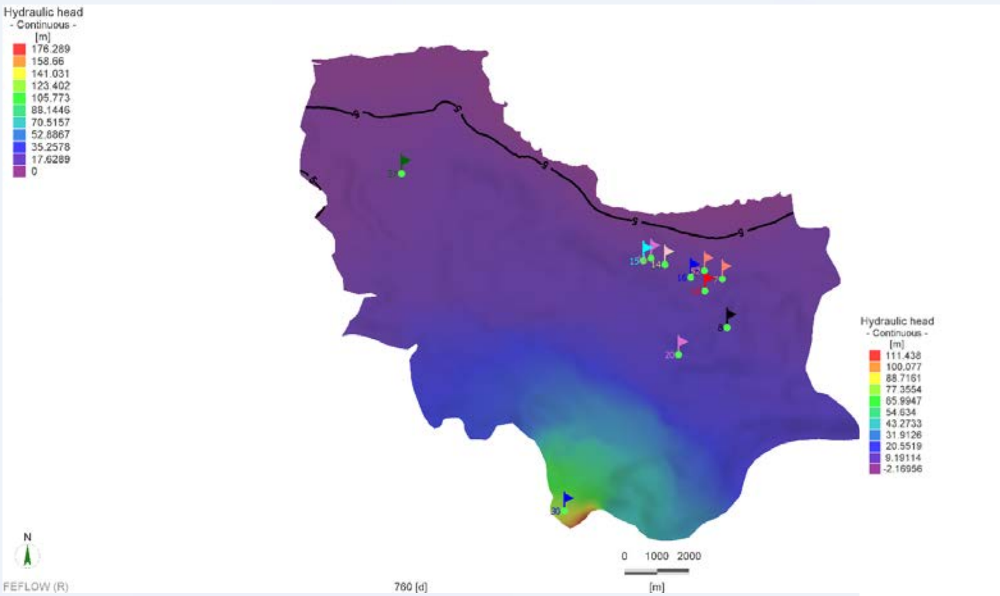

Hydraulic head
- Continuous -
[m]
135.232
120.095
104.958
89.8217
74.685
59.5483
44.4116
29.2749
14.1382
-0.998514
-16.1352
FEFLOW (R)
0 [d]
Jan 1 1976 11:15:57


Hydraulic head
- Isolines -
[m]
In-line labels
N
0 1000 2000
[m]
0 [d]
Jan 1 1976 11:15:57
FEFLOW (R)

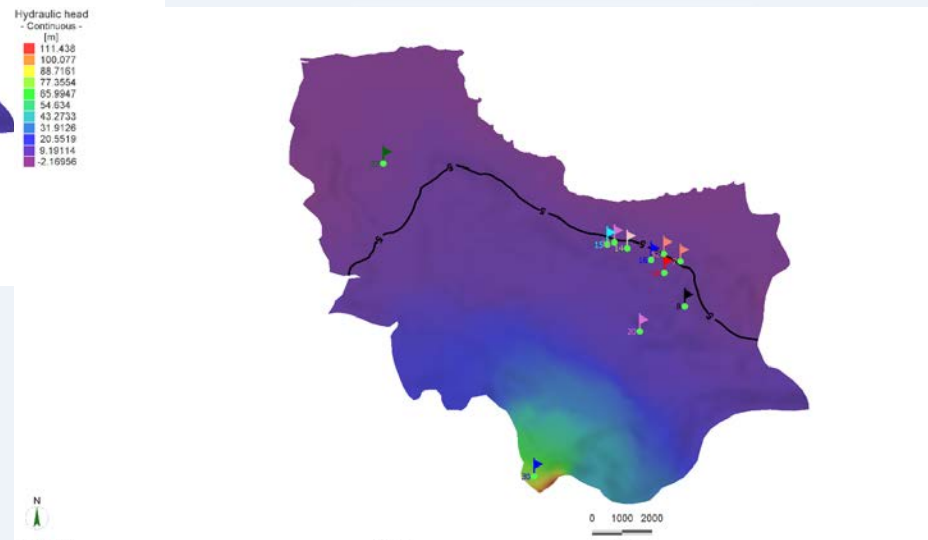

Darcy flux (nodal)
- Bullets -
[m/d]
13.6794
12.3114
10.9435
9.57556
8.20762
6.83969
5.47175
4.10381
2.73587
1.36794
0
N
0 1000 2000
[m]
FEFLOW (R)
1100 [d]


Conductivity: K_xx
- Patches -
[m/d]
500
268.58
144.27
77.4959
41.6277
22.3607
12.0112
6.45195
3.46572
1.86165
1
N
0 1000 2000
[m]
FEFLOW (R)
1100 [d]

Saltwater Intrusion Zone by Ghyben-Herzeberg



Wet Year



Dry Year

Climate Scenarios

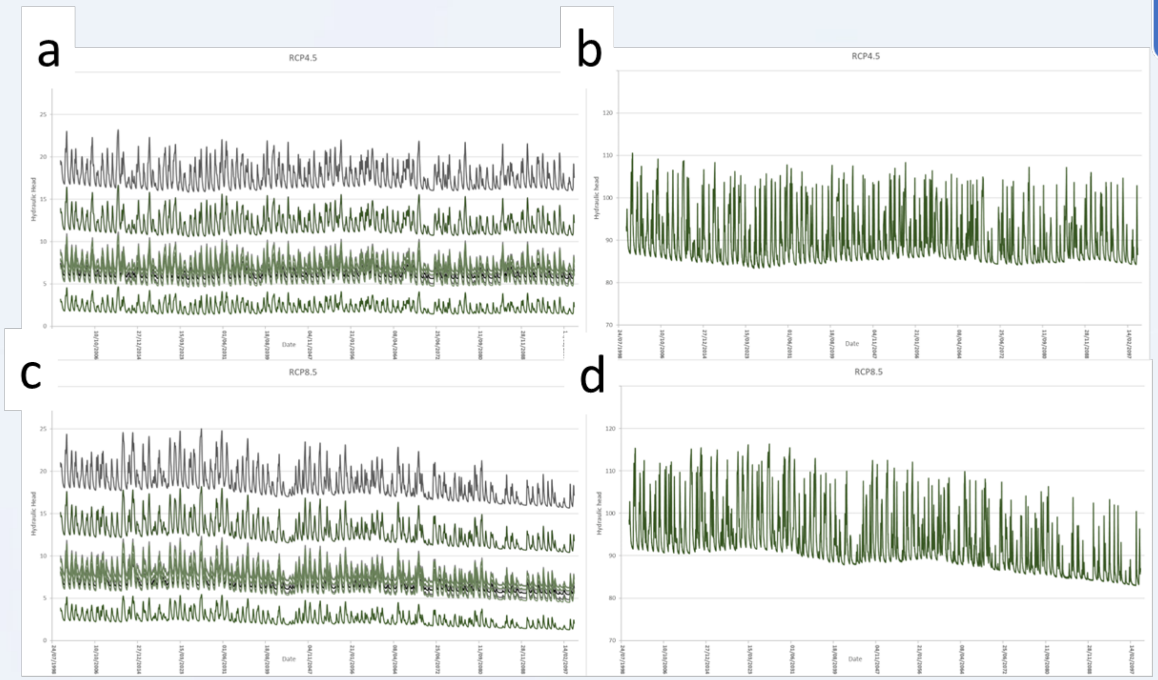
The scenarios are a combination of Regional Climate Models (RCMs) and General Circulation Models (GCMs)

They are based on the Representative Concentration Pathways (RCPs) 4.5 and 8.5

Data from 1976 – 2005 consist of historical simulation which is the control period

2006-2098 is the scenario period

Climate Scenarios Results – Hydraulic Head

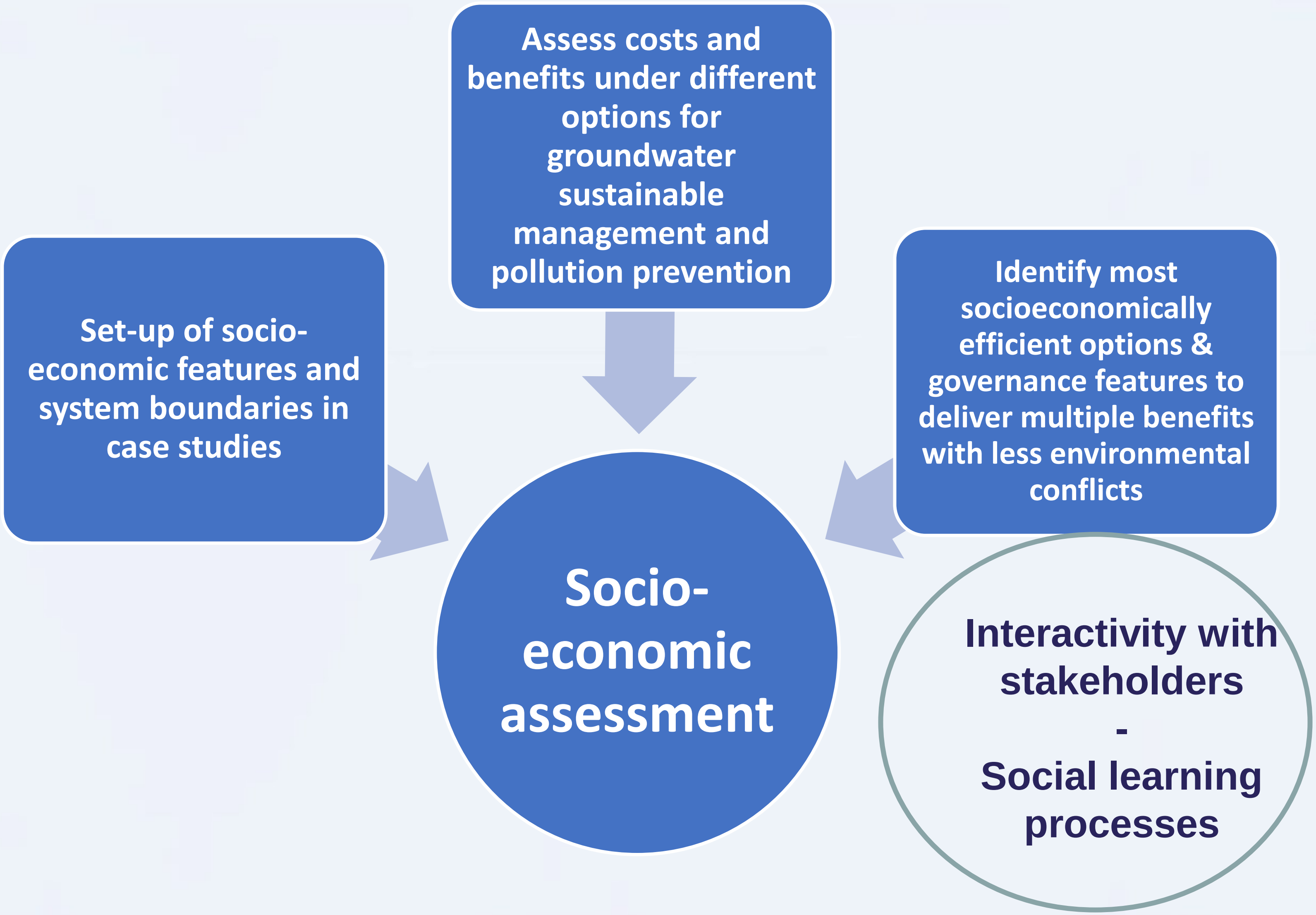


(University of Parma, Italy)

