



CALCULATING GROUNDWATER STRESS AND CLIMATE CHANGE-INDUCED VULNERABILITY OF KARST AQUIFERS ON A GLOBAL SCALE

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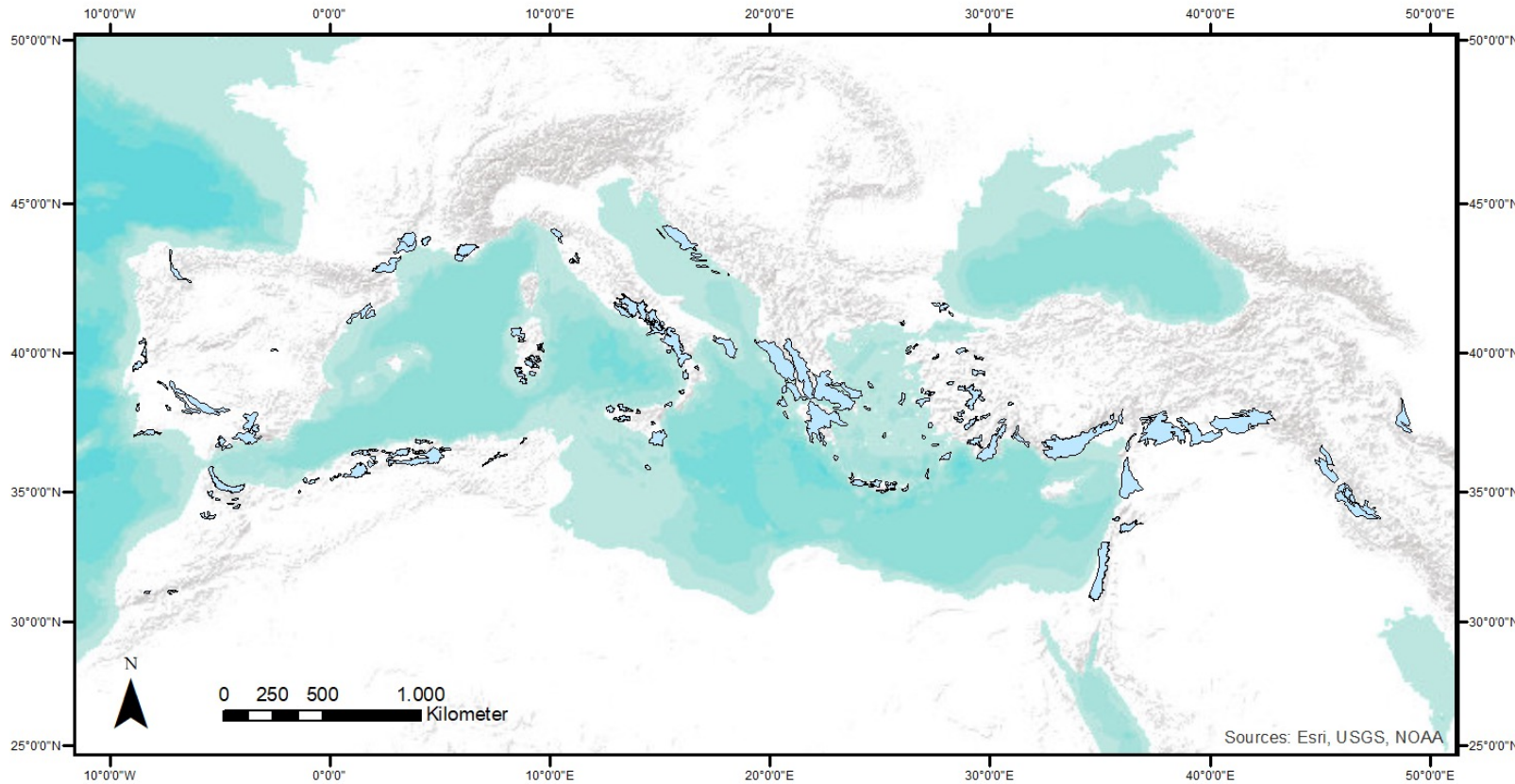
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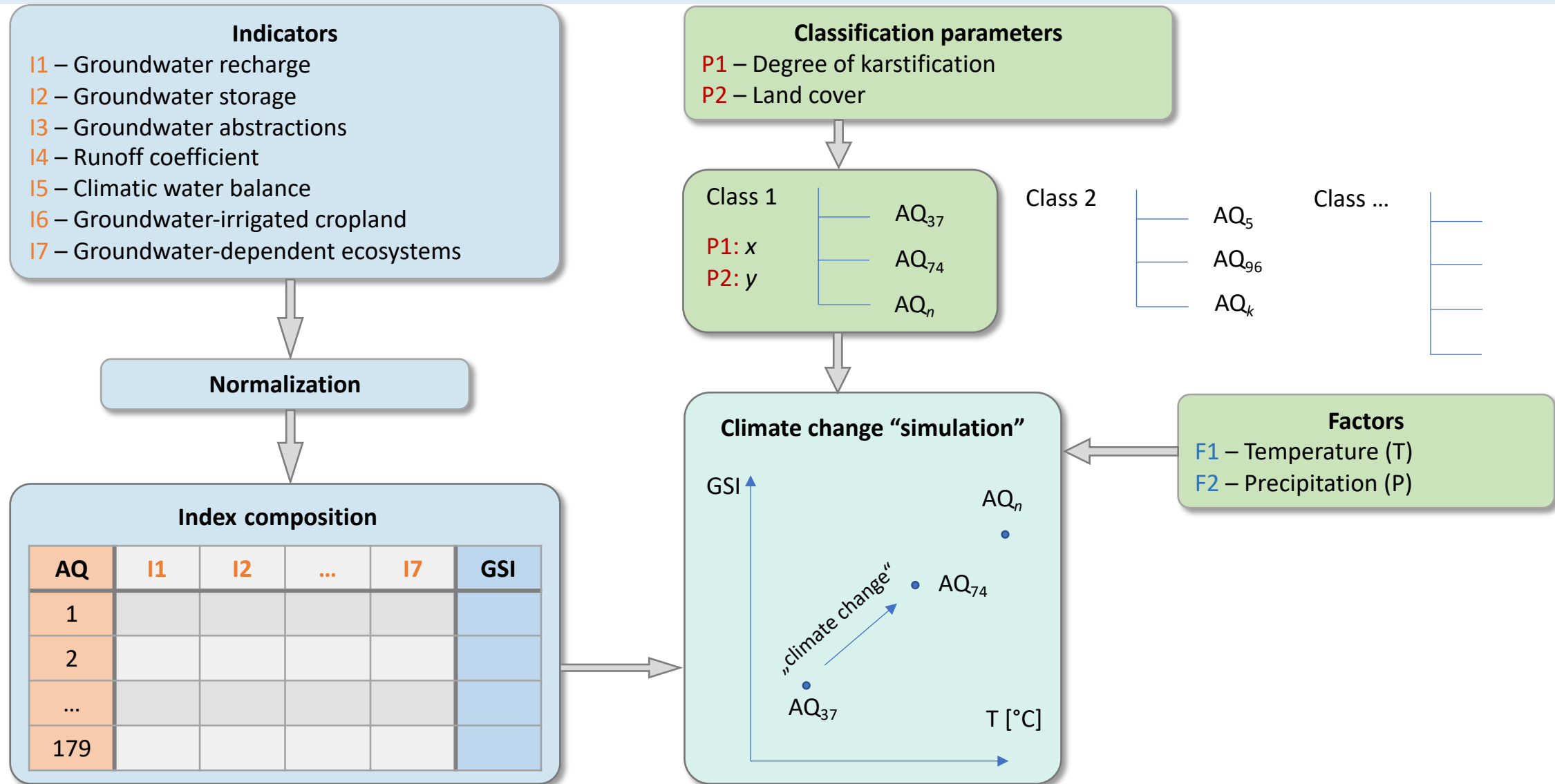
- To assess on the global scale...
 1. the current level of quantitative **groundwater stress** of karst aquifers with Mediterranean climates
 2. their **vulnerability** (defined as the change in groundwater stress) to expected changes in temperature and precipitation
- To visualize results in the form of **groundwater stress and vulnerability maps**

Karst aquifers with Mediterranean climates (Mediterranean only)



- WHYMAP WOKAM (Chen et al., 2017)
- Köppen/Geiger climate zones (Beck et al., 2018)
- Subdivision with HydroBASINS-data (Lehner & Grill, 2013)
- >50% of area assigned to Csa, Csb, and/or Csc
- **Selection of 179 Mediterranean karst aquifers**

Csa = Hot-summer Med. clim., **Csb** = Warm-summer Med. clim., **Csc** = Cold-summer Med. clim.



