



HAL
open science

Hydrological response characteristics of Mediterranean catchments: a review

Mohammed Merheb, Roger Moussa, Chadi Abdallah, François Colin, Charles Perrin, Nicolas Baghdadi

► **To cite this version:**

Mohammed Merheb, Roger Moussa, Chadi Abdallah, François Colin, Charles Perrin, et al.. Hydrological response characteristics of Mediterranean catchments: a review. *Hydrological Sciences Journal*, 2016, 61 (14), pp.2520-2539. hal-01579161

HAL Id: hal-01579161

<https://hal.science/hal-01579161>

Submitted on 30 Aug 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Hydrological of Mediterranean catchments: a review**

2 Mohammad Merheb ^{1,2}, Roger Moussa ³, Chadi Abdallah ^{2,*}, François Colin ⁴, Charles Perrin ⁵
3 and Nicolas Baghdadi ¹

4 ¹ IRSTEA, UMR TETIS, 500 rue J.F. Breton, 34093 Montpellier cedex 5, France.

5 ² National Council for Scientific Research, Remote Sensing Center, PO Box 11-8281, Beirut,
6 Lebanon.

7 ³ INRA, UMR LISAH, 34060 Montpellier Cedex 1, France

8 ⁴ Montpellier SupAgro, UMR LISAH, 34060 Montpellier Cedex 1, France

9 ⁵ IRSTEA, Hydrosystems and Bioprocesses Research Unit (HBAN), 1, rue Pierre-Gilles de
10 Gennes, CS 10030, 92761 Antony Cedex, France

11 *Corresponding author: chadi@cnr.fr

12

13 **Abstract** This work reviews 140 hydrological studies conducted in the Mediterranean
14 region. It identifies key characteristics of the hydrological responses of Mediterranean
15 catchments at various time scales and compares different methods and modelling
16 approaches used for individual-catchment studies. The study area is divided into the
17 northwestern (NWM), eastern (EM) and southern (SM) Mediterranean. The analysis
18 indicates regional discrepancies in which the NWM shows the most extreme rainfall
19 regime. A tendency for reduced water resources driven by both anthropogenic and
20 climatic pressures and a more extreme rainfall regime are also noticeable. Catchments
21 show very heterogeneous responses over time and space, resulting in limitations in
22 hydrological modelling and large uncertainties in predictions. However, few models have
23 been developed to address these issues. Additional studies are necessary to improve the
24 knowledge of Mediterranean hydrological features and to account for regional specificities.

25 **Keywords** hydrology; Mediterranean catchment; annual water balance; rainfall-runoff;
26 floods; droughts; modelling

27

28 **Caractéristiques de la réponse hydrologique des bassins versants méditerranéens**
29 **à pas de temps différents**

30 **Résumé** Ce travail examine 140 études hydrologiques menées dans la région
31 méditerranéenne. Il identifie les principales caractéristiques des réponses hydrologiques
32 des bassins versants méditerranéens à différentes échelles de temps et compare
33 également les méthodes et les approches de modélisation utilisées pour les études de
34 bassins versants individuels. La zone d'étude est divisée en nord-ouest (NWM), est (EM) et
35 sud (SM) de la Méditerranée. L'analyse indique les disparités régionales, la zone NWM
36 montrant le régime de précipitations le plus extrême. Une tendance à la réduction des
37 ressources en eau entraînées par les pressions anthropiques et climatiques et un régime
38 de précipitations plus extrêmes sont également perceptibles. Les bassins montrent des
39 réponses très hétérogènes dans le temps et l'espace, ce qui entraîne des limitations dans
40 la modélisation hydrologique et de grandes incertitudes dans les prévisions. Cependant,
41 peu de modèles ont été développés pour répondre à ces questions. Des études
42 supplémentaires sont nécessaires pour améliorer la connaissance des caractéristiques
43 hydrologiques de la Méditerranée et pour tenir compte des spécificités régionales.