RCP4.5
- Graphs a, b
- Low hydraulic head
- Small fluctuations in hydraulic head

RCP8.5
- Graphs c, d
- Hydraulic head decreases during the entire time period
- Until 2045 higher values for hydraulic head in comparison with RCP4.5

Socio-economic assessment



Socio-economic assessment

Estimating cost efficiency and cost-benefits of selected preventive options and cost-benefits of innovative governance features

EXAMPLE

Bayes risk

Step 1: Set up the decision-making problem by introducing the possible actions

- Groundwater use only
- Alternative scenario

Step 2: Provide the state of the goal function

- Groundwater cost (pumping and volume)
- Lost value of groundwater as a sustainable source
- Mitigation measure cost
- Annual operational cost for the examined auditing period
- Risk probability: water needs not to be covered from available water resources of the study area and
- Supplementary water supply (i.e., water transport)

Step 3: Development of subjective prior distributions for each parameter quantifying previous information (hydrological balance)

Step 4: Cost Benefit calculation using Bayesian Risk method

Step 5: Proposed sustainable water resources use and management

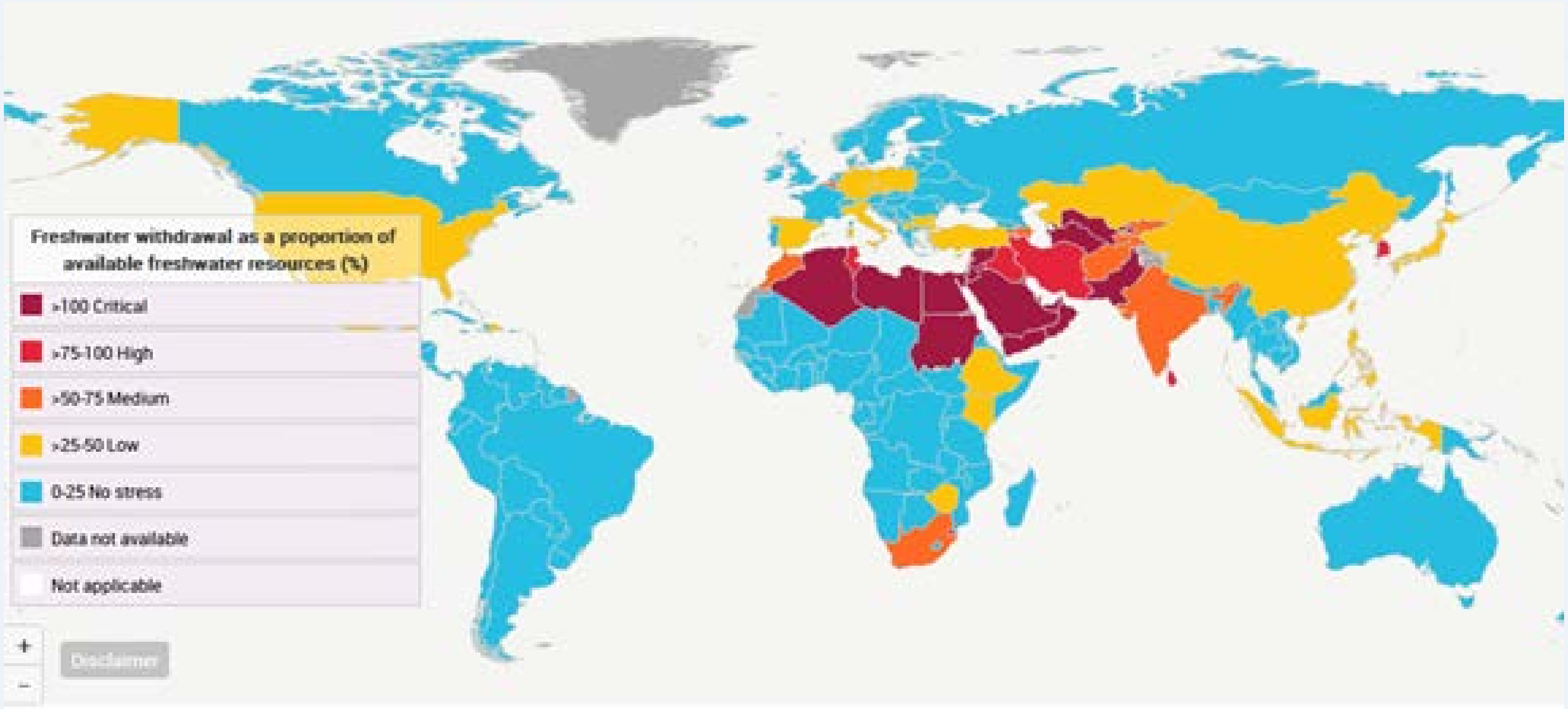
Cost Benefit Analysis

Proposed sustainable water resources use and management in each case study based on field data

Current situation (using in situ data on an annual base)

Case studies	Wadi El Bey, Tunisia	Erdemli Turkey	Arborea, Italy	Malia, Greece
Groundwater use	30%±7	34%±8	30%±2	30%±3
Surface water use	25%±4	43%±5	47%±3	55%±3
Other sources e.g. waste water treatment plant effluent	45%	23%	23%	15%
Aquifer recharge	77%±11 of groundwater use	81%±9 of groundwater use	75%±5 of groundwater use	80%±5 of groundwater use

The cost-benefit analysis model provides estimates of the required aquifer recharge to retain the improved WEI category. According to the UN SDG 6.4.2 (SDG#6 – 06.41 (UN 20022) Water exploitation index) ‘’level of water stress: freshwater withdrawal as a proportion of available freshwater resources (2019)’’ the countries where the MED sites are located belong to the following categories:



A cost benefic analysis was also performed using a weighted moving average impact for the following climate change scenarios:

'CNRM_CERFACS_CNRM_CM5_CCLM4_8_17'
DMI_HIRHAM5_NorESM1-M'
'ICHEC_EC_EARTH_HIRHAM5'
'IPSL-INERIS_WRF381P_IPSL-CM5A-MR'
'KNMI_CNRM-CM5'
'MPI_M_MPI_ESM_LR_RCA4'

2031

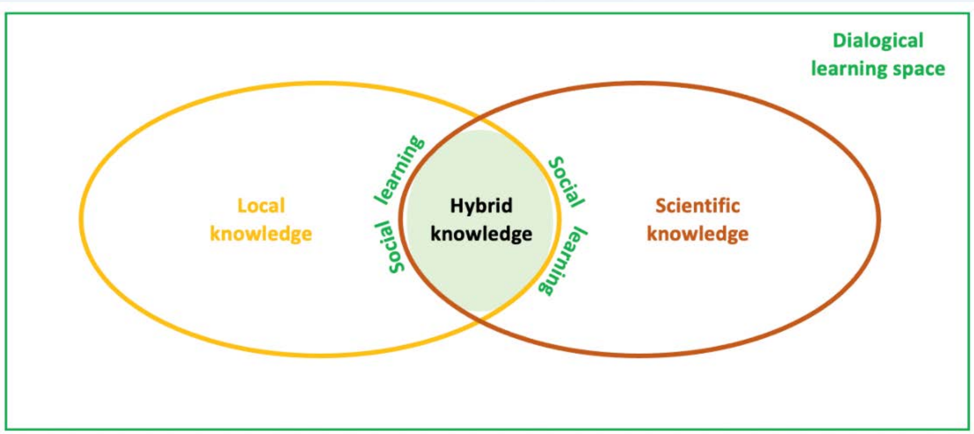
Case studies	Wadi El Bey, Tunisia	Erdemli Turkey	Arborea, Italy	Malia, Greece
Groundwater use	36%±8	40%±5	39%±6	36%±6
Surface water use	21%±7	35%±6	38%±7	51%±5
Other sources e.g. waste water treatment plant effluent	43%±9	25%±6	23%±8	13%±9
Aquifer recharge	67%±15 of groundwater use	72%±12 of groundwater use	68%±10 of groundwater use	76%±11 of groundwater use

2041

Case studies	Wadi El Bey, Tunisia	Erdemli Turkey	Arborea, Italy	Malia, Greece
Groundwater use	28%±7	30%±8	27%±2	25%±3
Surface water use	27%±4	39%±5	51%±3	62%±3
Other sources e.g. /waste water treatment plant effluent	45%	31%	22%	13%
Aquifer recharge	72%±7 of groundwater use	75%±11 of groundwater use	71%±9 of groundwater use	77%±8 of groundwa use

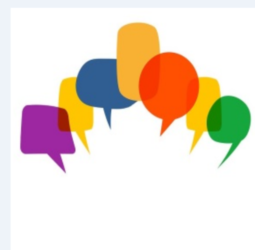
Innovative Governance

Design and facilitate dialogue, communication & engagement among multiple water related stakeholders on water related issues through bottom up and participatory approaches