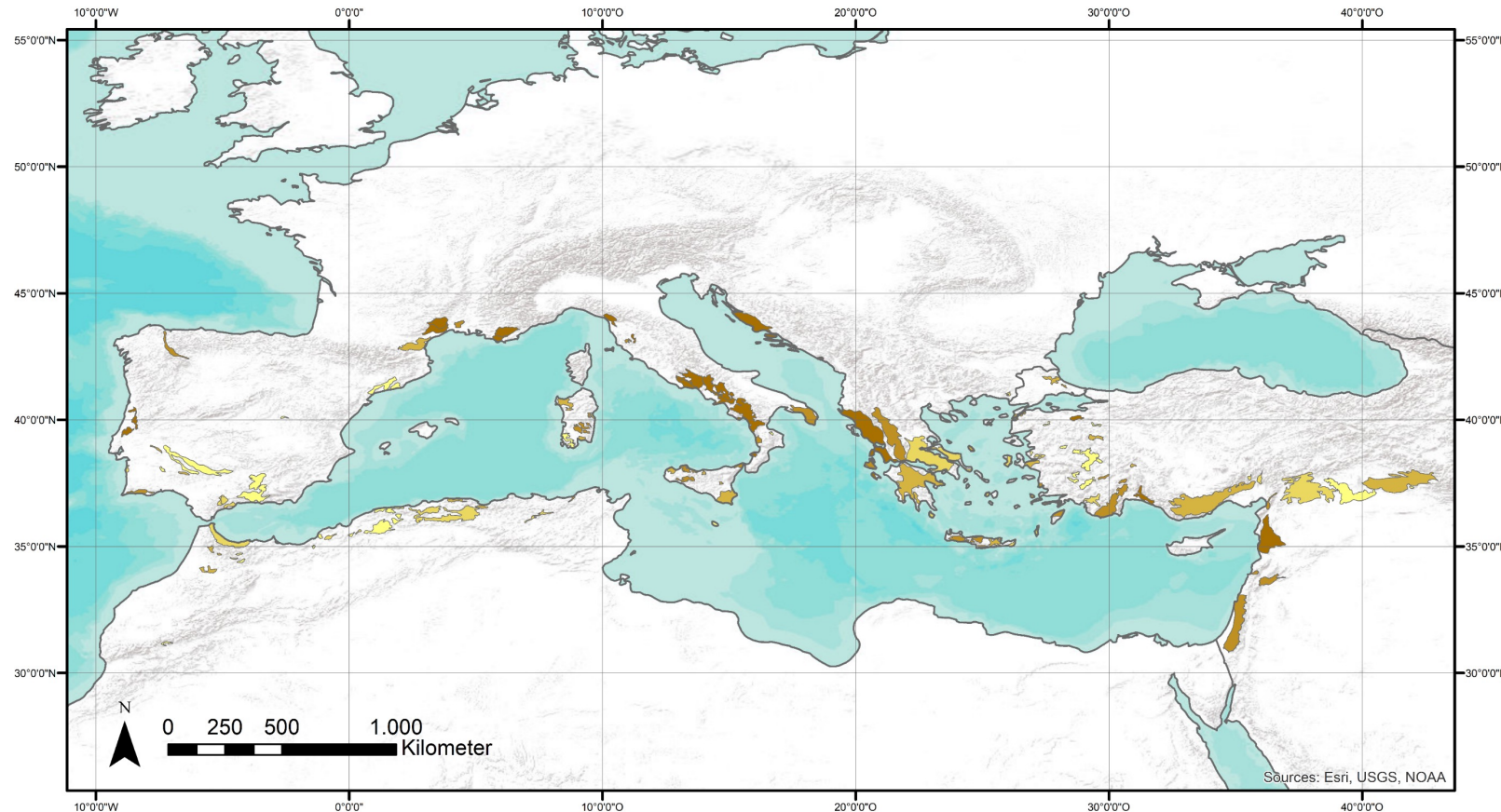
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Groundwater Stress Index

Indicators

- I1 – Groundwater recharge
- I2 – Groundwater storage
- I3 – Groundwater abstractions
- I4 – Runoff coefficient
- I5 – Climatic water balance
- I6 – Groundwater-irrigated cropland
- I7 – Groundwater-dependent ecosystems

I1 – Average annual groundwater recharge [2000-2016]



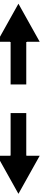
Karst Aquifers Recharge [mm/year]

Recharge Range [mm/year]	Color
6,82 - 45,78	Light Yellow
45,79 - 77,64	Yellow
77,65 - 98,90	Light Brown
98,91 - 129,06	Medium Brown
129,07 - 250,02	Dark Brown

- WaterGAP 2.2d
- 0.5° resolution (ca. 55 km)
- Monthly intervals
- mm/s → mm/a
- Averaged for 2000-2016

Groundwater recharge

Groundwater stress



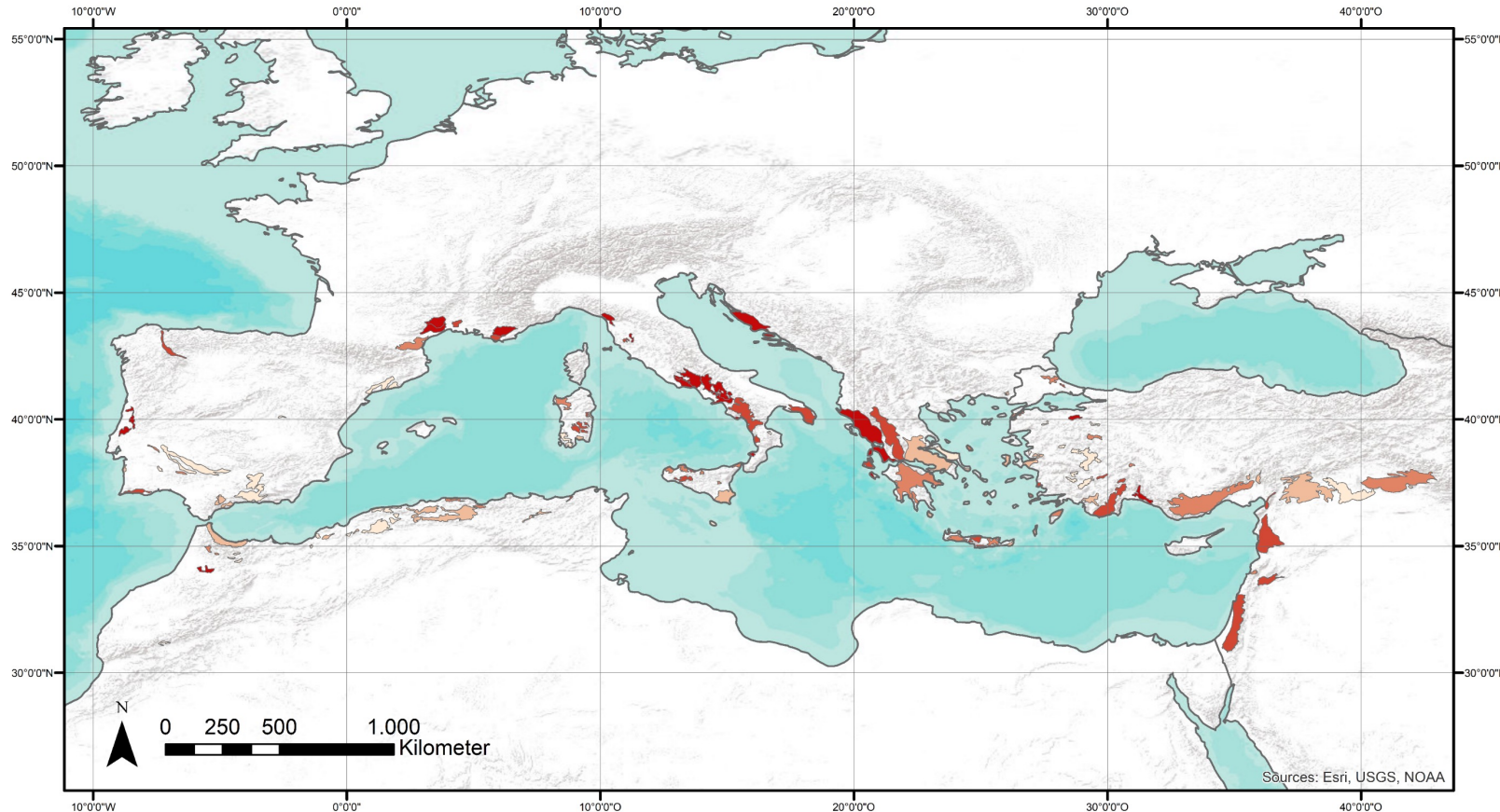
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I2 – Average annual groundwater storage [2000-2016]



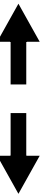
Karst Aquifers Storage [mm/year]

Storage Range [mm/year]	Color
21,21 - 154,54	Light Yellow
154,55 - 260,02	Yellow
260,03 - 332,88	Orange
332,89 - 441,01	Red
441,02 - 816,41	Dark Red

- WaterGAP 2.2d
- 0.5° resolution (ca. 55 km)
- Monthly intervals
- mm → mm/a
- Averaged for 2000-2016