44 **Mots-clés** hydrologie; bassin versant Méditerranéen ; bilan annuel; pluie-débit; crues;
45 sécheresse; modélisation

46

47 1 INTRODUCTION

48

49 1.1 The Mediterranean as a focus of research

50 The Mediterranean climate is characterized by high inter-annual variability in precipitation,
51 seasonal rainfall patterns, summer drought, and intense rainfall. Because of the characteristics
52 of the climate, Mediterranean areas face water availability problems (Morán-Tejeda et al. 2010).
53 In the last 20 years, many countries of the Mediterranean Basin have witnessed multi-year
54 drought periods (FAO 2006). Many studies (e.g., Parry et al. 2000, Milly et al. 2005, IPCC 2014)
55 predict that water resources will even become scarcer due to climate change and the increasing
56 demands on water by various economic sectors. Moreover, the irregular spatial distribution of
57 precipitation leads to large differences in water availability across territories (Morán-Tejeda et al.
58 2010). Furthermore, high-intensity but short rainfall events cause intense flooding (e.g.,
59 Vincendon et al. 2010, Moussa and Chahinian 2009 [France], Koutroulis and Tsanis 2010
60 [Greece], Brath et al. 2004 [Italy], Rozalis et al. 2010 [Israel]). Mediterranean catchments are
61 therefore characterized by three main features: limited water resources, dry summers and high-
62 intensity rainfall events that generate flash floods.

63 Many attempts have been made to provide an overview on the hydrology of the
64 Mediterranean region. Reviews have already detailed specific aspects of the hydrology of
65 Mediterranean catchments, such as rainfall interception (Llorens and Domingo 2007), the impact
66 of the Mediterranean forest on catchment responses (Cosandey et al. 2005), the dryland
67 hydrology (Cudennec et al. 2007), the impact of human activities on fluvial systems (Hooke,
68 2006), erosion processes (Shakesby et al. 2011; Garcia-Ruiz et al. 2013) and the hydrology of
69 mountainous catchments (Latron et al. 2009). Other studies synthesized the results of climate
70 change impact studies in the region, such as in Alpert et al. (2008) and Philandras et al. (2011)
71 and the impact of global changes on Mediterranean water resources (Garcia-Ruiz et al. 2011).
72 The Mediterranean region has been also studied as part of larger geographical areas (Marchi et
73 al. 2010, Cortesi et al. 2012, Salinas et al. 2014a, b).

74 Moreover, many international projects were conducted on the Mediterranean region to study
75 the hydrological cycle generally. Among others, the FRIEND Alpine and Mediterranean
76 Hydrology (AMHY) project was launched in 1991 as part of the UNESCO International
77 Hydrological Program (Servat and Demuth 2006, Gustard and Cole 2002). The project involves
78 19 countries from southern Europe and the Mediterranean Basin. Since 2007, the HyMeX
79 project (www.hymex.org) has been promoting a multidisciplinary approach to analyse all
80 components of the Mediterranean water cycle (see Llasat et al. 2013 for more details). This
81 project focuses on physical aspects, the socio-economic impacts of extreme events, and the
82 adaptation capacity to changes. Another example of current initiatives in the Mediterranean is
83 the MEDEX project (<http://medex.aemet.uib.es>), which focuses on meteorological scenarios with
84 high hydrological impacts.

85

86 1.2 Objectives of the review

87 This paper aims to present an overview of the hydrological response characteristics of
88 Mediterranean catchments and to identify the main objectives and modelling approaches of
89 studies conducted in the region. It focuses on studies related to annual water balance, flood
90 events and droughts.

91 The methodology consists of analysing recent individual catchments studies that have been
92 published over the last two decades. It starts by defining the study area, followed by the
93 collected database representation. The hydrological response characteristics and the methods
94 used for a general discussion of the main outcome of this review is provided answering the
95 following questions:

- 96 - Can we identify regional hydrological tendencies in the Mediterranean region?
- 97 - What is required to model Mediterranean catchments?

98 - What are the main challenges for future research in the Mediterranean?
 99

100 Note that this analysis does not specifically review the studies on ungauged catchments for
 101 sake of brevity. The reader may refer to the recent general reviews on prediction on ungauged
 102 basins proposed by Blöschl et al. (2013) or Hrachowitz et al. (2013), which include studies on
 103 the Mediterranean basin.
 104

105 **2 THE MEDITERRANEAN REGION**

107 **2.1 Boundary of the Mediterranean region**

108 The Mediterranean climate is not confined to the Mediterranean Sea region. In fact, much of
 109 California, parts of Western and South Australia, southwestern South Africa, and parts of central
 110 coastal Chile have Mediterranean climates. According to the Köppen (1936) classification,
 111 Mediterranean climates are characterized as subtropical climates with dry summers.
 112 Nevertheless, this paper was intentionally limited to the Mediterranean basin because this region
 113 shares more than climatic features. The basin has homogenous geological and physiographic
 114 settings (Wainwright and Thornes 2004), and it forms a geographical unit that faces the
 115 challenges of large socio-economic exchanges and enormous anthropogenic pressure.

116 There is no worldwide consensus on the definition or boundaries of the Mediterranean region
 117 (Hooke 2006, Shakesby 2011). Several characteristics are commonly used to define the
 118 Mediterranean region (Fig. 1a):

119 -The boundaries of the basins that drain into the Mediterranean Sea (e.g., Milano et al.
 120 2012): such a definition omits regions that share similar climatic and physiographic
 121 characteristics, such as Portugal, and adds regions that might not be considered
 122 Mediterranean from a climatic and hydrological point of view, such as parts of Libya and
 123 Egypt.

124 -The climate regime: several definitions and classifications denote boundaries that are not
 125 completely consistent (e.g., Köppen 1936, Thornthwaite 1948). For example, the Köppen
 126 (1936) classification, which is commonly used, classifies regions that are usually
 127 considered Mediterranean, such as southeastern and central Spain, as cold semi-arid
 128 regions; it also uncharacteristically extends the Mediterranean to areas in the Middle East.

129 -The vegetation types (e.g., Quezel 1985): such definitions are usually called bio-climatic
 130 because vegetation reflects the climatic conditions. Nevertheless, such definitions inherit
 131 some of the problems of the climatic definition. The distribution of many species
 132 considered as indicators of the Mediterranean (e.g., olive trees) are highly related to
 133 human activities.

134 -The administrative divisions of the countries surrounding the Mediterranean Sea: these
 135 definitions are also problematic because they often have no natural basis (Wainwright and
 136 Thornes 2004).

137 In this work, the “Mediterranean” is considered as any catchment falling within one of the
 138 above-mentioned boundaries and defined by authors as Mediterranean but excluding the
 139 administrative boundaries from this assumption Figure 1 (a, b, & c)
 140

141 **2.2 Physical characteristics of the Mediterranean region**

142 The Mediterranean region has a total area of approximately 1,100,000 km² (Grove and Rackham
 143 2001). Mountain ranges surround the Mediterranean Sea (Fig. 1a): the Pyrenees in south-
 144 western Europe, the Alps in southern France and north-western Italy, the Apennines along the
 145 Italian coast, the Dinaric Alps along the coast of the Adriatic Sea, the mountains of Greece, the
 146 Taurus Mountains in Turkey, Mount Lebanon in the eastern Mediterranean and the Atlas
 147 Mountains in northern Africa. The proximity of the mountain ranges to the sea explains why a
 148 majority of the Mediterranean catchments are medium-sized and sloping. Lower hills, such as

149 the Cevennes region in France, and plains also exist along the coasts and in some interior
150 regions; thus, the landscape is quite heterogeneous.

151 Most of the underlying geology comprises limestone with sandstone, sedimentary deposits
152 and metamorphic granites (Di Castri 1981). The prevalence of limestone rocks means that
153 karstic catchments are very common in the region.

154 Vegetation is mainly dominated by evergreen trees and shrubs (the famous Mediterranean
155 “Maquia” or “Garrigue”). In mountainous areas with wetter conditions, several deciduous tree
156 species prevail. Conversely, the driest areas are dominated by steppe (Bonada and Resh 2013).
157 However, Mediterranean catchments exhibit a particular relief-driven organization in the
158 distribution of land types. Hence, forests grow directly under the rocky summits of Mediterranean
159 mountains; agricultural terraces exist downslope. Further down, the Mediterranean Garrigue is
160 present. Finally, agriculture dominates the coastal plains. This pattern is partly attributed to past
161 human activities, but it is now disturbed by the intense urbanization in Mediterranean coastal
162 plains and the abandonment of the agricultural terraces for Mediterranean forests, particularly in
163 Europe (e.g., Gallart and Llorens 2004, Lana-Renault et al. 2007, Ceballos-Barbancho et al.
164 2008, Moran-Tejeda et al. 2010). These changes certainly have an impact on the hydrological
165 responses of Mediterranean catchments.

166 **3 REVIEW EXTENT AND DATABASE**

167 **3.1 Review information**

168 A total of 140 studies on the Mediterranean region published over the last two decades were
169 analysed.

170 To study regional tendencies in the Mediterranean zone, the study region was divided into:

- 171 - the North-Western Mediterranean (NWM), encompassing Mediterranean Albania, Croatia,
172 France, Italy, Montenegro, Portugal, Slovenia and Spain, with 84 analysed studies
- 173 - the Eastern Mediterranean (EM), encompassing Cyprus, Egypt, Greece, Israel, Lebanon,
174 Palestinian territories, Syria and Turkey, (42 studies) ;
- 175 - and the Southern Mediterranean (SM), encompassing Algeria, Egypt, Libya, Morocco and
176 Tunisia, (14 studies).

177 These studies were divided into three groups focusing on the annual water balance (58
178 studies), flood events (49 studies) and droughts (33 studies).

179 For each study, the key information that was systematically collected and analysed includes:

- 180 (i) Basin location (reference and coordinates)
- 181 (ii) Study objectives
- 182 (iii) Basin characteristics, such as the area, mean elevation, mean slope, land use, soil
183 classes, geology and the possible presence of karst;
- 184 (iv) Hydro-meteorological data characteristics, such as the rainfall-runoff measurement
185 period, the time step of the measurements, the mean annual precipitation, the reference
186 evapotranspiration, the mean annual runoff, the runoff coefficient and the snow
187 contribution; for event-based studies, detailed information on catchment responses
188 (rainfall, runoff, peak discharge) for each event was also extracted when available;
- 189 (v) Mode characteristics, such as the model name and original reference, the simulated
190 hydrological processes, the spatial resolution (lumped, semi-distributed or distributed),
191 the time step and the model evaluation criteria.

192 **3.2 Annual water balance studies**

193 The reviewed studies (Fig. 1b) with information about the components of the water balance
194 equation (40 out of 58) include approximately 139 Mediterranean catchments: 70 catchments in
195 the NWM, 43 in the EM and 26 in the SM (Table 1). The majority (27 out of 40) are studies on
196 individual catchments, while only 13 compare 2 or more catchments. The catchment areas range
197 from 0.35 km² to 16,000 km², with a median of 286 km²; 75% of the catchment areas are below
198 640 km². Eighteen catchments are karstic, having hydrogeological boundaries that do not
199 necessarily match the topographic boundaries. Snow represents a significant portion of the
200 precipitation for 21 catchments. Thus, it is an essential component in those water balances.

201 **3.3 Rainfall-Runoff event-based studies**

202 Among the forty nine flood studies, twenty one includes useful information for quantitative on 136
203 catchments and 191 events (Fig. 1c and Table 2).