Multi-stakeholder engagement and stakeholder mapping

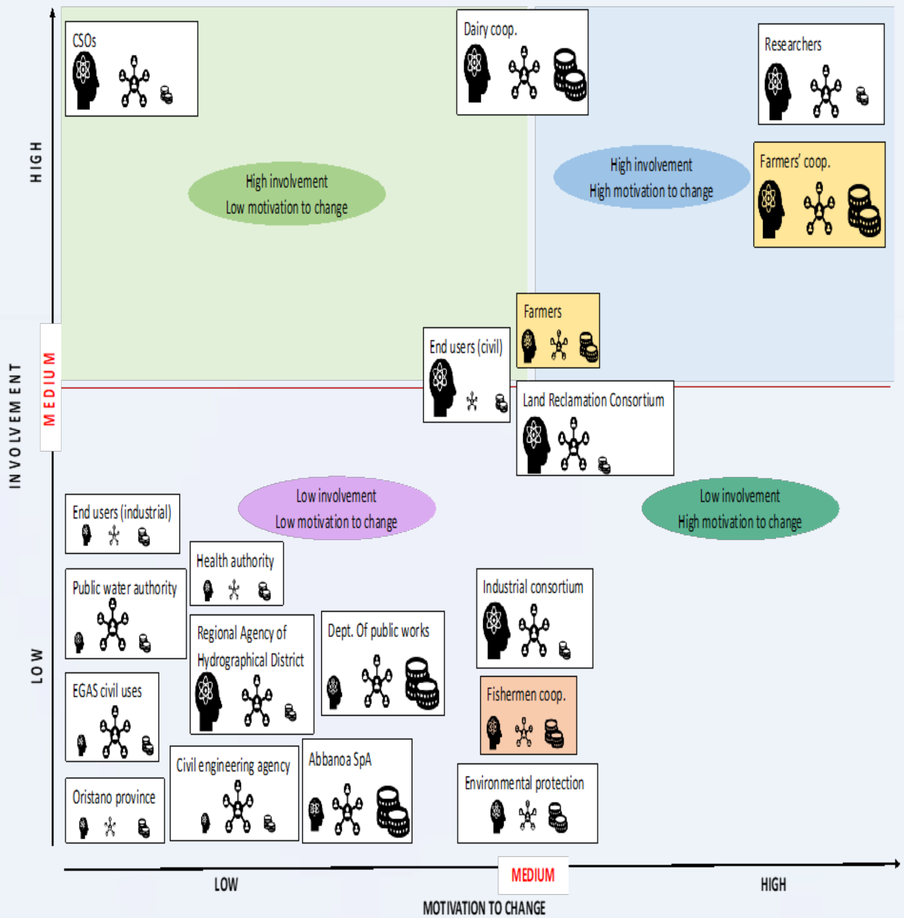
Water governance using new social learning spaces

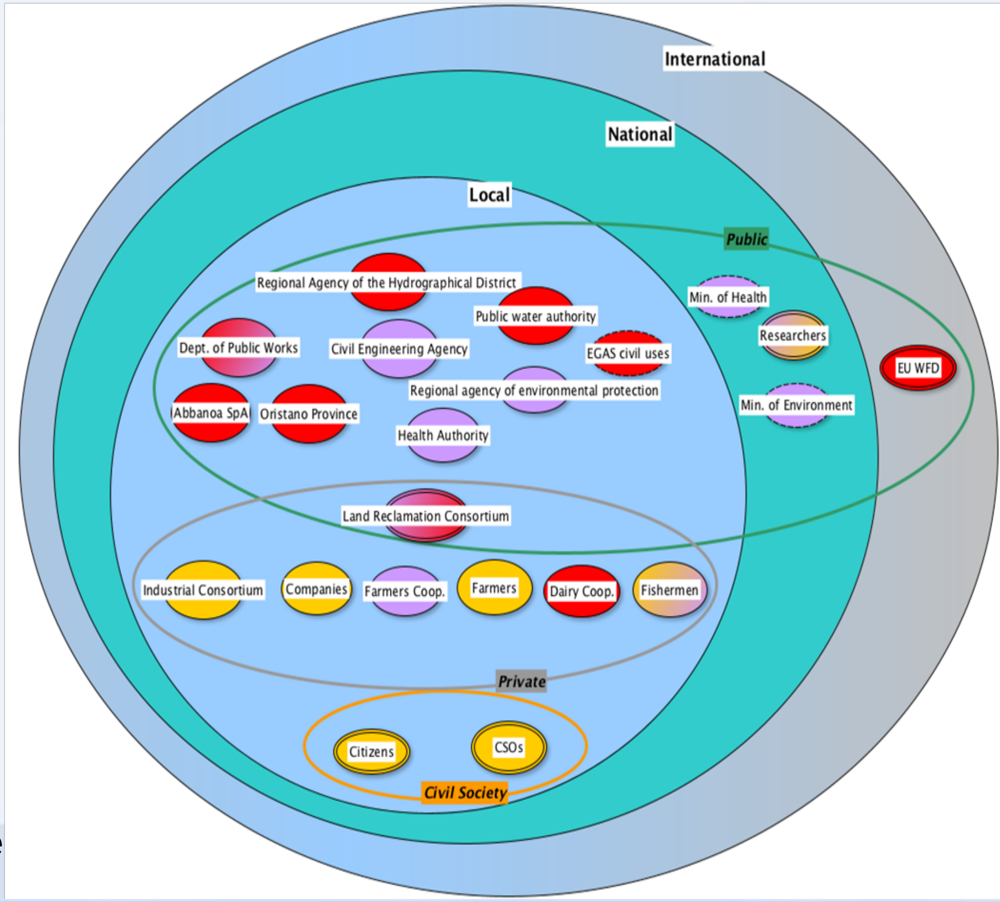


Dialogue among different actors, participatory interactive sessions and Living Labs

Conflict mediation exploration

Stakeholder mapping





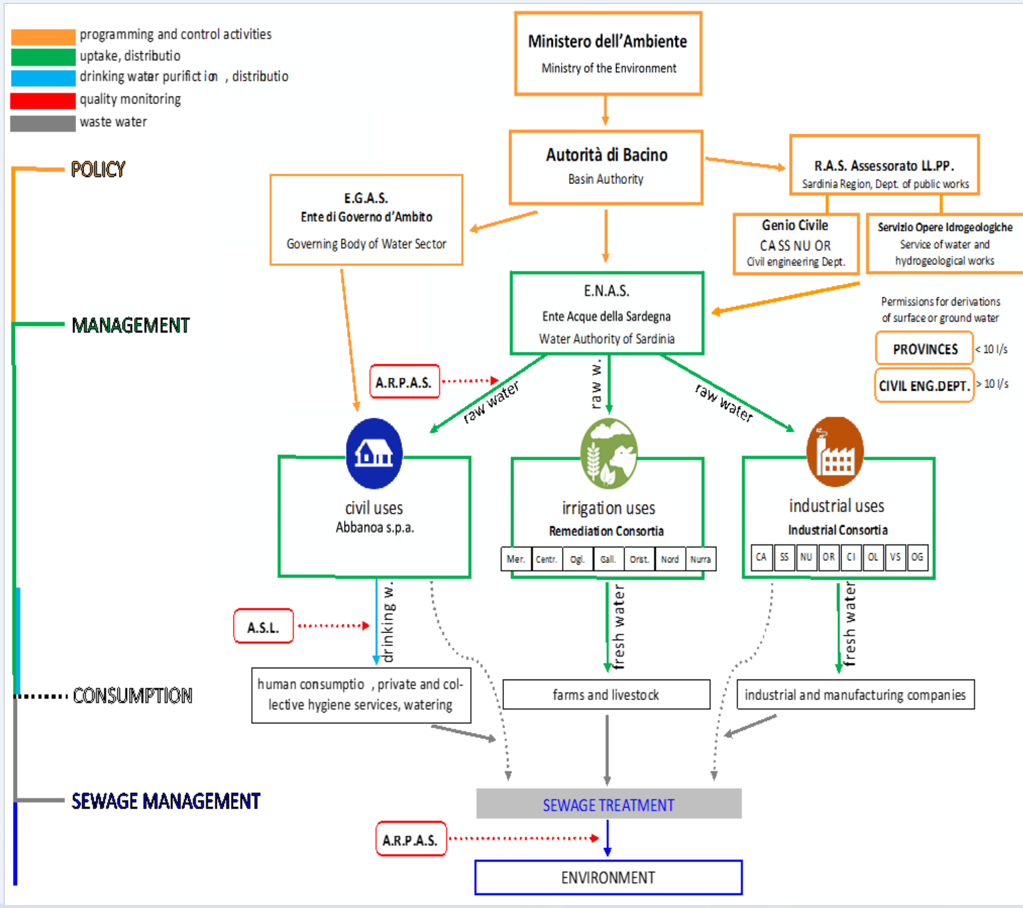
ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ
TECHNICAL UNIVERSITY OF CRETE

Comparative assessment of governance structure and processes

- Identification of governance characteristics that **contribute to more sustainable water management**

  - **Clear** legal framework
  - **Public and decentralized** water network
  - **Private sector** involvement
  - Stakeholder **engagement**
  - Public agencies for **hygienic-sanitary-environmental monitoring**
- Identification of governance characteristics that **prevent sustainable water management**

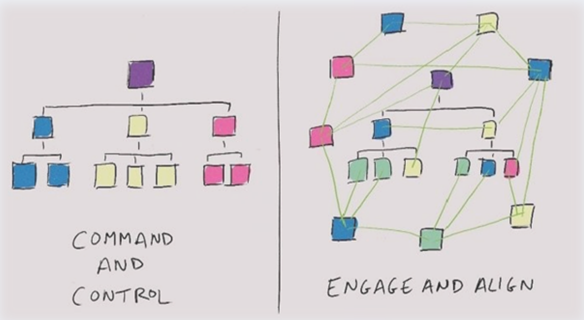
  - Low levels of **participation**
  - **Fragmentation**
  - Cumbersome **bureaucratic** procedures



Environmental conflict mediation

- **Collaborative practices** such as **mediation** can be effective ways of managing and preventing environmental conflicts
- Mediation processes generate **inclusive, shared, legitimate decisions** that are endorsed by both authorities and social communities
- Creating an **innovative dialogical space** to identify opportunities and barriers for mitigating pollution and promoting sustainable groundwater management

Some outcomes from the living labs

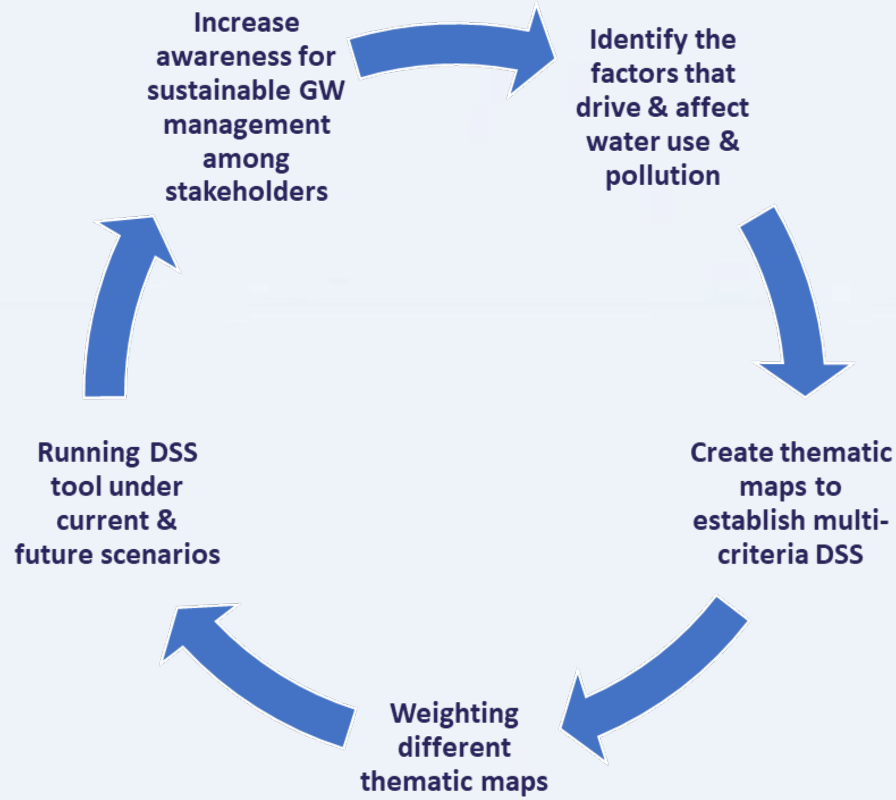


	Arborea	Wadi El Bey	Malia	Erdemli
Perceptions on water-related issues	**Nitrate pollution** «**Double bind**» situation: productivity vs. environment dilemma	Farmers focus on their **short-term** needs (access)	**Little sense of urgency**	**Little sense of urgency**
Water governance	Perceived **ineffectiveness of top-down** measures	Perceived **ineffectiveness of top-down** measures Water management is a **technical** but also a **social** matter	**Decentralized** water governance system prevents conflicts and increases users' responsibility Focus on **technical fixes**	Focus on **technical fixes** **Fragmentation** and lack of collaboration among institutions
Climate change	**Perceived** impact on livestock and crop systems Impact on water not perceived	Will increase the risks of groundwater **salinization** caused by **overpumping**	Not perceived as a pressing threat at the moment	**Perceived** impact on agriculture
Emerging changes/strategies for the future	**Circular economy** Investment on **NBS** for the mitigation of groundwater pollution Need to invest in human capital and **social learning**	Need to invest in **social learning** spaces to increase **awareness** and support action **Non-conventional water** resources	**Regenerative tourism** vs. mass tourism	Need to invest in **social learning** spaces

Decision Supporting System

- To establish a Decision Support System (DSS) in order to determine the suitability and vulnerability of coastal aquifer in terms of industrial, domestic and agricultural use under the pressure of dynamic variables (such as climate, land use and water consumption) and static variables (such as soil type, geological and some hydrological factors), by evaluating multiple criteria to be established with stakeholders in each case study.

- To increase awareness for sustainable groundwater management among the different stakeholders including: farmers, farmer associations, SMEs, local environment and agriculture councils, touristic industry and civil society.



Decision Supporting System (DSS)

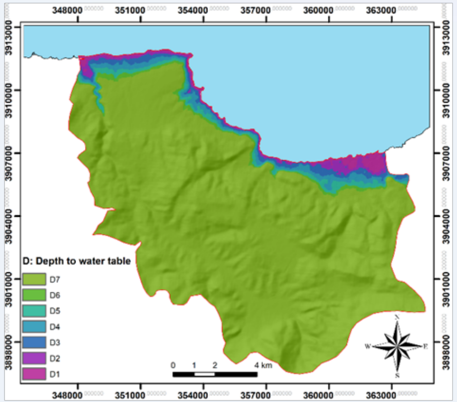
Analytic Hierarchy Process investigatement

Main criteria	*D*	*R*	*A*	*S*	*T*	*I*	*C*	*Lu*	W_i
(D)	1								0.248
(R)	1/2	1							0.143
(A)	1/3	1/2	1						0.081
(S)	1/7	1/3	1/2	1					0.047
(T)	1/9	1/6	1/4	1/3	1				0.024
(I)	1	2	4	3	7	1			0.237
(C)	1/3	1/3	1/2	2	3	1/4	1		0.065
(Lu)	1/2	1	3	5	6	1/2	2	1	0.154

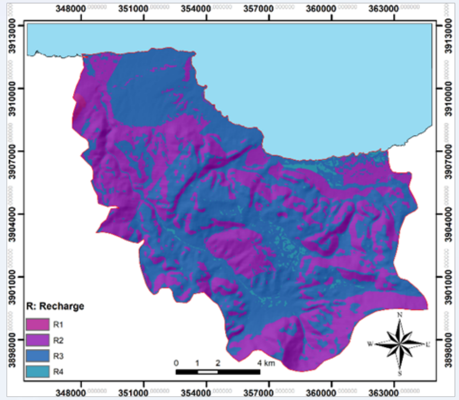
- **D** • Depth to water table
- **R** • Net recharge
- **A** • Aquifer media
- **S** • Soil media
- **T** • Topography
- **I** • Impact of Vadose zone
- **C** • Hydraulic conductivity
- **Lu** • Land use classes

• Malia Coastal Aquifer (MCA) Crete -GREECE

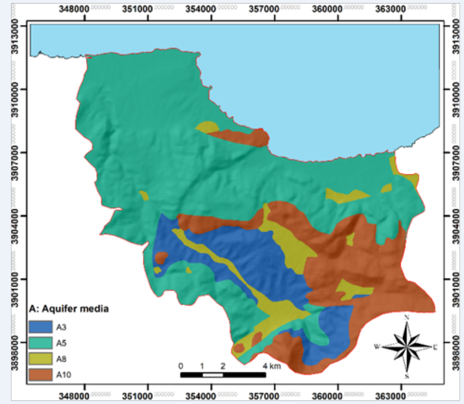
D: **D**epth to water table



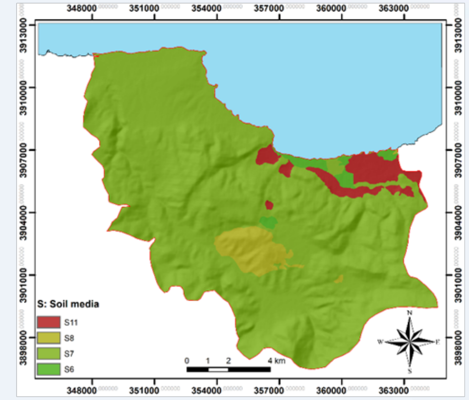
R: net **R**echarge



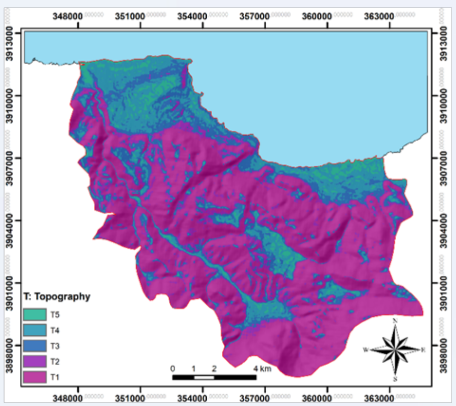
A: **A**quifer media



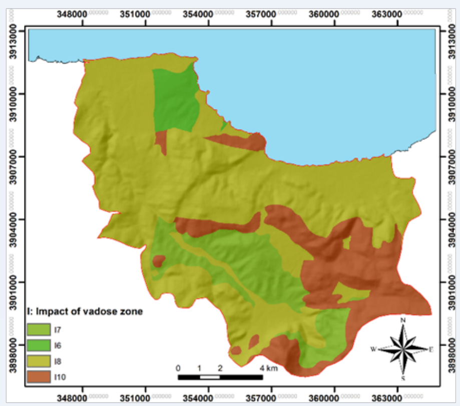
S: **S**oil media



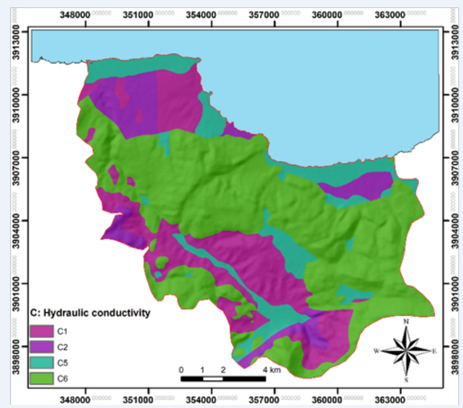
T: Topography



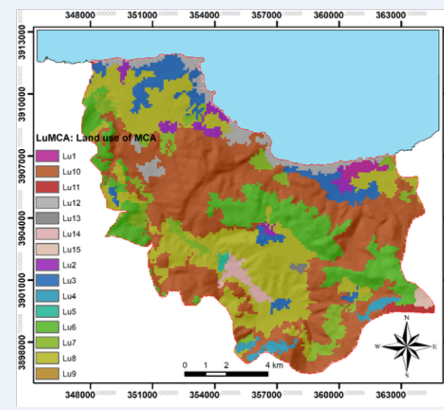
I: **I**mpact of the vadose zone



C: hydraulic **C**onductivity



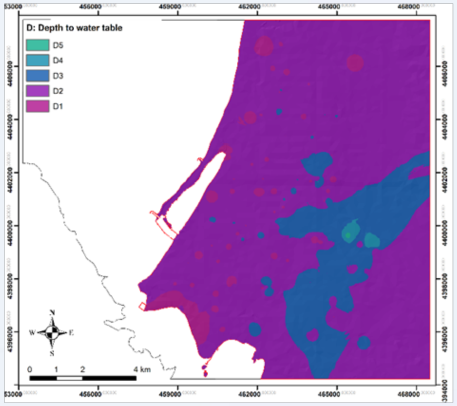
Lu: Landuse



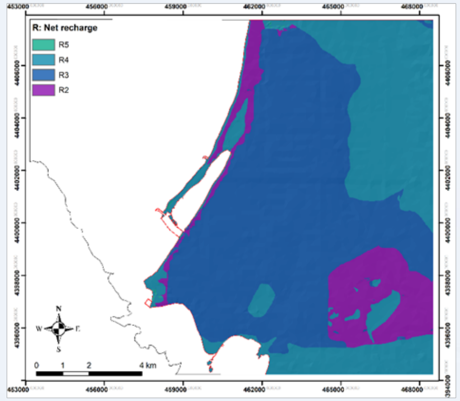
ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ
TECHNICAL UNIVERSITY OF CRETE

• Arborea Coastal Aquifer (ACA) Arborea -ITALY

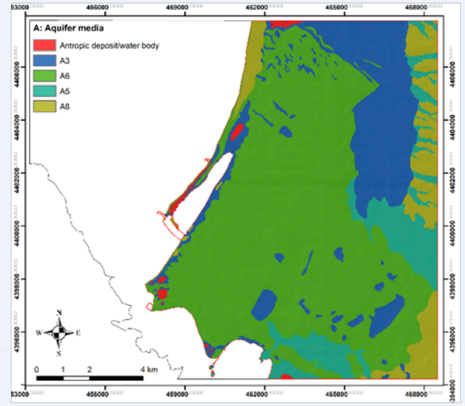
D: **D**epth to water table



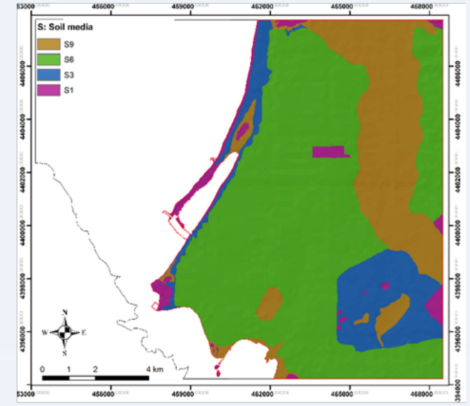
R: net **R**echarge



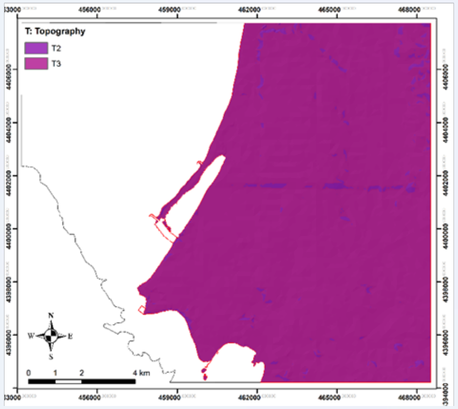
A: **A**quifer media



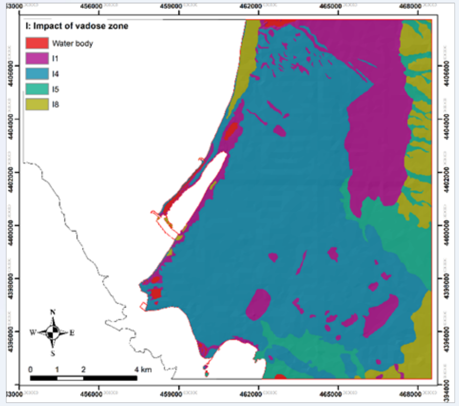
S: **S**oil media



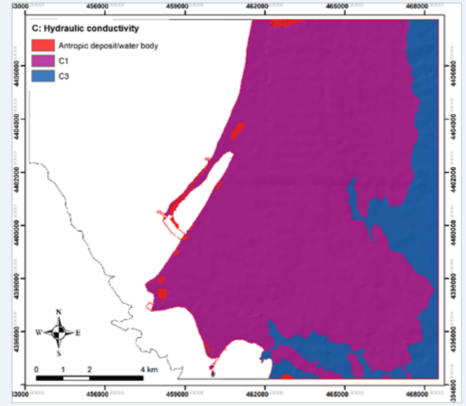
T: Topography



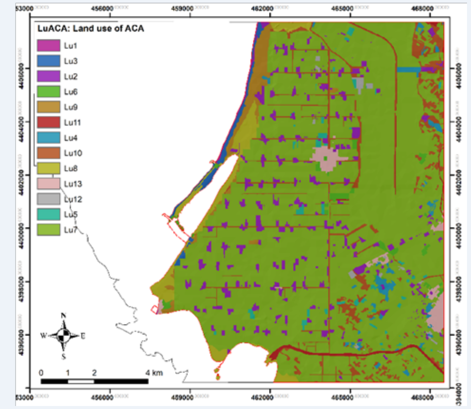
I: **I**mpact of the vadose zone



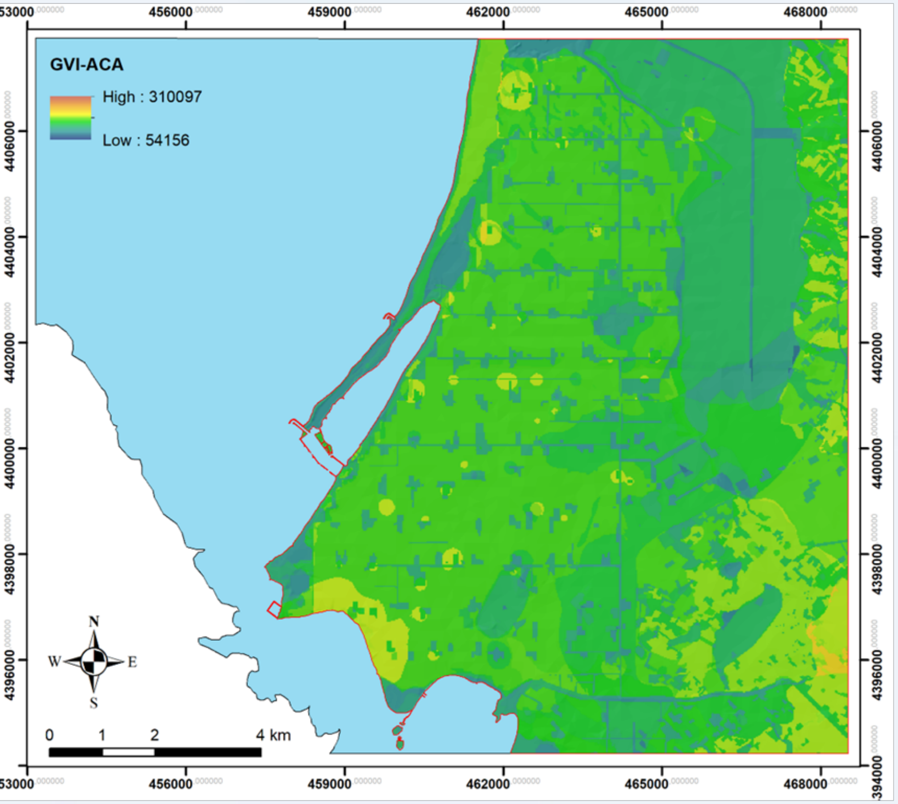
C: hydraulic **C**onductivity



Lu: Landuse

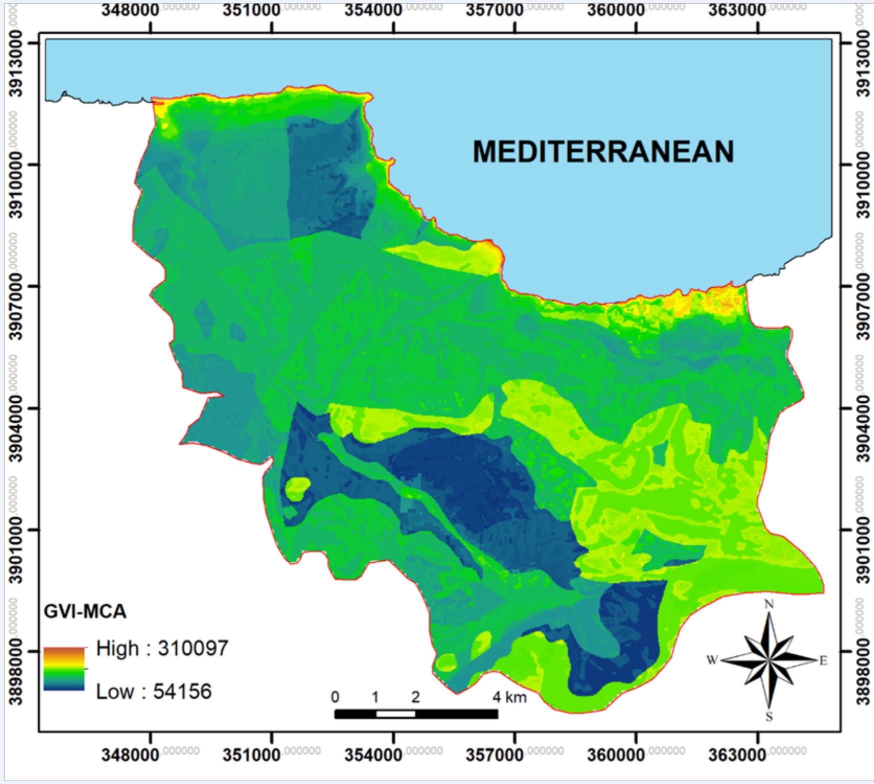


Vulnerability Maps



Arborea Coastal Aquifer (ACA) Arborea -ITALY

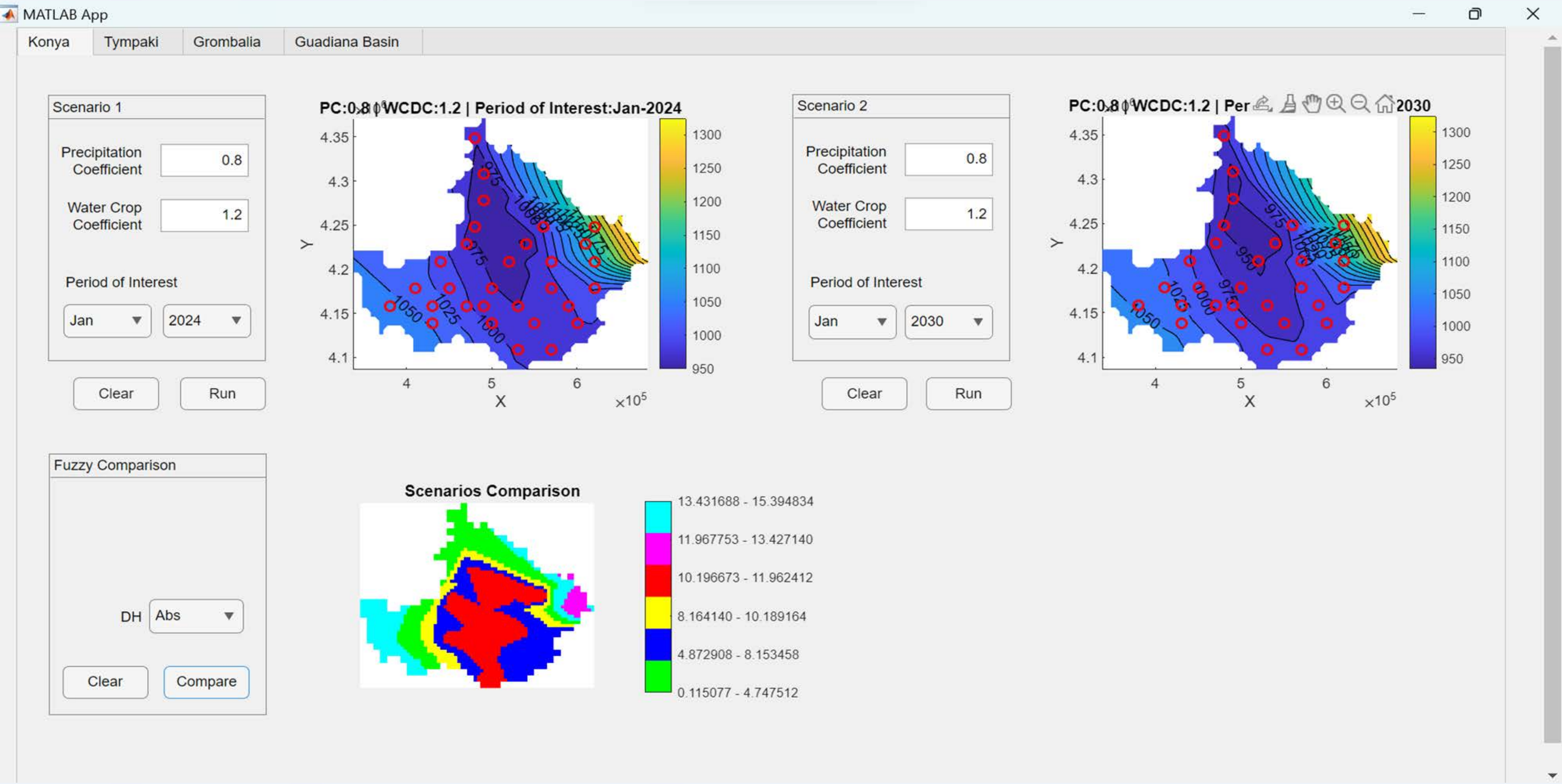
Min: 76.78 Max: 250.98 Mean: 153.90

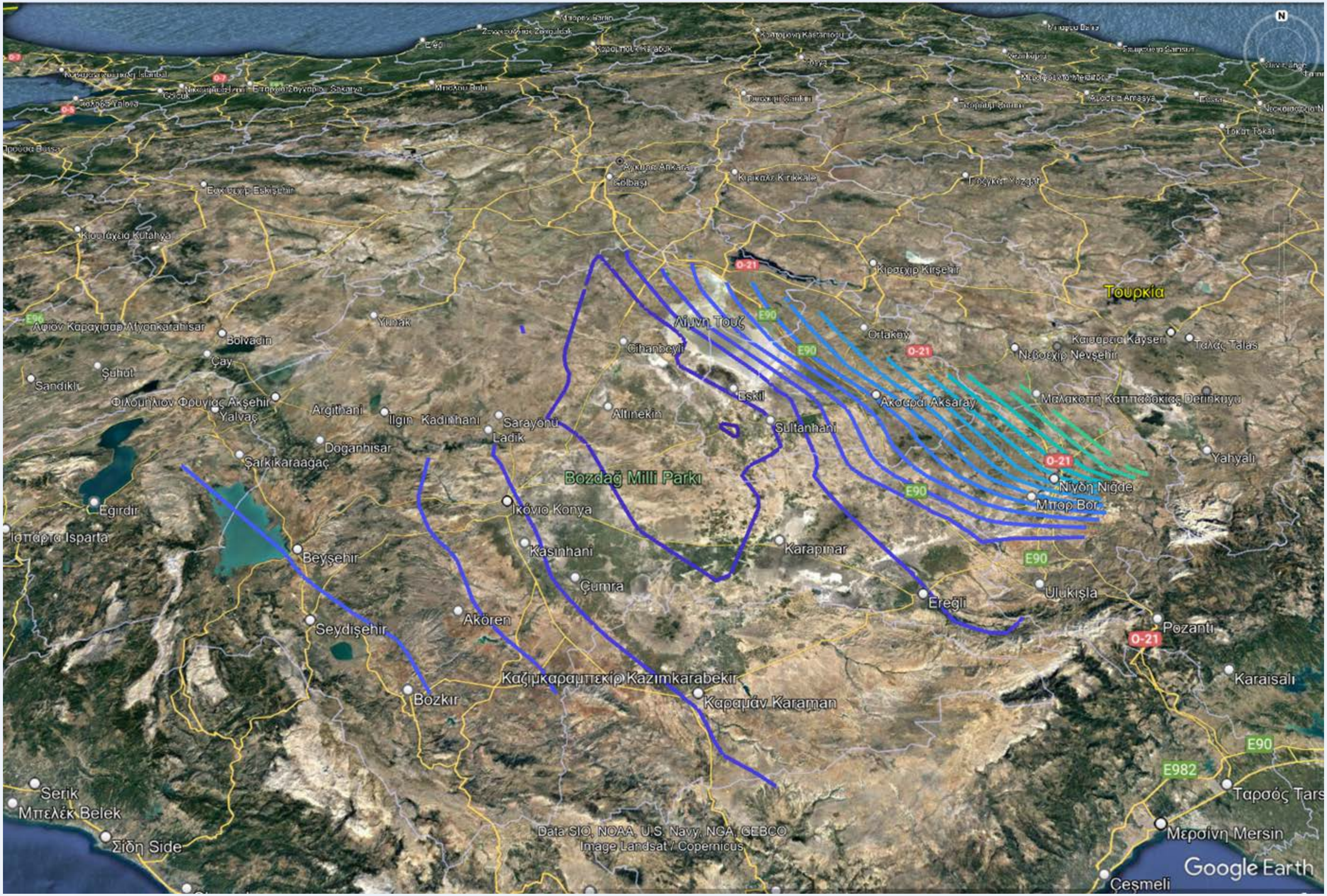


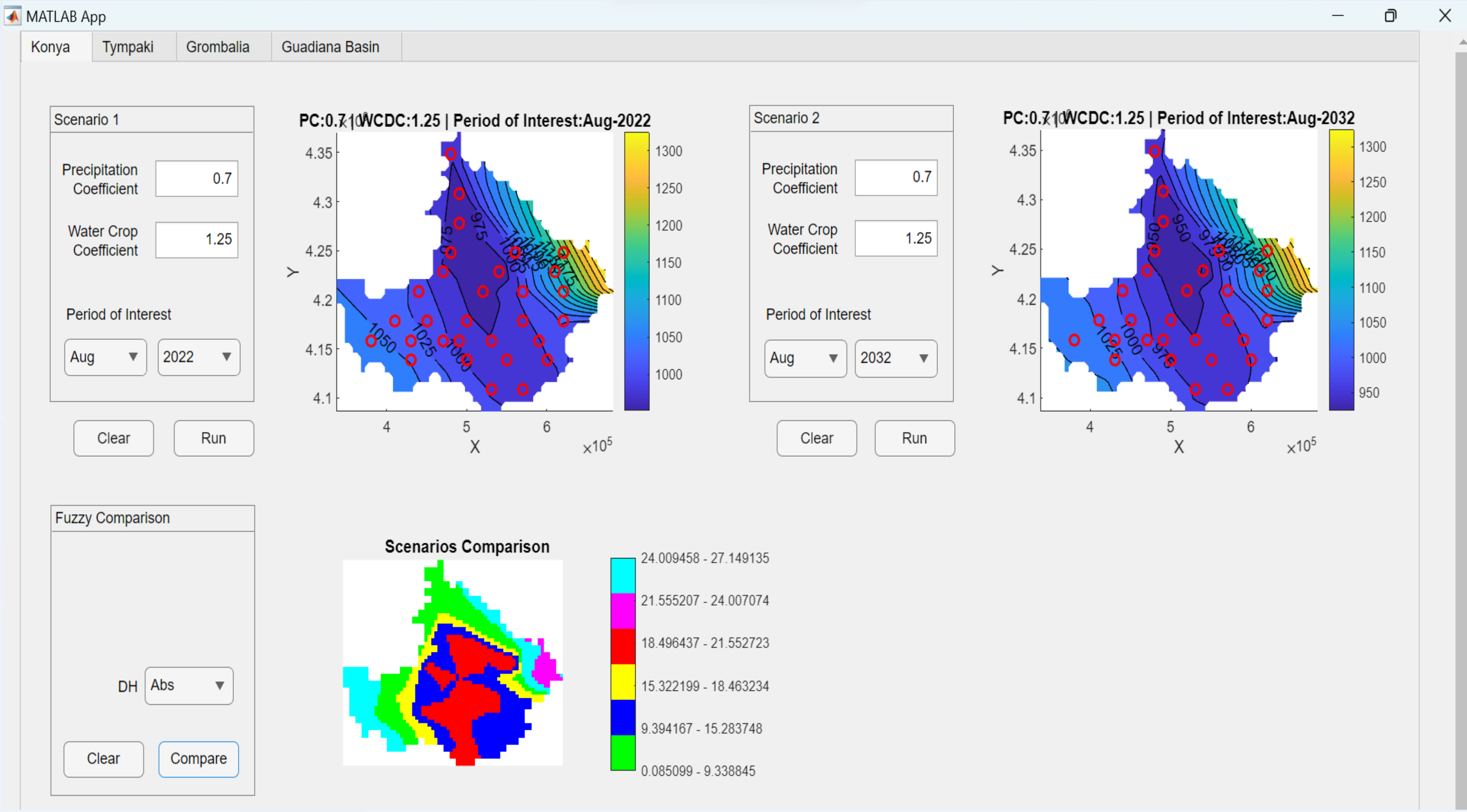
Malia Coastal Aquifer (MCA) Crete -GREECE

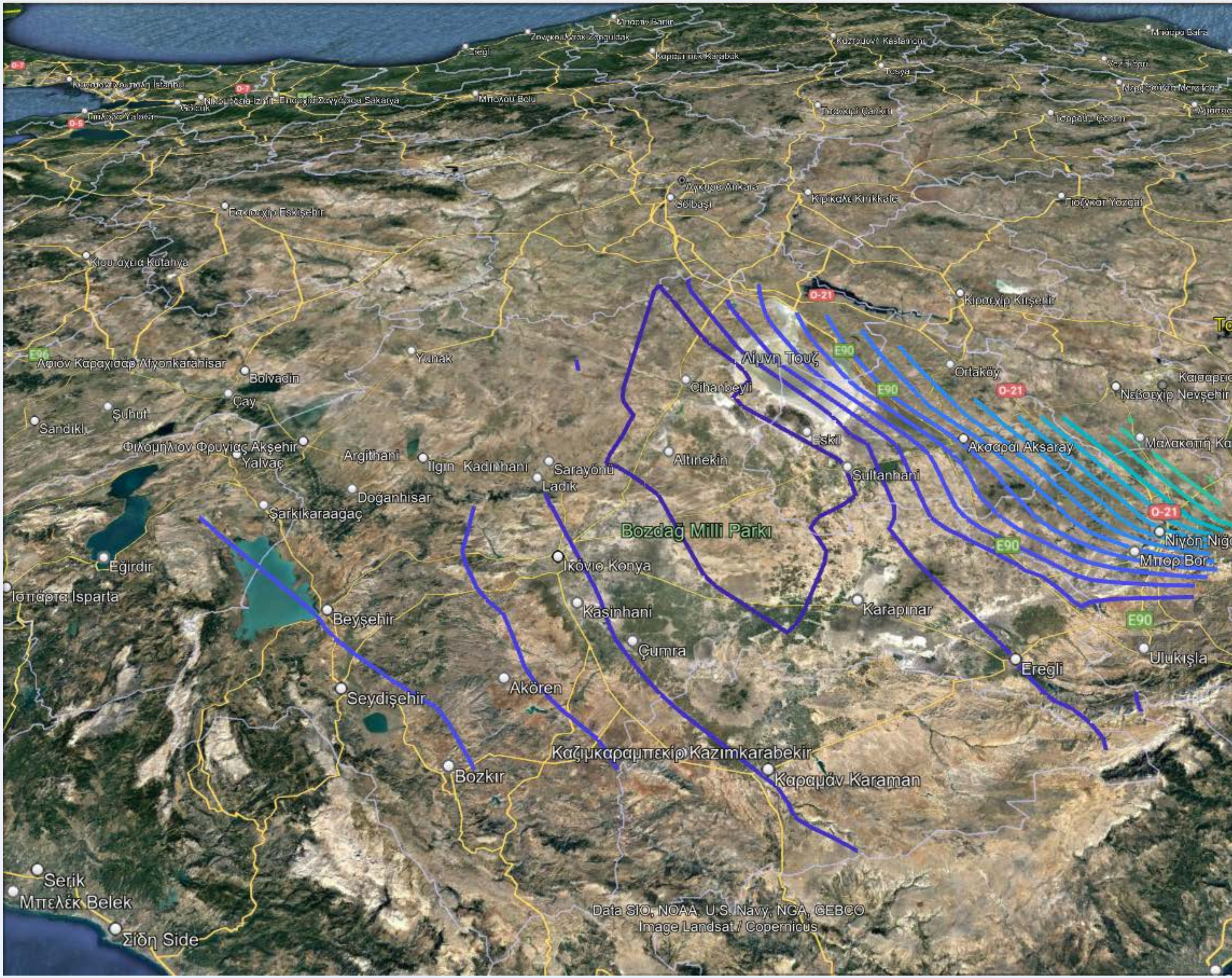
Min: 57.75 Max: 310.09 Mean: 133.26

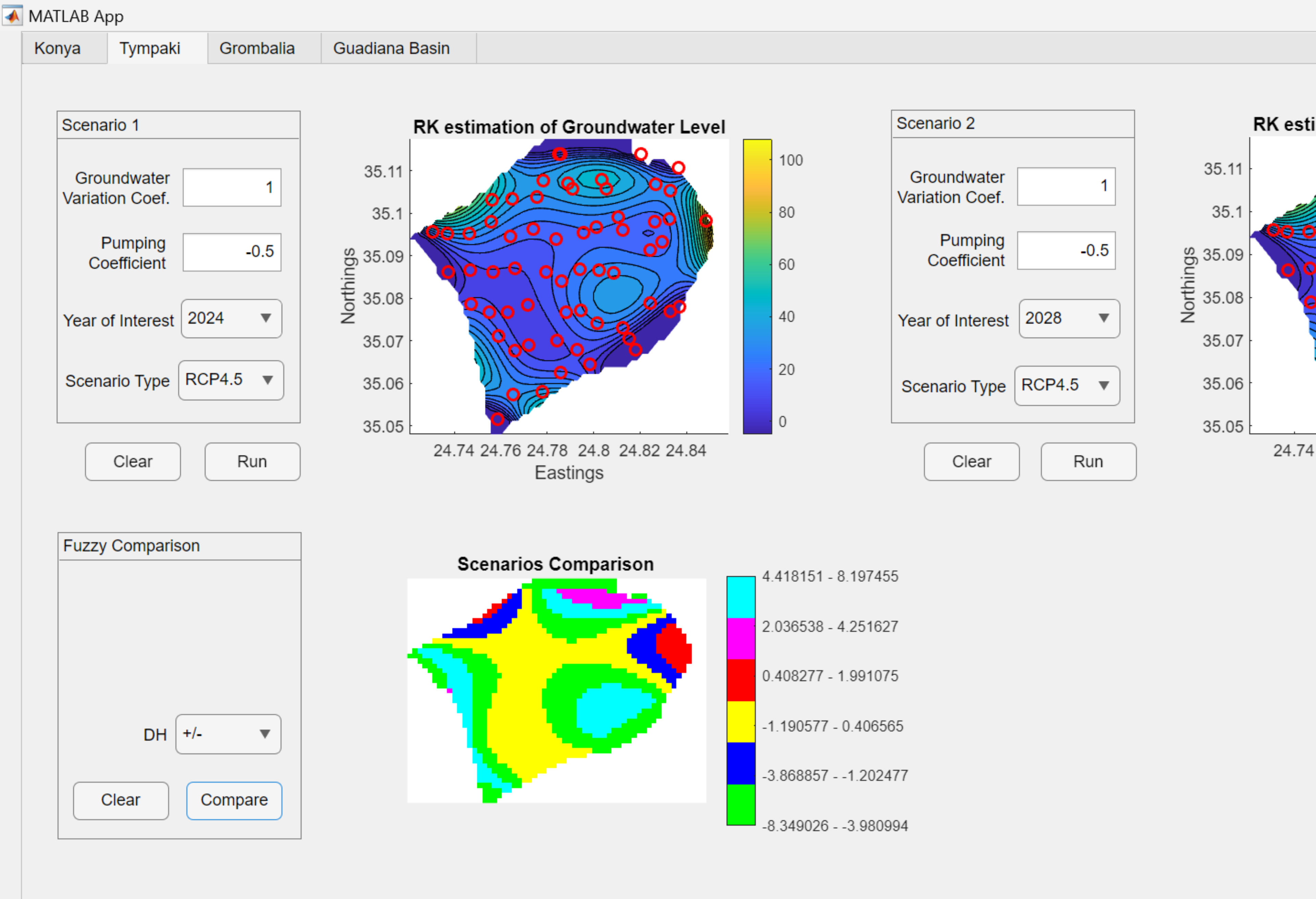
Decision Supporting System (DSS)

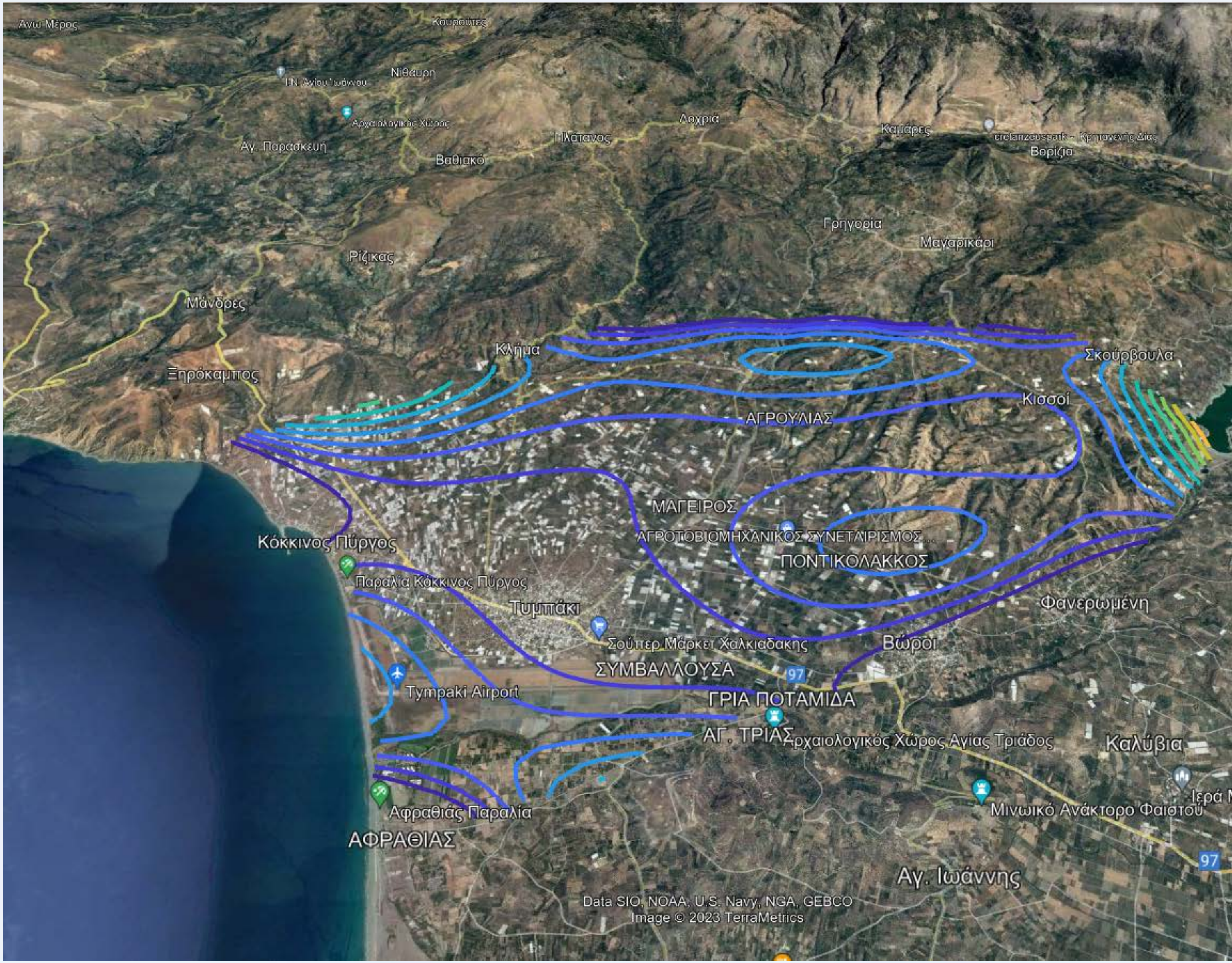



Λίμνη Τουζ
Τουρκία
Bozdağ Milli Parkı
Κιρσεχίρ Kirşehir
Ortaköy
Καισάρεια Kayseri
Ταλάς Talas
Νεβσεχίρ Nevşehir
Μαλακοπή Καππαδοκίας Derinkuyu
Ακσαράι Aksaray
Yahyalı
Νίγδη Niğde
Μπορ Bor
Cihanbeyli
Eskil
Altınekin
Sultanhanı
Karapınar
Ulukışla
Ereğli
Pozantı
Karaisalı
Ικόνιο Konya
Kaşınhanı
Çumra
Akören
Sarayönü
Ladik
Kadınhanı
Ilgın
Argıthani
Doğanhisar
Şarkikaraağaç
Yalvaç
Φιλομήλιον Φρυγίας Akşehir
Yunak
Bolvadin
Çay
Şuhut
Sandıklı
Αφιόν Καραχισάρ Afyonkarahisar
Εσκί Σεχίρ Eskişehir
Κιουτάχεια Kütahya
Eğirdir
Ισπάρτα Isparta
Beyşehir
Seydişehir
Bozkır
Καζίμκαραμπεκίρ Kazımkarabekir
Καραμάν Karaman
Serik
Μπελέκ Belek
Σίδη Side
Ταρσός Tarsus
Μερσίνη Mersin
Çeşmeli
Άγκυρα Ankara
Gölbaşı
Κιρικκαλέ Kırıkkale
Γιοζγκάτ Yozgat
Τοκάτ Tokat
Αμάσεια Amasya
Σαμψούντα Samsun
Yalova
Bursa
Κωνσταντινούπολη İstanbul
Σαγγάριος Sakarya
Μπολού Bolu
Κιουτάχεια Kütahya
E90
E96
E982
O-21
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Google Earth


MATLAB App
Konya
Tympaki
Grombalia
Guadiana Basin
Scenario 1
Precipitation Coefficient
0.7
Water Crop Coefficient
1.25
Period of Interest
Aug
2022
Clear
Run
PC:0.7 | WCDC:1.25 | Period of Interest:Aug-2022
Scenario 2
Precipitation Coefficient
0.7
Water Crop Coefficient
1.25
Period of Interest
Aug
2032
Clear
Run
PC:0.7 | WCDC:1.25 | Period of Interest:Aug-2032
Fuzzy Comparison
DH
Abs
Clear
Compare
Scenarios Comparison
24.009458 - 27.149135
21.555207 - 24.007074
18.496437 - 21.552723
15.322199 - 18.463234
9.394167 - 15.283748
0.085099 - 9.338845


Eskişehir
Kutahya
Afyonkarahisar
Bolvadin
Çay
Şuhut
Sandikli
Akşehir
Yalvaç
Argithani
Ilgın
Kadınhanı
Sarayönü
Ladik
Doğanhisar
Şarkikaraagaç
Eğirdir
Isparta
Beyşehir
Seydişehir
Bozkır
Akören
Kasinhani
Çumra
Ικόνιο Konya
Bozdağ Milli Parkı
Cihanbeyli
Altınekin
Eskil
Sultanhani
Λίμνη Τουζ
Ακσαράι Aksaray
Ortaköy
Karapınar
Ereğli
Ulukışla
Νίγδη Niğde
Μπορ Bor
Νεβσεχίρ Nevşehir
Κιρσεχίρ Kırşehir
Κιρικαλέ Kırıkkale
Άγκυρα Ankara
Gölbaşı
Γιόζγκατ Yozgat
Yunak
Καζιμκαραμπεκίρ Kazımkarabekir
Καραμάν Karaman
Serik
Μπελέκ Belek
Σίδη Side
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus


MATLAB App
Konya
Tympaki
Grombalia
Guadiana Basin
Scenario 1
Groundwater Variation Coef.
1
Pumping Coefficient
-0.5
Year of Interest
2024
Scenario Type
RCP4.5
Clear
Run
RK estimation of Groundwater Level
Northings
Eastings
35.11
35.1
35.09
35.08
35.07
35.06
35.05
24.74 24.76 24.78 24.8 24.82 24.84
100
80
60
40
20
0
Scenario 2
Groundwater Variation Coef.
1
Pumping Coefficient
-0.5
Year of Interest
2028
Scenario Type
RCP4.5
Clear
Run
Fuzzy Comparison
DH
+/-
Clear
Compare
Scenarios Comparison
4.418151 - 8.197455
2.036538 - 4.251627
0.408277 - 1.991075
-1.190577 - 0.406565
-3.868857 - -1.202477
-8.349026 - -3.980994


Άνω Μέρος
Καμαράκι
Νίθαυρη
Αγ. Παρασκευή
Βαθιακό
Πλάτανος
Λοχριά
Καμάρες
Βορίζια
Γρηγοριά
Μαγαρικάρι
Ρίζικας
Μάνδρες
Ξηρόκαμπος
Κλήμα
Σκούρβουλα
Κισσοί
ΑΓΡΟΥΛΙΑΣ
ΜΑΓΕΙΡΟΣ
ΑΓΡΟΤΟΒΙΟΜΗΧΑΝΙΚΟΣ ΣΥΝΕΤΑΙΡΙΣΜΟΣ...
ΠΟΝΤΙΚΟΛΑΚΚΟΣ
Κόκκινος Πύργος
Παραλία Κόκκινος Πύργος
Τυμπάκι
Σούπερ Μάρκετ Χαλκιαδάκης
Φανερωμένη
Βώροι
ΣΥΜΒΑΛΛΟΥΣΑ
Tympaki Airport
ΓΡΙΑ ΠΟΤΑΜΙΔΑ
ΑΓ. ΤΡΙΑΣ
Αρχαιολογικός Χώρος Αγίας Τριάδος
Καλύβια
Αφραθιάς Παραλία
ΑΦΡΑΘΙΑΣ
Μινωικό Ανάκτορο Φαιστού
Αγ. Ιωάννης
97
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2023 TerraMetrics

In conclusion

- **Water resources management and water governance in coastal aquifers is an important and urgent challenge.**

- **Despite the big effort to develop comprehensive <u>water laws and policies</u> and to harmonize features and goals in water governance (e.g., decentralisation, basin-wide management planning, better coordination of horizontal and vertical decision-making, multi-stakeholder participation and increased role for the private sector), there are still <u>weaknesses</u> on the <u>effective implementation</u> of water governance.**

“To achieve more effective water governance, it is necessary to create an enabling environment, which facilitates private and public-sector initiatives as well as private-public partnerships that fit within the social, economic and cultural setting of a given society. Water governance is perceived as competent when it is open and transparent, inclusive and communicative, coherent and integrative, equitable and ethical, accountable, efficient, responsive, and sustainable.”

Report of the Conference on Water Governance in MENA and wider Mediterranean region, December 2017, Barcelona, Spain

This work was developed under the scope of **Sustain-COAST** and **InTheMED** PRIMA projects.

Sustain-COAST is funded by the General Secretariat for Research and Innovation of the Ministry of Development and Investments under the PRIMA Programme.

InTheMED is part of the PRIMA programme supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 1923.

PRIMA is an Art.185 initiative supported and co-funded under Horizon 2020, the European Union's Programme for Research and Innovation.

Powered by

The PRIMA programme is supported and funded under Horizon 2020, the Framework European Union's Programme for Research and Innovation

PRIMA
PARTNERSHIP FOR RESEARCH AND INNOVATION IN THE MEDITERRANEAN AREA