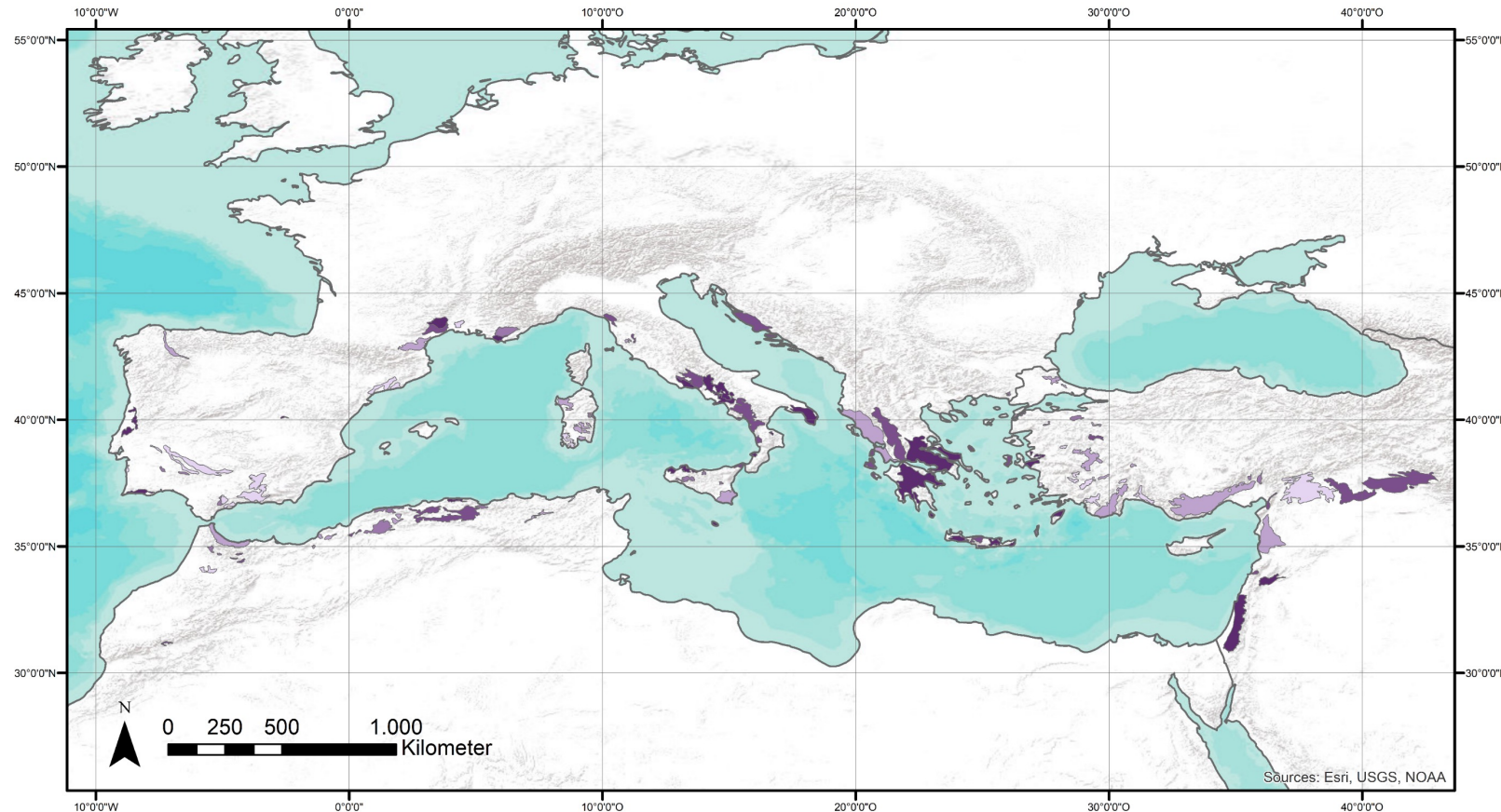
Groundwater storage

Groundwater stress



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I3 – Average annual groundwater net abstractions [2000-2016]



- WaterGAP 2.2d
- 0.5° resolution (ca. 55 km)
- Monthly intervals
- mm/s → mm/a
- Averaged for 2000-2016

Groundwater abstractions
Groundwater stress



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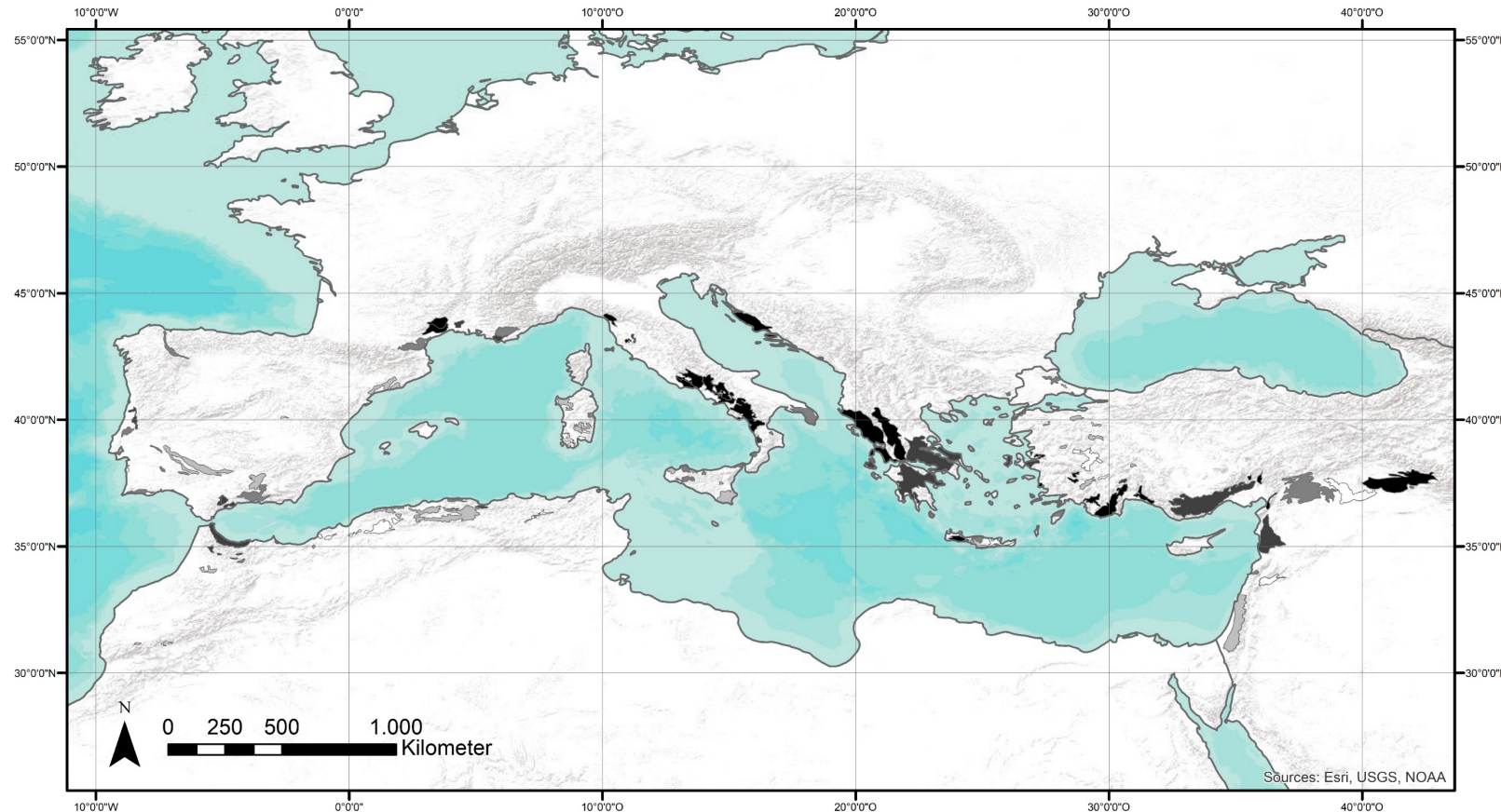


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I4 – Average annual runoff in relation to precipitation [2000-2019]

- ECMWF (ERA5)
- 0.1° resolution (ca. 9 km)
- Monthly intervals
- mm → mm/a
- Averaged for 2000-2019



Runoff coefficient
Groundwater stress



Karst Aquifers Share of surface runoff of total precipitation [%] 1 - 2 3 4 - 6 7 8 - 26

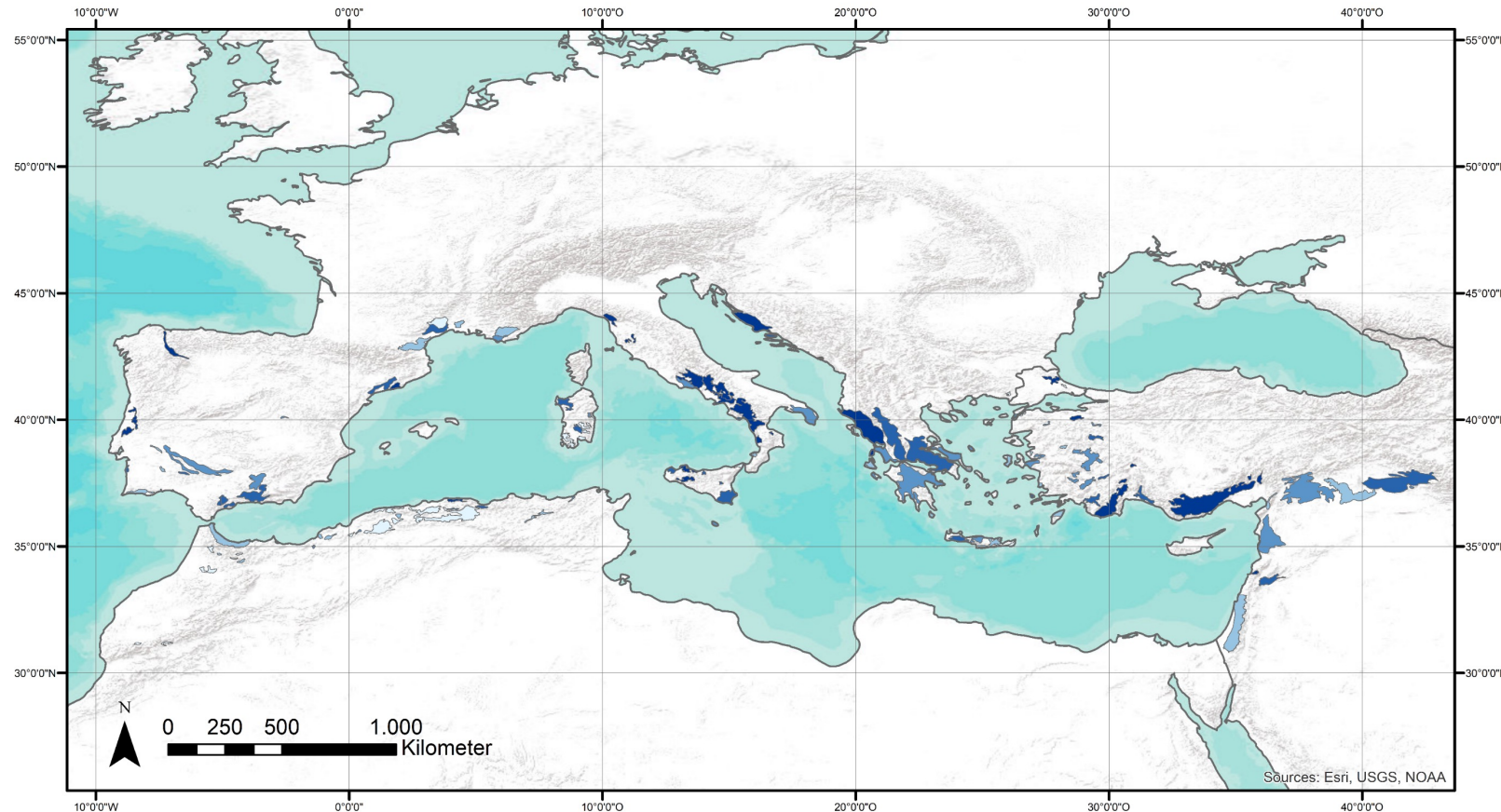
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I5 – Average annual climatic water balance [2000-2019]



Karst Aquifers Climate water balance [mm/year]

Water Balance Range [mm/year]	Color
-9225 - -2966	Lightest Blue
-2965 - -1898	Light Blue
-1897 - -1532	Medium Blue
-1531 - -1147	Dark Blue
-1146 - 107	Darkest Blue

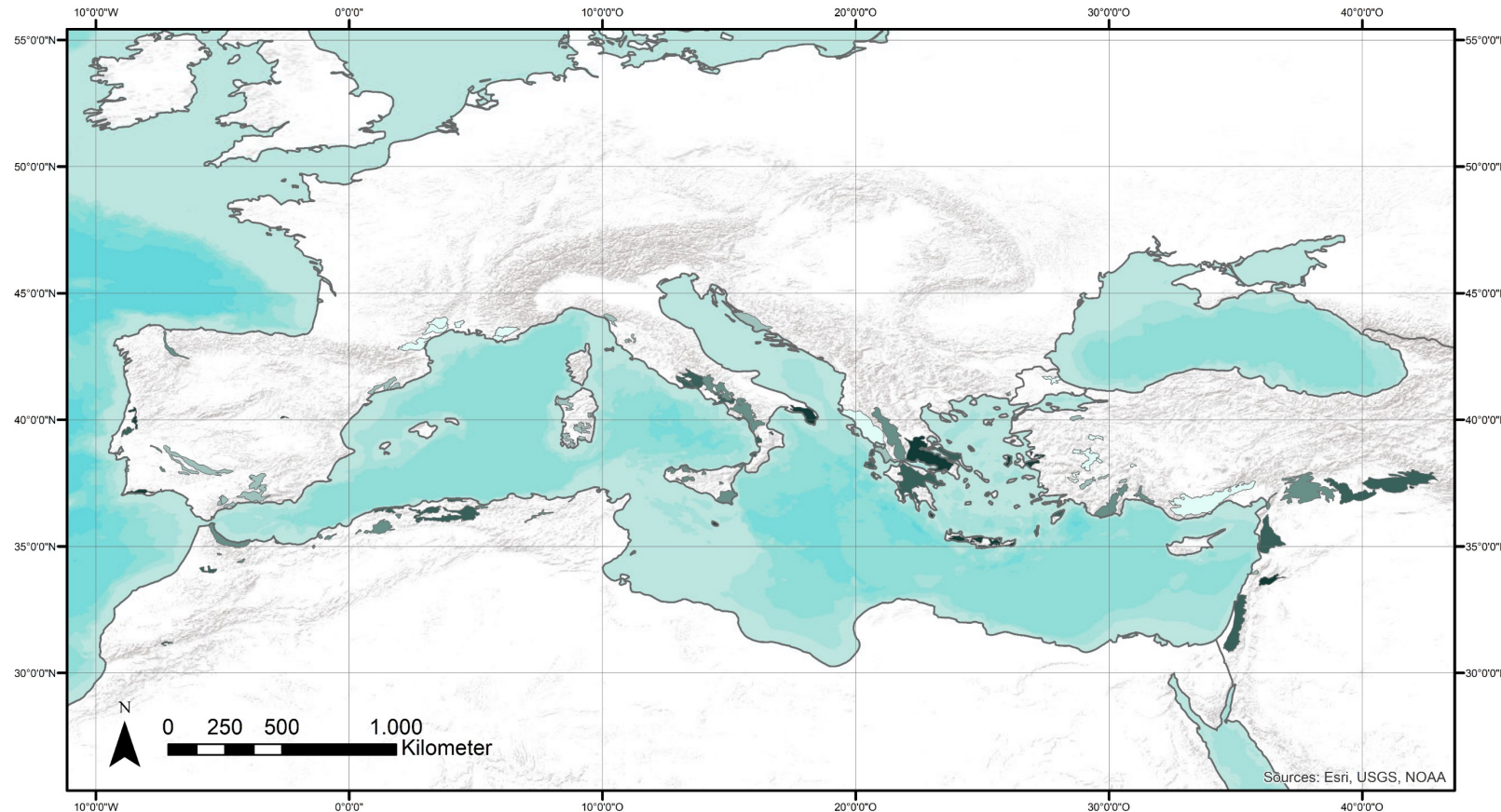
- ECMWF (ERA5) ($P - ET_p$)
- 0.1° resolution (ca. 9 km)
- Monthly intervals
- mm $\rightarrow$ mm/a
- Averaged for 2000-2019

Climatic water balance $\uparrow$

Groundwater stress $\downarrow$

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I6 – Area of groundwater-irrigated cropland [2005]



Karst Aquifers irrigated cropland [%]

Percentage Range [%]	Color
2 - 21	Lightest Blue
22 - 39	Light Blue
40 - 53	Medium Blue
54 - 64	Dark Blue
65 - 99	Darkest Blue

- AQUASTAT (FAO)
- 0.1° resolution (ca. 9 km)
- 2005 values

Groundwater-irr. cropland ↑
Groundwater stress ↑

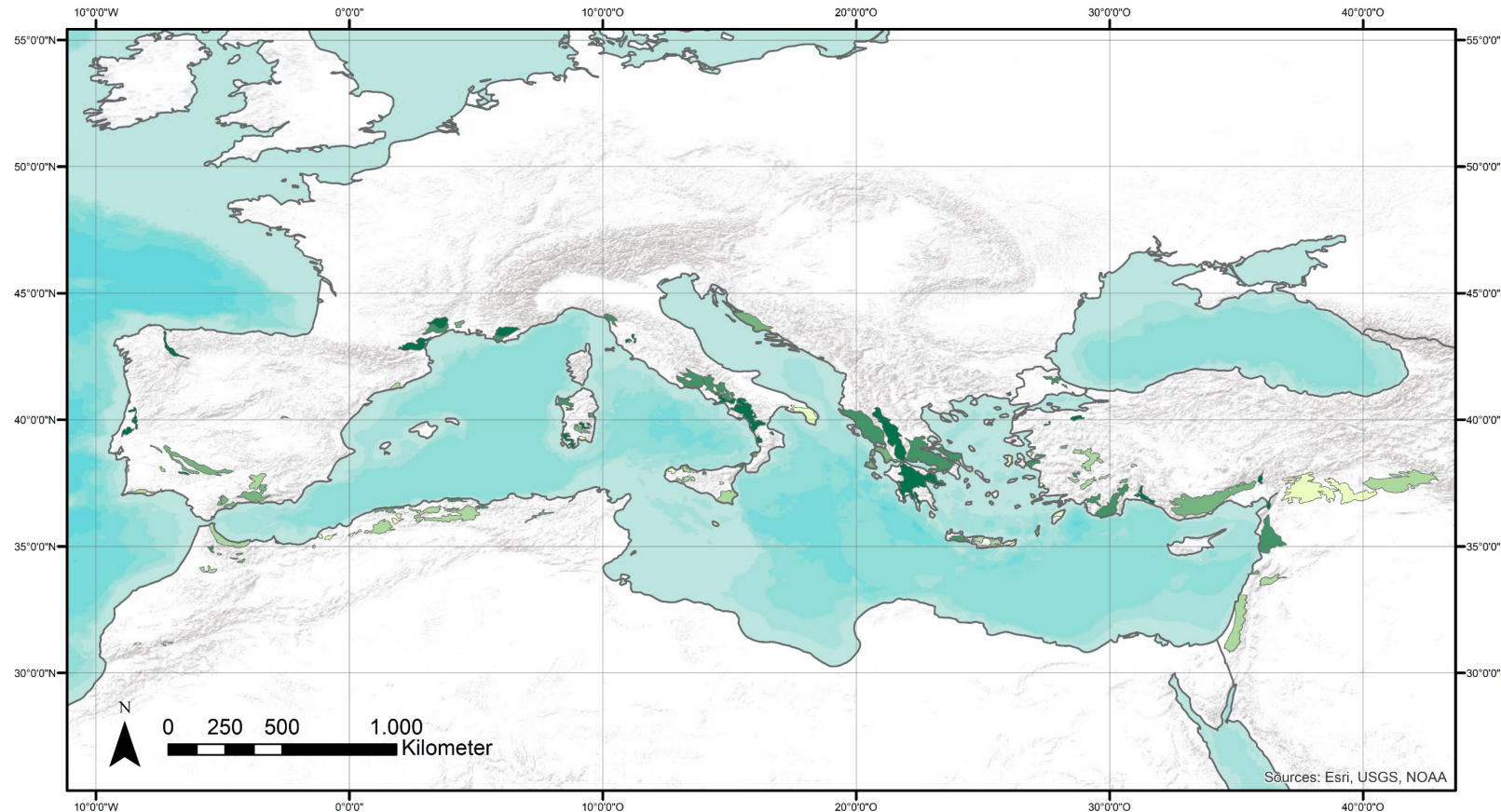
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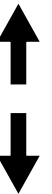


17 – Average annual area of groundwater-dependent ecosystems [2003-2018]



- MOD13Q1, (ESA Land Cover CCI)
- 250m resolution
- 16-day intervals
- Averaged for 2003-2018

Relative area of GDEs
Groundwater stress



Karst Aquifers GDE to total area [%]

Color	Range [%]
Light Yellow	0,00
Yellow	0,01 - 0,75
Light Green	0,76 - 2,90
Medium Green	2,91 - 14,65
Dark Green	14,66 - 50,35

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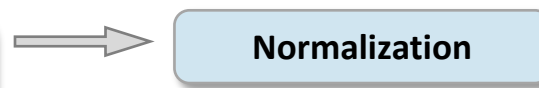
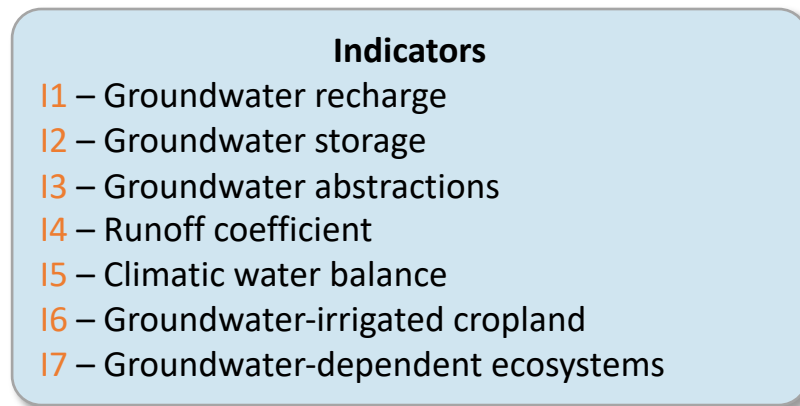


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Index composition – normalization

- **Complex attribute table** derived for 133 aquifers with I1-7 values (no index was calculated if the value of at least one indicator could not be determined)
- **Normalization** of each indicator (0 = no water stress; 1 = extreme water stress)
- **Inversion** for I1, 2, 5, 7 (inverse relationship between indicator and groundwater stress)
- **Equal indicator weights**



$$Z_i = \frac{x_i - \min(x)}{\max(x) - \min(x)}$$

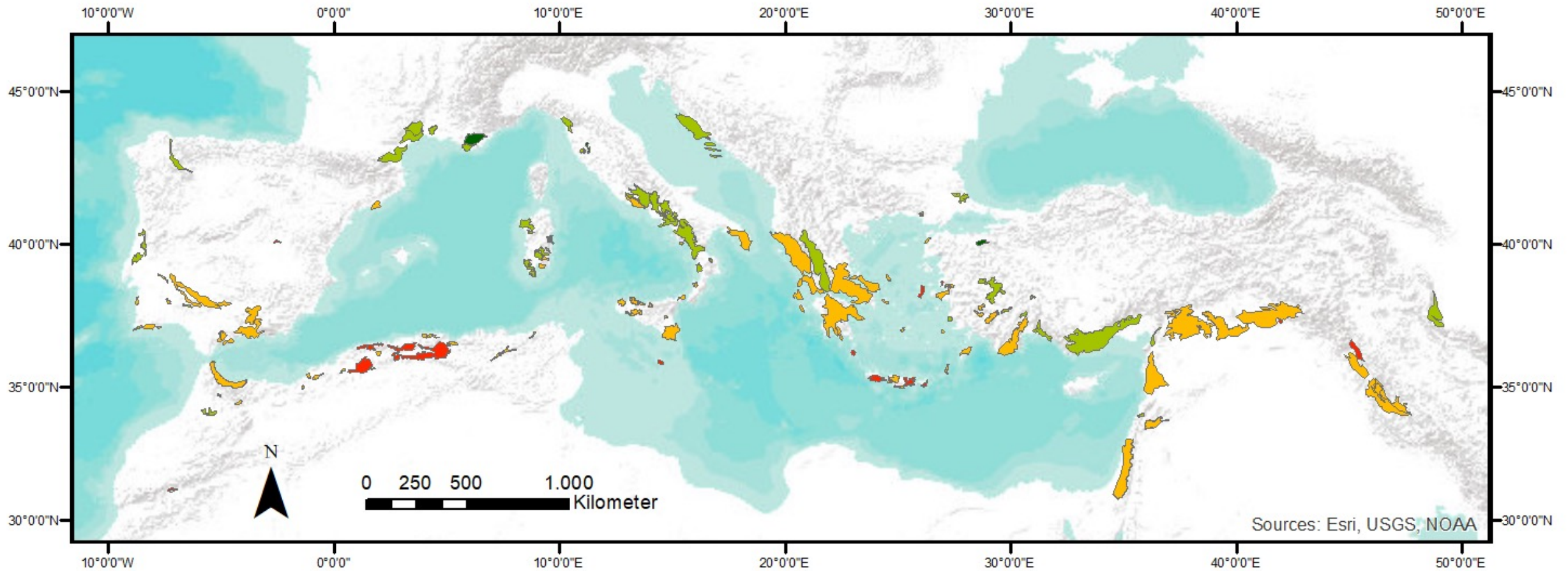
AQ	I1	...	I7	GSI
1				
2				
...				
133				

Index composition – Correlation analysis

	I1	I2	I3	I4	I5	I6	I7
I1	1						
I2	0,9920	1					
I3	-0,1062	0,0161	1				
I4	-0,5389	-0,5439	-0,0201	1			
I5	0,1978	0,1831	-0,1368	-0,2936	1		
I6	0,1604	0,2069	0,3442	-0,2033	0,1538	1	
I7	0,3180	0,3183	-0,0305	-0,2653	-0,0379	0,1177	1

- High correlation between Recharge (I1) & Storage (I2)
- Moderate correlation between Runoff coefficient and I1/I2
- **I2 is not included** in calculating the GSI

GSI results

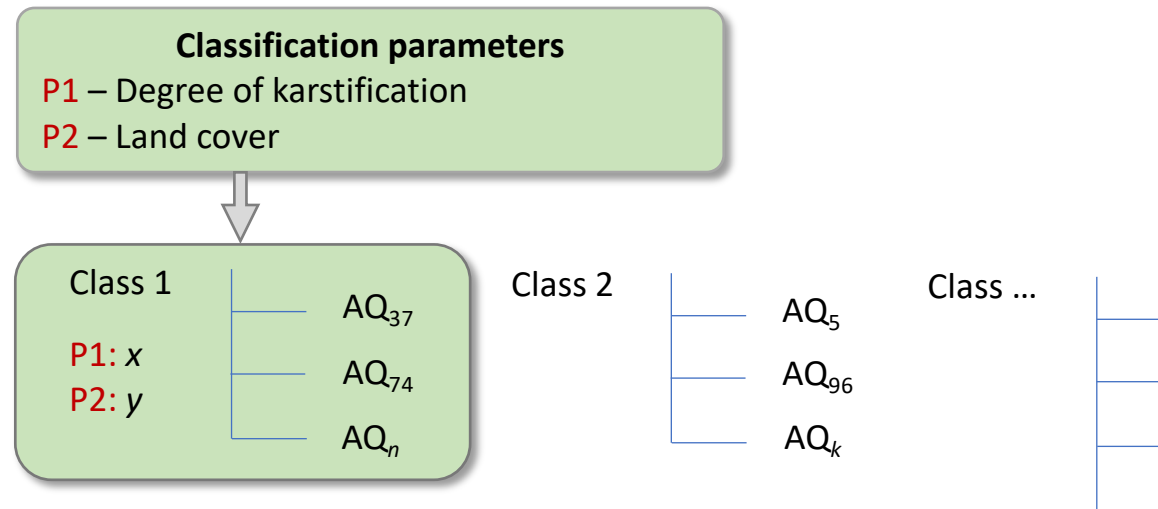


Groundwater Stress Index

0,3 - 0,4	0,4 - 0,5	0,5 - 0,6	0,6 - 0,7
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Vulnerability assessment

Aquifer classification

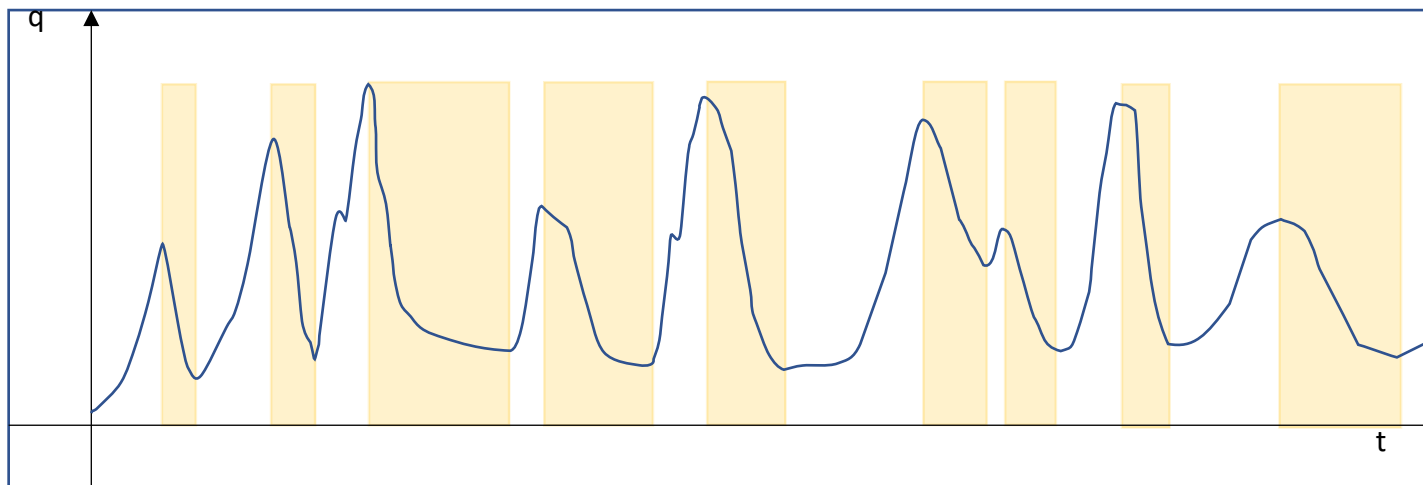


- **WoKaS; Olarino et al., 2020**
(discharge time series of karst springs)
- **Classic hydrograph analysis** could characterize the karst system (recession after recharge events)
- **Spring/aquifer association** was a problem

Classification parameters

P1 – Degree of karstification

P2 – Land cover



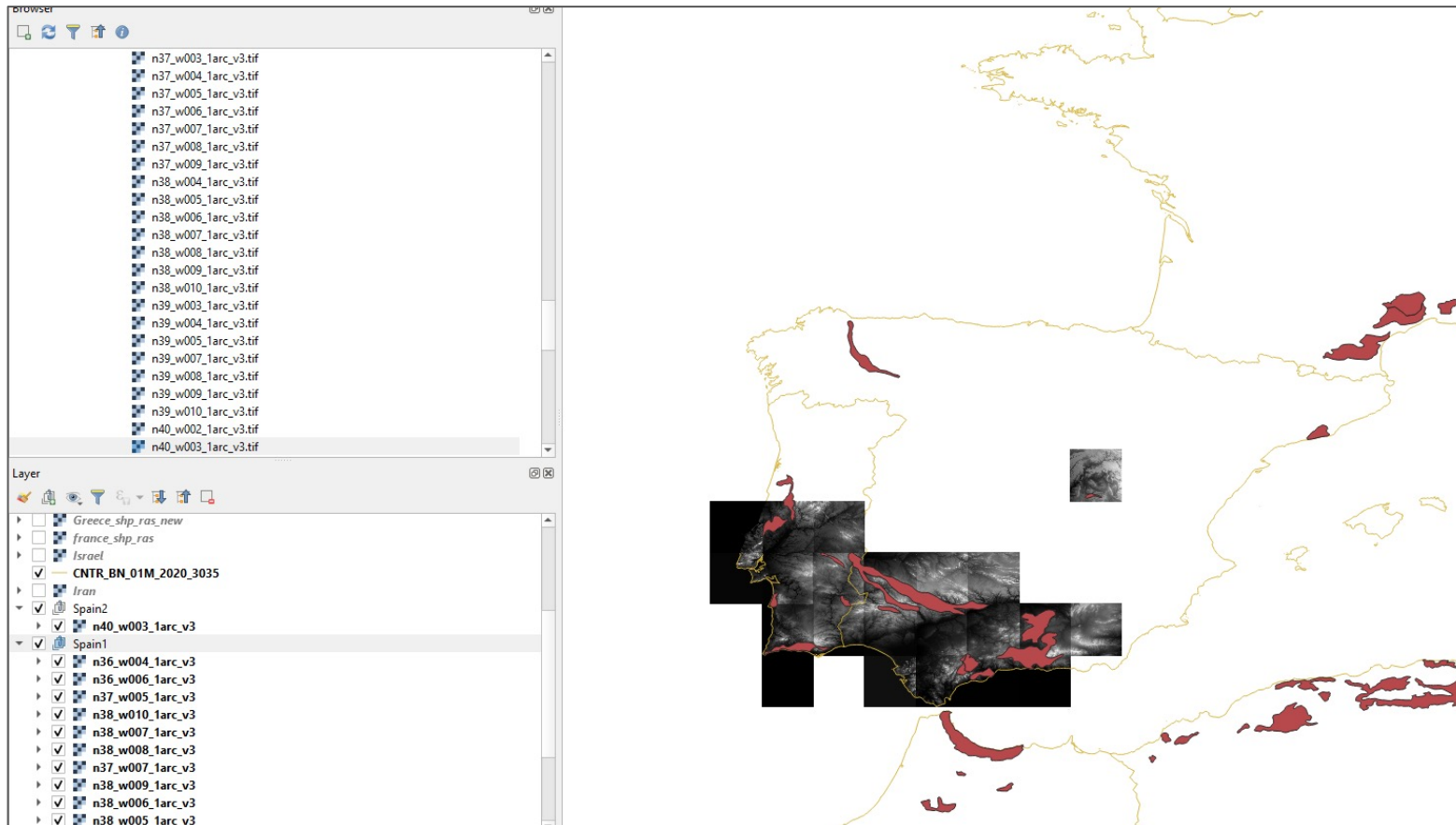
P1 – Degree of karstification

Classification parameters

P1 – Degree of karstification

P2 – Land cover

- Characterization of **geomorphology**
- Derived from **DEM products**
- Variability of **terrain** (slope)
- Direct conclusions about **degree of karstification** are impossible



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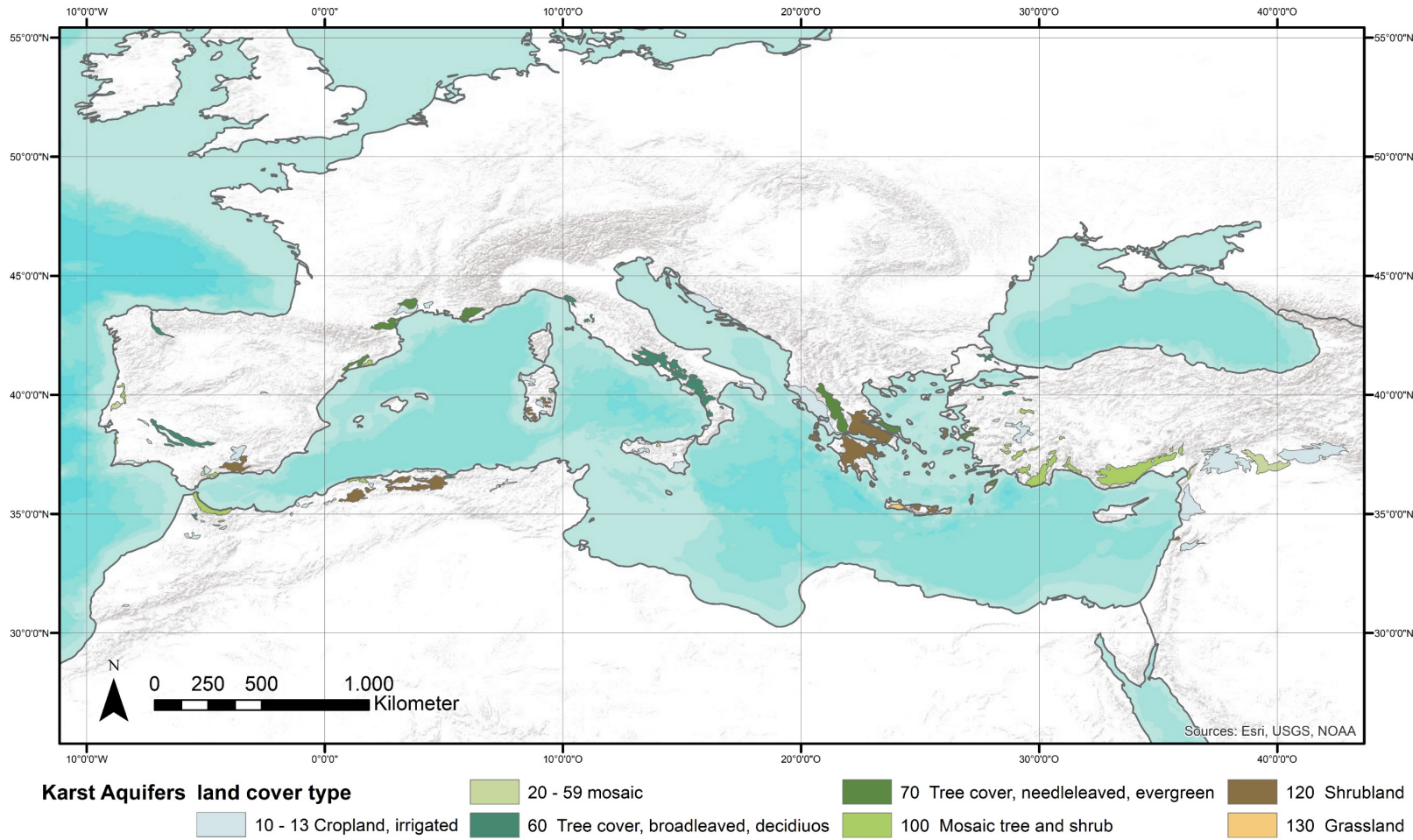


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P2 - Major land cover type [2018]



Classification parameters

P1 – Degree of karstification

P2 – Land cover

- ESA Land Cover CCI
- Land cover classes **grouped for generalization**
- Most dominant class selected according to **highest relative area**

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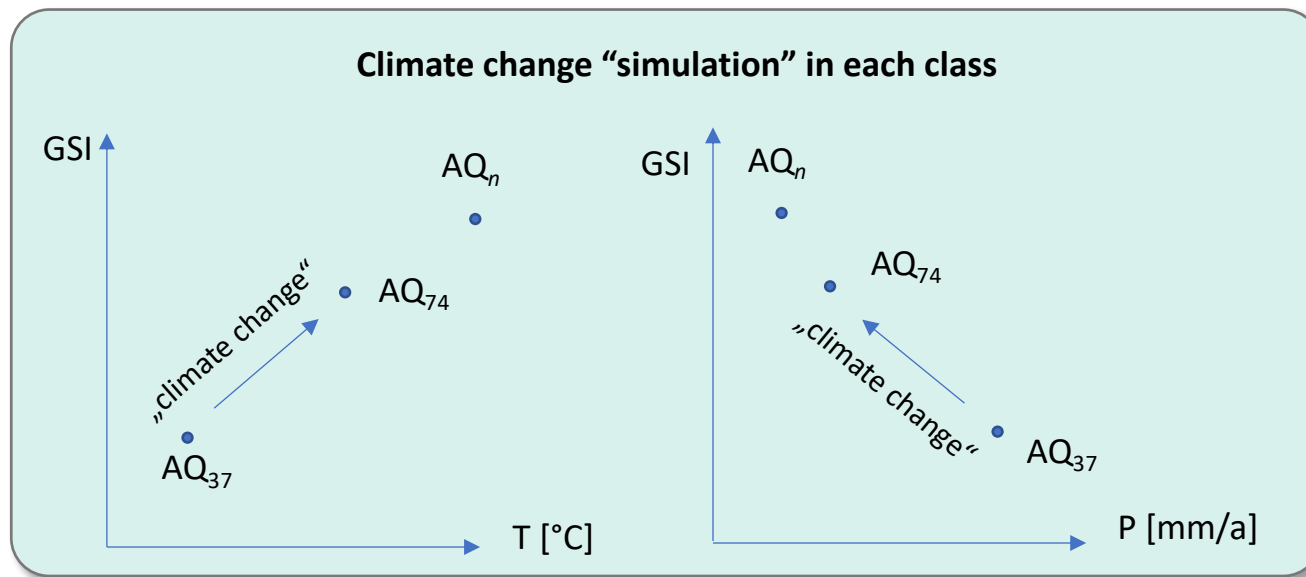


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Vulnerability assessment

Climate change “simulation”



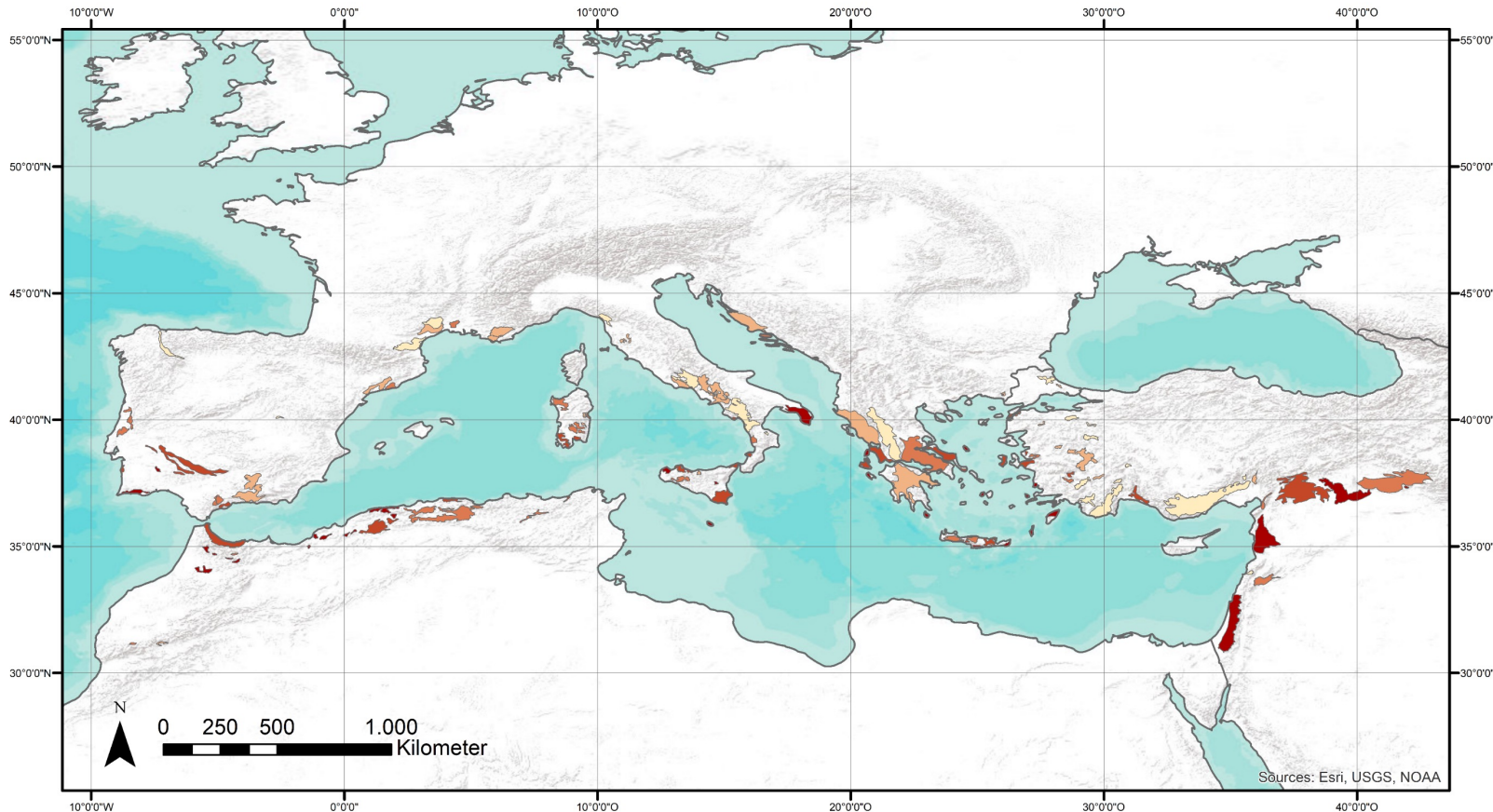
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F1 – Average annual temperature [2000-2019]

Factors
F1 – Temperature (T)
F2 – Precipitation (P)



Karst Aquifers Mean annual temperature [°C]

Temperature Range [°C]	Color
0,00 - 13,12	Light Yellow
13,13 - 14,57	Yellow
14,58 - 15,86	Orange
15,87 - 17,07	Dark Orange
17,08 - 19,46	Dark Red

- ECMWF (ERA5)
- 0.1° resolution (ca. 9 km)
- Monthly intervals
- Averaged for 2000-2019

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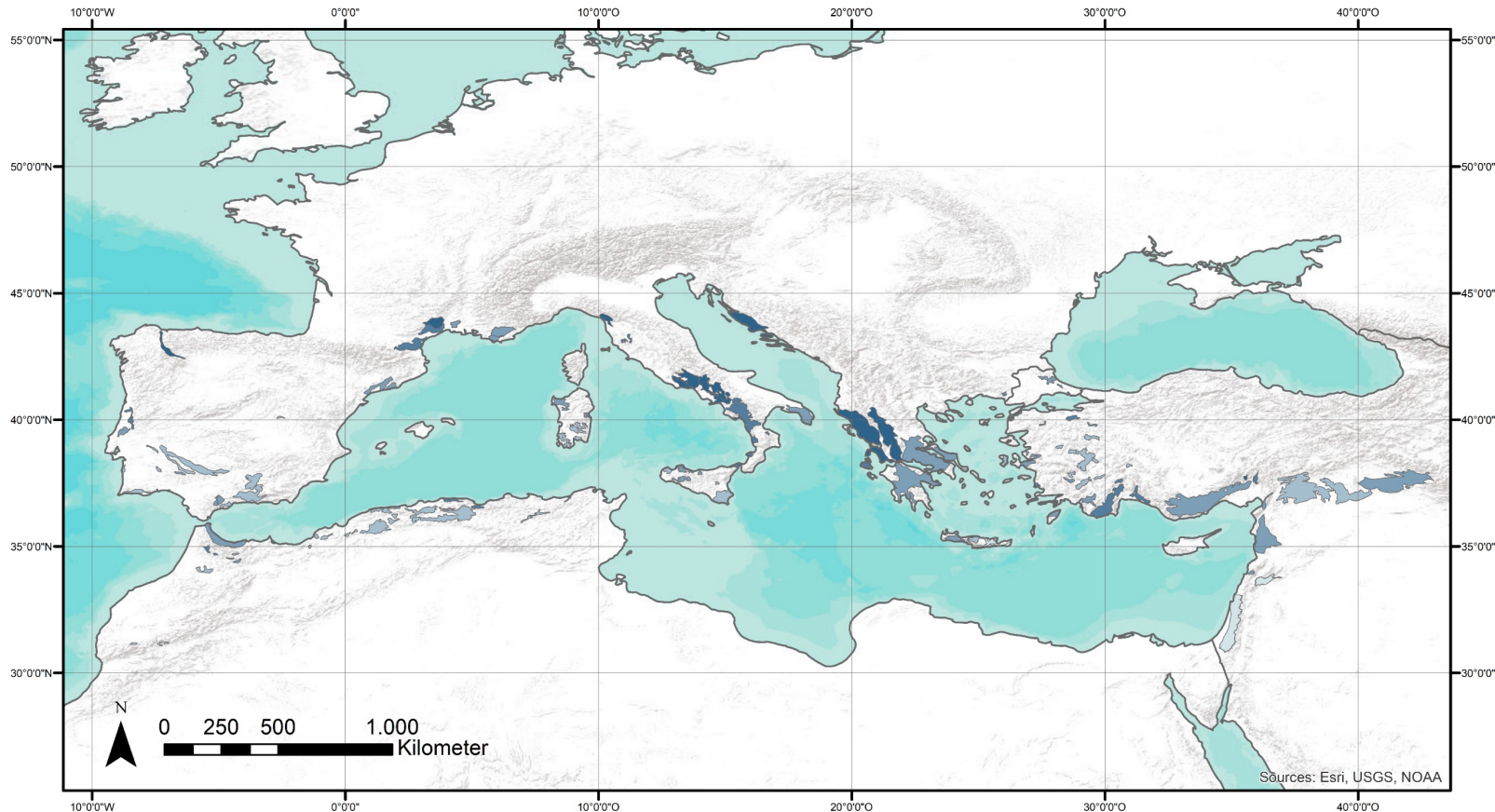
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F2 – Average sum of annual precipitation [2000-2019]

Factors
F1 – Temperature (T)
F2 – Precipitation (P)



Karst Aquifers Mean annual sum of precipitation [mm/year]

Precipitation Range [mm/year]	Color
0 - 358	Lightest Blue
359 - 602	Light Blue
603 - 785	Medium Blue
786 - 1050	Dark Blue
1051 - 1747	Darkest Blue

- ECMWF (ERA5)
- 0.1° resolution (ca. 9 km)
- Monthly intervals
- Averaged for 2000-2019

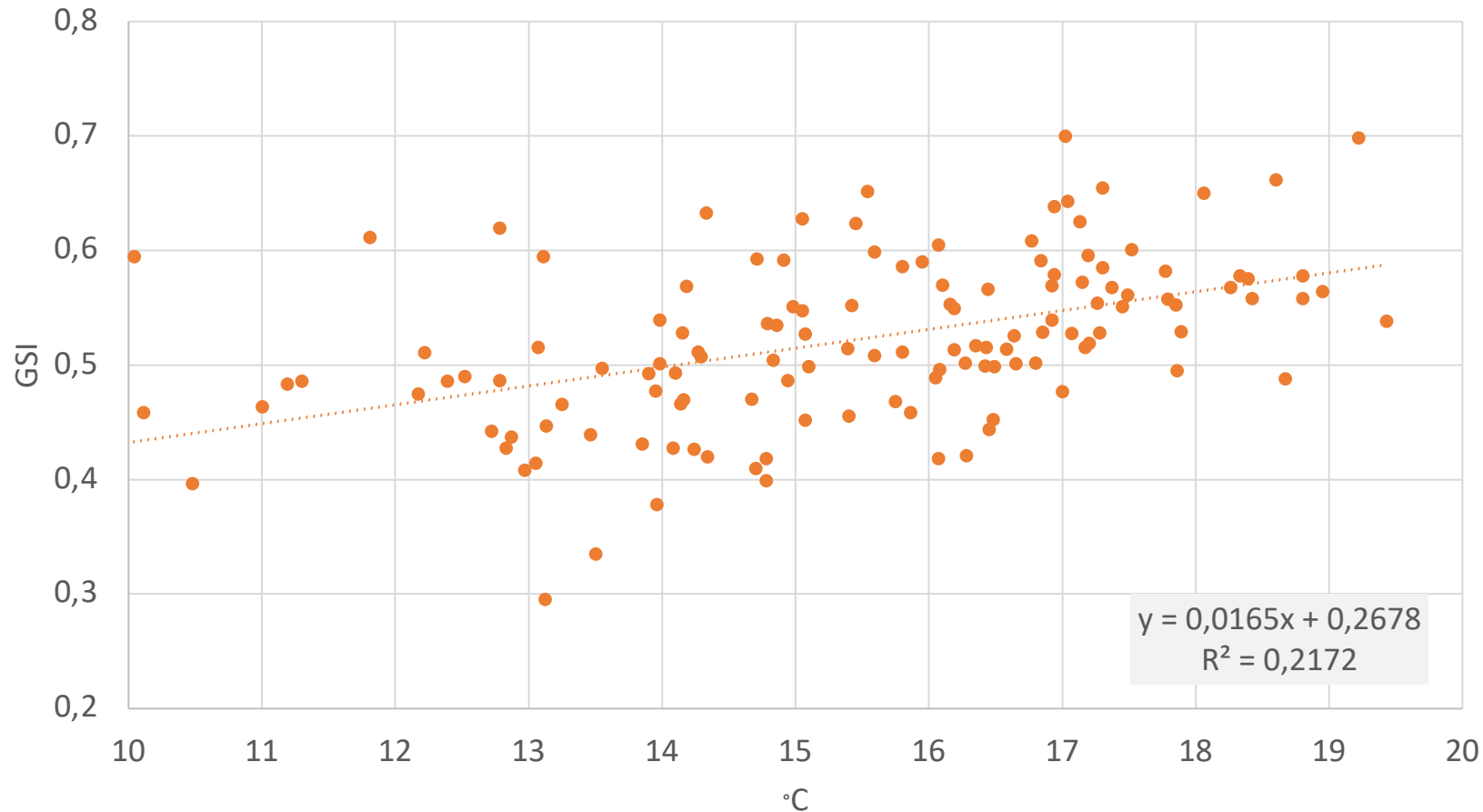
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Relationship between average annual temperature and GSI



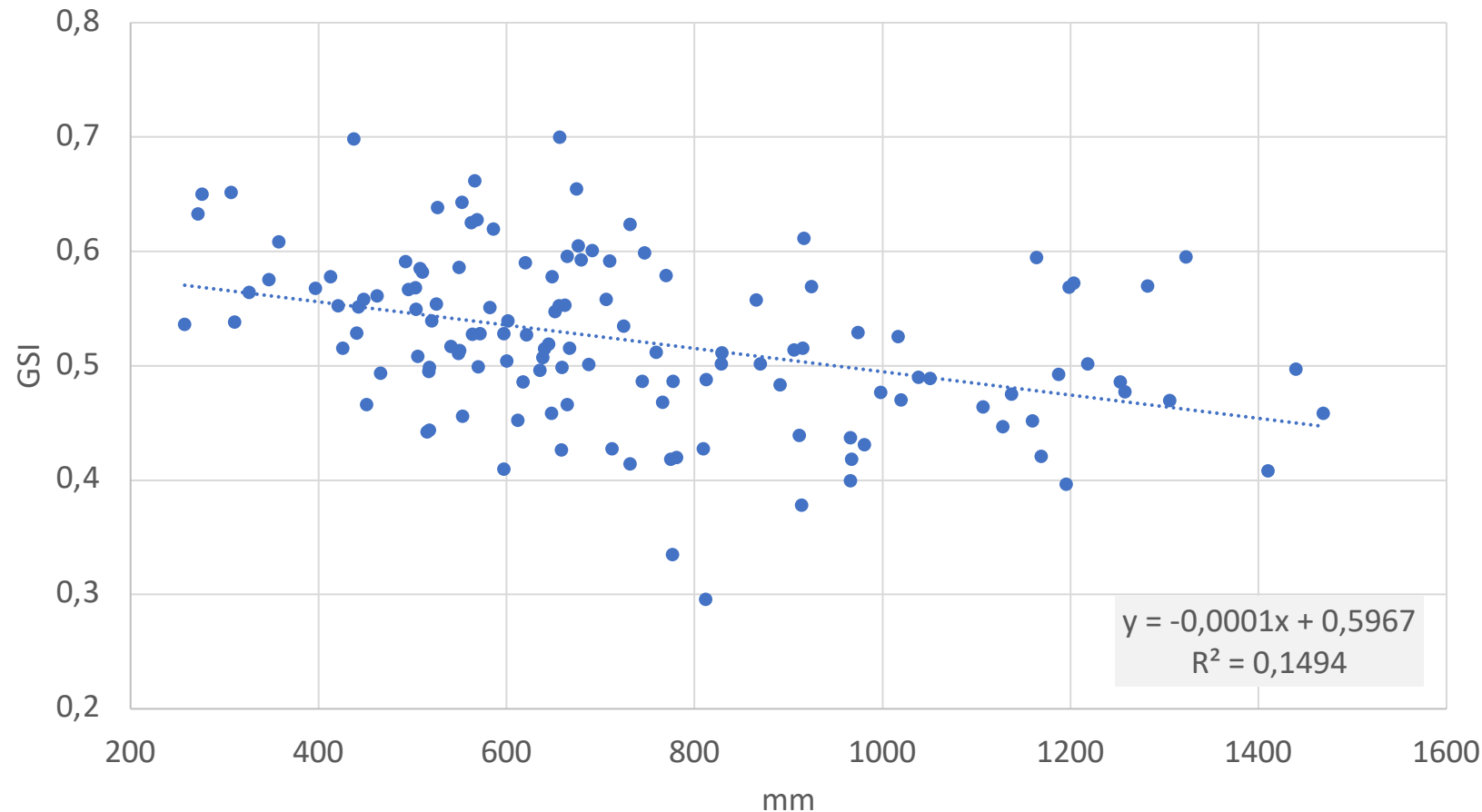
Factors

F1 – Temperature (T)

F2 – Precipitation (P)

- Low R^2 , but GSI shows a **positive trend** with increasing temperature
- R^2 should increase with aquifer grouping

Relationship between average sum of annual precipitation and GSI



Factors

F1 – Temperature (T)

F2 – Precipitation (P)

- Low R^2 , but GSI shows a **negative trend** with increasing precipitation
- R^2 should increase with aquifer grouping

Indicators

- I1 – Groundwater recharge
- I2 – Groundwater storage
- I3 – Groundwater abstractions
- I4 – Runoff coefficient
- I5 – Climatic water balance
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- I7 – Groundwater-dependent ecosystems

Normalization

Index composition

AQ	I1	I2	...	I7	GSI
1					
2					
...					
133					

Classification parameters

- P1 – Degree of karstification
- P2 – Land cover

Class 1

P1: x
P2: y

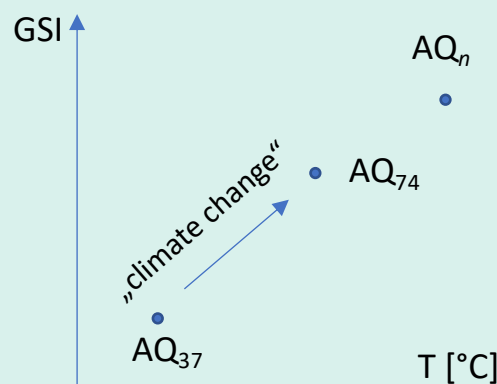
AQ₃₇
AQ₇₄
AQ_n

Class 2

AQ₅
AQ₉₆
AQ_k

Class ...

Climate change "simulation"



Factors

- F1 – Temperature (T)
- F2 – Precipitation (P)

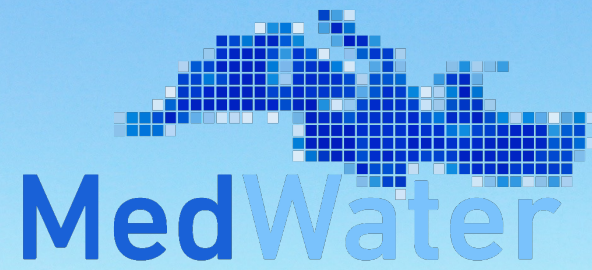
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