204 The analysis was only conducted on hydrological studies at the catchment scale. Hence,
205 studies focusing on the hydraulic aspects of the catchment response at the reach scale were
206 excluded. These studies are not limited to extreme flood events (such as Marchi et al. 2010 and
207 Tarolli et al. 2012) but comprise any runoff-generating rainfall event study that contains
208 substantial event-related information. However, this information is not equally available to all.
209 Details on each study and event-related data are presented in Table 6. Here, one must clarify
210 that a single event can affect more than one catchment and that more than one event could be
211 reported for the same catchment. Among these studies, 13 were conducted in NWM, 5 in EM,
212 and 3 in SM. One study (Tarolli et al. 2012) was an analysis of flash flood regimes in the
213 northwestern Mediterranean (France, Spain, Italy) and the southeastern Mediterranean region
214 (Israel). Moreover, 69 catchments out of a total of 136 are located in the NWM. The rest of the
215 catchments are divided between the EM (22) and SM (45). The catchments areas range from
216 3.83 km² for the Valsecure catchment (a headwater catchment of the Gardon d'Anduze,
217 Southern France; Trambly et al. 2010) to 16,330 km² for the Negada catchment at Lassoud in
218 Tunisia (Abida and Ellouze 2008).

220 **3.4 Drought studies**

221 Drought definitions vary according to the variables used to describe the drought (Mishra and
222 Singh 2010, 2011). One can define three major types of droughts: meteorological or climatic
223 drought (WMO 1986); agro-meteorological or agricultural drought (FAO 1983); and hydrological
224 drought (Gumbel 1963, Palmer 1965).

225 Socioeconomic impacts of drought are defined in terms of losses from an average or
226 expected return and are measured by both social and economic indicators (Mishra and Singh
227 2010). All these droughts aspects are interrelated and are measured in terms of their intensities,
228 durations and frequencies. In this work, we cite recent studies in the Mediterranean region that
229 characterize droughts, and we discuss the main objectives and methods used (Fig. 1d).

230 Droughts are usually studied in a regional context due to their large-scale characteristics
231 (Mishra and Singh 2009). Here, thirty-one drought-related studies published in the last decade in
232 the Mediterranean region are presented (Table 3). Eighteen studies are conducted at the
233 catchment scale, while the others have a greater spatial extension, generally an entire country or
234 geographical region. Approximately half of the studies are conducted in the NWM, with a
235 majority (10 articles) in the Iberian Peninsula (mostly Spain), 11 studies were conducted in the
236 EM and only 4 were conducted in the SM region. Drought studies are usually conducted at long
237 time scales (several decades).

238 4 HYDROLOGICAL RESPONSE CHARACTERISTICS

239 In this section we analyse the hydrological response characteristics of the studied Mediterranean
240 catchments based on the collected data described above, in terms of annual water balance,
241 rainfall-runoff events and drought.

242 4.1 Annual water balance studies

243 The mean annual precipitation (MAP), reference evapotranspiration (ET₀), and mean annual
244 runoff (MAQ) are highly variable across the three Mediterranean sub-regions. The median
245 values show decreasing MAP, MAQ, MAQ/MAP and an increasing ET₀ from NWM to EM and
246 SM (Table 4).

247 The relationship between MAQ and MAP is plotted where each point represents a studied
248 catchment (Figure 2). The results show a significant correlation ($R^2=0.745$) between MAQ and
249 MAP reported in all studies. Most low-yielding catchments with MAP values lower than 400 mm
250 are located in the SM. For a larger MAP, the graph shows important scattering. The graph also
251 shows that even for large MAP values (800 - 900 mm), the runoff yield can be very low
252 (approximately 30 mm); this is true for catchments in Crete (Koutroulis et al. 2013). Thus, the
253 catchment yield is highly variable. The trend for the EM and the NWM catchments is quite
254 similar, with an intercept close to 500-550 mm and comparable slopes. The trend is different for
255 the SM catchments with an intercept close to 250-300 mm and a lower slope. For a few
256 catchments (especially in NWM and EM), the MAQ is larger than the MAP. Here, two factors
257 may explain this phenomenon: the contribution of snow amounts in mountainous catchments
258 that is underestimated and the presence of karsts that may greatly increase the effective
259 catchment area.

260 A similar analysis (not shown) that accounted for catchment area and elevation was
261 undertaken. Catchment area does not appear to influence catchment response, expressed as
262 the water depth (mm per time step). The impact of the elevation, however, could not be
263 neglected because both the MAP and catchment runoff increased with elevation.

264 To investigate the climatic features of Mediterranean catchments, a Budyko-type plot (Budyko
265 1974, Andréassian and Perrin 2012) (Fig. 3) shows the mean annual runoff coefficient
266 MAQ/MAP as a function of the aridity index $AI = ET_0/MAP$. When $ET_0/MAP < 1$, wet conditions
267 prevail. When $ET_0/MAP > 1$, dry climatic conditions prevail. The lines $MAQ/MAP = 1$ and
268 $MAP = MAQ + ET_0$ represent the water and energy limits. Catchments are expected to fall within
269 these limits for a closed water balance. Otherwise, the catchment is either gaining (catchment
270 with $MAQ/MAP > 1$) or losing (catchment with $MAP < MAQ + ET_0$) water, or there might be errors in
271 the data. Four catchments fall outside the water or energy limits. These catchments are karstic
272 (e.g., Nikolaidis et al. 2013 [Greece], Longobardi and Vallini 2008 [Italy]), which may explain the
273 presence of underground water gain or loss processes. Most catchments (60%) can be
274 considered water-stressed, with an aridity index greater than 1.

275 Figure 3 shows a geographical cluster of catchments: (i) NWM catchments with the lowest
276 aridity index and a large variation in catchment water yields (MAQ/MAP); (ii) SM catchments with
277 the lowest runoff yields; (iii) EM catchments with a large variation in both the aridity index and
278 catchment water yields. This large heterogeneity in the climatic features and hydrological
279 response of EM catchments can be explained by the complex geomorphologic features of this
280 region and the prevalence of karstic and mountainous catchments.

281 To summarize, Mediterranean catchments exhibit a high variability in terms of both climatic
282 characteristics and catchment hydrological responses at the annual scale. The latter can highly
283 vary, even for the same amount of rainfall input, which may seriously challenge any modelling
284 approach. Nevertheless, some regional patterns exist, and catchments in each of the above-
285 mentioned sub-regions appear to have somewhat similar characteristics.

286 **4.2 Rainfall-runoff event-based studies**

287 **4.2.1 Rainfall events: amount and duration**

288 The monthly distribution of the number of events per geographic zone is presented in Fig. 4.
289 Events in the NWM mostly occur in autumn (September to December), whilst in the EM region,
290 events mostly occur in winter (January and February). For the SM, most of the studied events
291 occur between September and February, with the highest frequency in January.

292 For the 191 events presented here, the duration of the runoff generated by a rainfall event
293 greatly varies between 2 h and 8 days. Similarly, event rainfall amounts show great variability,
294 from 10.4 mm in the Giofyros Basin, Greece (Koutroulis and Tsanis 2010), to 540 mm in the
295 Gard River Basin, France (Vincendon et al. 2010) over various durations. More extreme events
296 were also reported in the literature, particularly in southern France. On 12-13 November 1999,
297 the Aude River [Southern France] witnessed an extreme flood event generated by 700 mm of
298 rainfall in 24 hrs (Gaume et al. 2004). The famous 8-9 September 2002 flood in the Gard region
299 (southern France) was generated by approximately 600 mm of rainfall in 48 hrs.

300 Figure 5 represents the cumulative event rainfall as a function of the event duration, with
301 large scattering in the relationship. For the same event duration, the total amount of cumulative
302 rainfall can greatly vary over a location. Moreover, the rainfall amounts during a single event vary
303 according to the geographical location, with the highest event rainfall (> 100 mm) located in the
304 NWM.

305 **4.2.2 Peak discharge**

306 Event peak discharge is widely used as an indicator of the hydrological response of catchments.
307 Here, we represent the catchment unit peak discharge (the peak discharge per km²) as a
308 function of a catchment's area (Fig. 6a) and cumulative event rainfall (Fig. 6b). Numerous
309 studies found a dependence of peak discharge on catchment area (e.g., Herschey and
310 Fairbridge 1998, