Determination of Hydrologically Homogeneous Mediterranean Catchments Based on Multivariate Analysis

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MOTIVATION

Mediterranean is one of the most sensitive regions to climatic variations and anthropogenic pressures.

- Socio-economically, the demographic evolution is causing critical water stress periods.
- Climatically, the trend towards warming and aridification of the Mediterranean is becoming a fact. Each of the last three decades, the surface of the Earth has been successively warmer than any previous decade since 1850 (IPCC, 2014).
- Hydrologically, the increase of water management challenges facing small administrative divisions require better management plans for medium scale catchments.

The objective is to identify similar Mediterranean catchments through the regionalization of hydrologic indices of a set of donor catchments based on a CCA with their physio-climatic indices.

The mapping of hydrologically homogeneous Mediterranean regions is one of the basic studies to be used by researchers, engineers, governments and international organizations which Mediterranean region form their target study areas. These results could help in catchment scale studies like PUB or regional scale studies like climate, landuse or demographic evolution impact prediction on Mediterranean hydrology.

STUDY AREA & DATABASE

HOW WOULD THE MEDITERRANEAN BOUNDARY BE DEFINED?

- Climatic boundary, defined according to Köppen's classification where a set of regions share similar temperature and precipitation characteristics known for their warm and dry summers and cold and humid winters (Köppen, 1936).
- Topographic boundary, defined by the set of catchments discharging into the Mediterranean Sea (Milano, 2013). This definition neglects some climatic regions like Portugal, part of Spain and give advantage to geographically adjacent regions like Egypt and Libya.
- Agricultural-bioclimatic boundary, defined by the set of regions sharing the same types of vegetation considered as indicators of the Mediterranean region such as olives (Moreno, 2014).
- Administrative boundary, defined by the set of countries adjacent to Mediterranean Sea but has a problematic definition independent of a natural base (Wainwright & Thornes, 2004). This boundary includes several climatic classes and cover larger areas then the topographical limits.

The **Topographic boundary** was adopted as a study area with a set of catchments mostly within the climatic boundary as shown in Figure 1.

HOW MANY CATCHMENTS ARE THERE?

The European Commission's Joint Research Centre (JRC) has done extensive and elaborate work on the delimitation of catchments in Europe and some adjacent countries as part of the "Catchment Characterization and Modelling" (CMM) project (De Jager & Vogt, 2010). HydroSHEDS catchments from World Wildlife Fund project was adopted for Middle East and Northern Africa, (Lehner & Grill, 2013).

According to these databases, there are **3682 catchments** that discharge into the Mediterranean from which **1270 range between 100 and 3000 km^2 forming 28%** of total area without the Nile.

WHERE DID ALL THIS DATA COME FROM?

Climatic data used for this study has two types,

- WorldClim-2, 1-km resolution climate surface data averaged for each catchment (Fick and Hijmans 2017)
- At sites data collected from several National and International database.

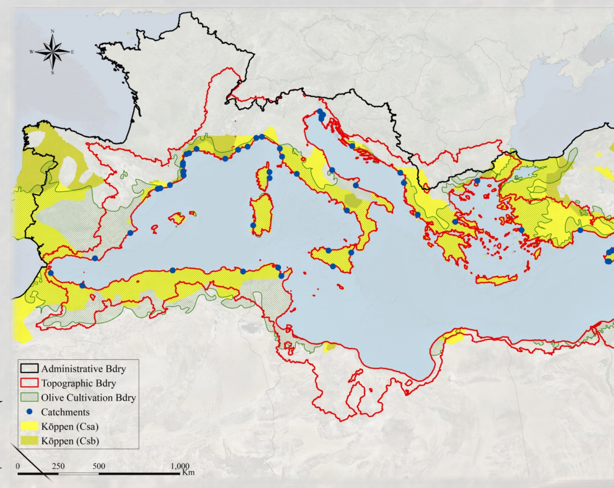


Figure 1. Mediterranean Boundary

Physiographic data were derived from global databases using GIS.

- Digital Elevation Map (SRTM)
- CLC 2012 map at a scale of 1:1 M from the EAE and GLC 2000 for North African catchments.
- Geologic and lithologic map at a scale of 1:5M (Ian Jackson, 2002; Hartmann, 2012)
- World Karstic Aquifer Map WHYMAP (Chen et al, 2017)
- Soil map at 1:1 M from ESDAC (Panagos & al, 2012)

Hydrologic set of 55 catchments covering 16 Mediterranean countries was collected from ACA, SAIH, HYDRO, ISPRA, ARSO, DHMZ, YPEKA, ONL, SIEREM, GRDC & MedHycos based on data availability at their outlet and respecting the following criteria

- Hydroclimatic timeseries at a daily timestep, climatic stations located within or at catchment vicinity
- Continuous daily data with at least uninterrupted 10 years mostly between 1950 and present;
- Limited influence of hydraulic structures and management projects.

CLIMATIC CLASSIFICATION

The objective of this section is to establish a fine climate classification of the Mediterranean that highlights climatic continuity and could evaluate change trends from one catchment to another. The proposed approach for both climatic and physiographic classification consists of

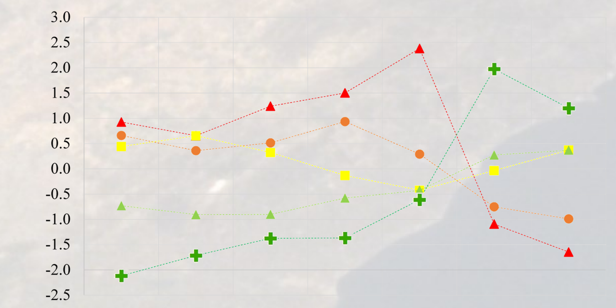
(a) PCA to reduce the number of climate indices and consider only the most contributory.

(b) K-Means Classification distributing into 5 catchment classes.

(c) Decision tree construction based on the distances to classes kernels to determine whether a place belongs to a Mediterranean climate or not and to which type it belongs to if so.

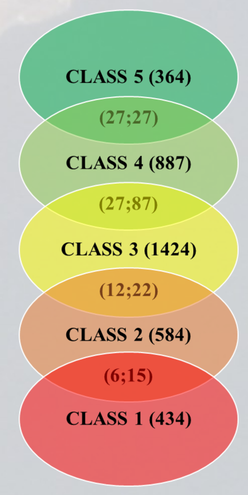
The PCA of 18 Climatic Indices showed that I_s, $P_{25\%}$, $S_{P1.5}$, S_{Tm}, I_{Arid}, S_{ETP} and $T_{25\%}$ were the most contributing for the first two components with 70% total variance explained.

The K-Means classification showed that a distribution into 5 classes coincided with a geographical distribution.



	I_s	$S_{P1.5}$	$P_{25\%}$	S_{Tm}	I_{Arid}	$T_{25\%}$	S_{ETP}
CLASS 1	0.93	0.65	1.24	1.50	2.38	-1.09	-1.65
CLASS 2	0.66	0.36	0.51	0.94	0.29	-0.75	-0.99
CLASS 3	0.44	0.66	0.32	-0.13	-0.42	-0.03	0.37
CLASS 4	-0.73	-0.91	-0.90	-0.58	-0.43	0.27	0.37
CLASS 5	-2.12	-1.71	-1.38	-1.37	-0.61	1.98	1.20

Table 1. Climatic Classes Kernels



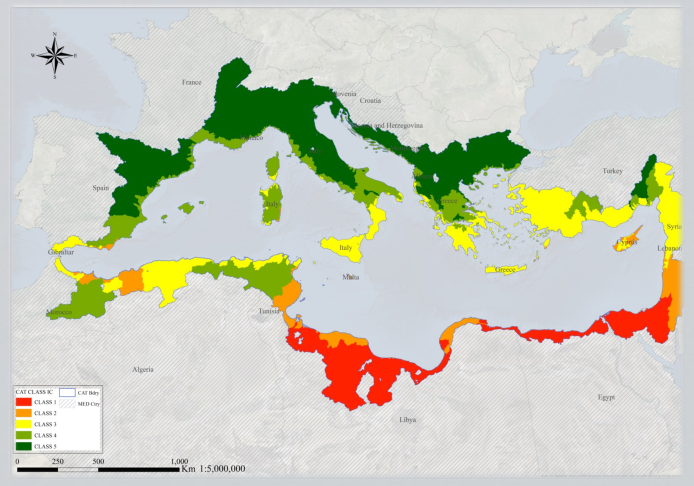


Figure 2. Climatic Classification

Climatic classification is a fuzzy classification with several arbitrary classes. The analysis of interclass connectivity showed that climate is continuous from one place to another, since some catchments can meet the membership criteria of adjacent classes.

The Mediterranean climatic characteristics and specifically precipitation seasonality, main contributor to the PCA climatic classification, plays a key role in the hydrological mechanisms of Mediterranean catchments and flow intermittence. The climatic classification carried out in this study will be analysed within the framework of a hydrological regionalization hereafter along with hydrological and physiographic characteristics.

PHYSIOGRAPHIC CLASSIFICATION

Physiographic Indices described catchments shapes, landform, geology & karst, Available Water Capacity, soil types, landuse, etc…. PCA/K-Means classification was then applied on the 1270 catchments dataset and reduced the number of PIs to 13 with A, Z_{Mean}, ZS_{Mean}, T_AWC, Leptosols and CLC2&3 subtypes as the most contributing in the first 5 components and 64% of total variance explained.

K-Means clustering into 10 classes showed a widespread diversity all over the Mediterranean with kernels' indices showing mixed distribution.

Average area A ranges between 180 and 838 km2 except for Class 9 representing wide cultivated catchment of 2146 km2. Average altitude Z_{Mean}, ZS_{Mean} and I_{Hypso} indicate morphological contribution with high landforms provoking orographic precipitations if exposed to cold fronts case of Class 4 with a snow cover lasting over 1 month/year and low landforms dissipate any possible precipitation and permit desertic influence in North Africa through low corridors case of Class 7, 8 and 10 preventing any vegetation except for sparse shrubs or herbaceous covers.

T_AWC conditions catchments natural landcover, accordingly, it was deduced that only shrubs and needle leaved trees grow in leptosols, low T_AWC and high seasonality, case of Class 6 dominant in East Mediterranean region. Highly cultivated and managed catchments are dominant in North Mediterranean countries and Italy where low lands and wide fields are suitable for agricultural activities Class 1 and 9. Mixed leaved tree forests dominant in North West Mediterranean Class 5, while broadleaved trees preferred North Eastern Mediterranean where high T_AWC and low seasonality reigns case of Class 2.

KNOW YOUR CATCHMENT? CLASSIFY IT!!!

CLASS	NO	REGION	DESCRIPTION	A (km^2)	ZMean (m)	ZSMean (m)	T_AWC mm)	LpSols (%)	BA (%)	CMA (%)	SC_COD (%)	SHC (%)	TC_BCD (%)
1	304	North West	Small, Highly Cultivated and Managed at 70%	286	184	-	50.8	11%	1%	71%	7%	1%	2%
2	62	South West & Italy	Broadleaved Tree Covered at 60%	415	497	224	51.3	12%	0%	10%	7%	0%	60%
3	351	Mediterranean	No specific overwhelming influence	221	289	-	49.6	13%	1%	12%	34%	3%	2%
4	105	North and East	High altitude with Snow and Karst influence	662	871	1462	38.6	51%	1%	16%	30%	4%	8%
5	88	North West	Mixed leaf Tree Covered 26 %	266	398	-	50.8	17%	0%	19%	8%	2%	12%
6	190	East & Libya	Shrub Covered at 50 %, low T_AWC and Leptosols at 78%	181	341	-	27.4	79%	0%	13%	52%	1%	1%
7	10	Sinai	Desertic	730	107	-	0.8	0%	87%	0%	0%	8%	0%
8	29	Egypt, Libya	Desertic	838	124	-	51.6	16%	70%	0%	0%	25%	0%
9	49	Mediterranean	Wide and Highly Cultivated & Managed at 50% with Snow Influence	2146	411	428	50.3	26%	0%	49%	11%	4%	12%
10	75	Egypt Libya Tunisia	Semi Desertic, Sparse Herbaceous or Shrub Covered at 87%	537	133	-	49.5	19%	5%	1%	3%	87%	0%

Table 2. Physiographic Classes Kernels

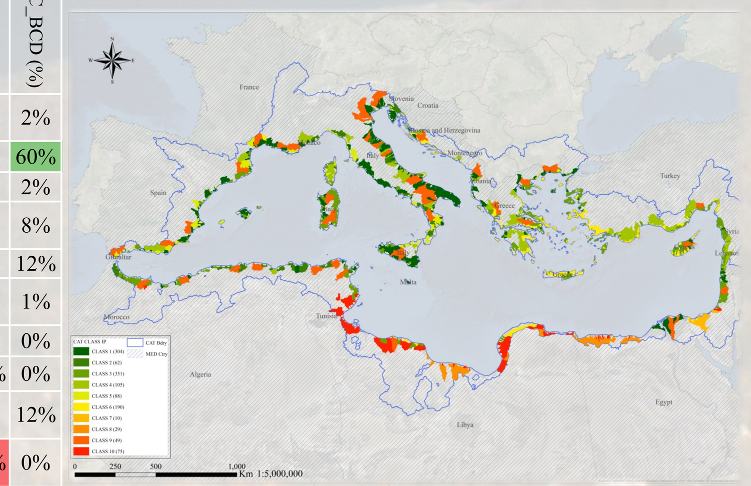


Figure 3. Physiographic Classification

HYDROLOGIC HOMOGENEITY

A Canonical Correlation Analysis was performed between the most contributing PCIs obtained previously and 90-days High-flow & Low-flows magnitude and frequency indices to determine hydrologically homogeneous Mediterranean catchments. CCA results for both HF and LF, illustrated in correlation circles (figure 4), highlight a relationship between the two groups of indices with a correlation of 0.83 for the first canonical variable and zero value for Wilks significance test. The most significant P-CIs were found to be A, $T_{25\%}$, MAP and T_AWC.

Another valuable illustration is the sample dataset representation on the canonical space of the P-CIs and HIs based on the regression equations from raw coefficients shown in figure 5. Scatter diagrams didn't show any organized distribution at first but once coloured according to classes, homogeneous clusters were well identified with limited overlapping between class.

The similarity of catchments distribution between diagrams is observable, where catchments of same class are evenly positioned vis-a-vis other catchments in both physio-climatic and hydrological canonical variables charts.

	HIGH FLOWS				LOW FLOWS			
Canonical Variable	Eigenvalue	Pct. %	Canon Cor.	Sig. of F	Eigenvalue	Pct. %	Canon Cor.	Sig. of F
1	2.17	88.21	0.83	0.00	2.43	92.12	0.84	0.00
2	0.29	11.79	0.47	0.01	0.21	7.9	0.41	0.02
	Correlation		Coefficients		Correlation		Coefficients	
PCIs	1	2	1	2	1	2	1	2
T_AWC	0.23	-0.74	-0.14	-0.80	0.00	-0.73	0.10	-0.75
A	-0.76	0.38	0.77	0.29	0.58	0.15	-0.55	0.52
MAP	-0.75	-0.44	0.75	-0.42	0.44	-0.83	-0.46	-0.21
$T_{25\%}$	-0.83	-0.32	0.83	0.06	0.28	0.49	-0.26	-0.49
HIs	1	2	1	2	1	2	1	2
DH_5/DL_5	-0.95	0.31	0.91	0.42	0.78	0.69	-0.87	0.57
FH_1/FL_1	-0.55	-0.83	0.66	-0.75	0.44	-0.94	-0.32	-1.00

Table 3. CCA Results

Figure 4. Correlation Circles

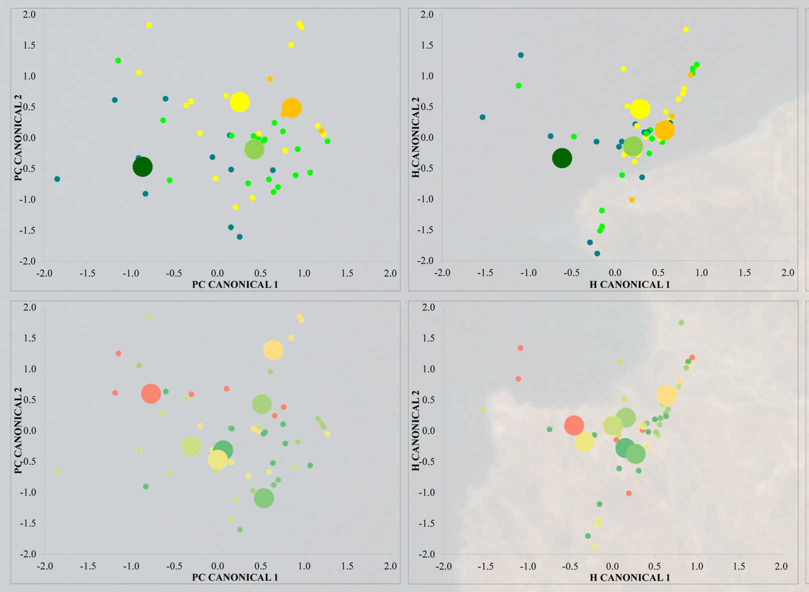


Figure 5. High Flows Scatter Diagrams

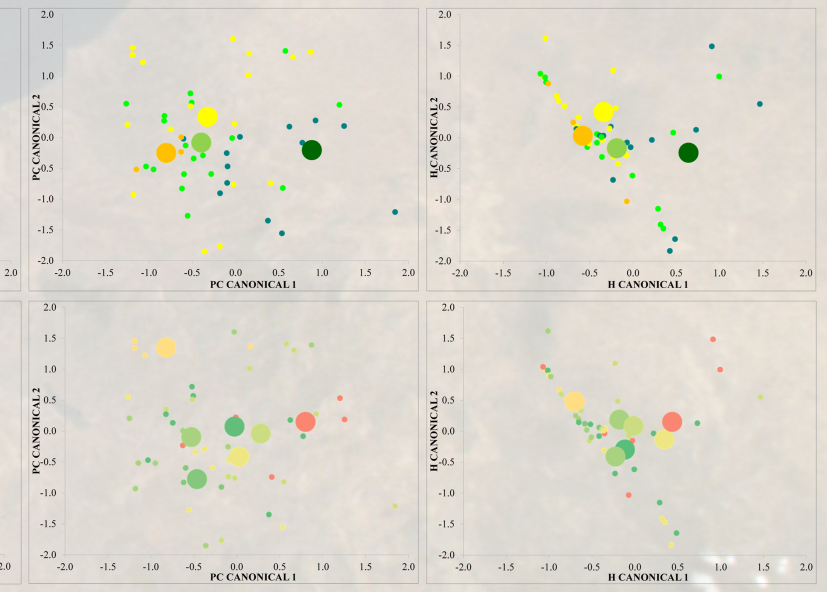


Figure 6. Low Flows Scatter Diagrams

DISCUSSION

A hydrological database was developed for the Mediterranean region including climatic, physiographic and hydrologic data with the focus on 1270 catchments ranging between 100 and 3000 km^2 and outflowing towards Mediterranean Sea. The main challenge consisted of the spatial spread and the work on a very wide and diversified area.

Relying on multivariate analysis methods, PCA and K-Means were performed and catchments were clustered into 5 climatic and 10 physiographic classes. CCA helped identifying hydrological homogeneity out from physio-climatic indices. The illustration of canonical diagrams according to their climatic and physiographic clusters helped identifying the homogeneous clusters in the canonical spaces. The climatic indices might have forced some spatial clustering due to their uniform distribution despite that physiographic indices are very variable across the Mediterranean.

This homogeneity will serve for regionalizing flow indices and water balance metrics across the Mediterranean, emphasizing the assumption that if catchments attributes are similar, one would expect a hydrologic similarity. This could be validated by also applying CCA and multiple regression separately for each of the physiographic classes.

Mediterranean hydrological sensitivity to climatic and anthropogenic variations could now be tested for

- Socio-economic trends of cultivation and demographic change
- Climate change trends
- Water management optimisation
- Discovery of similar or exceptional catchments

Photography encouraged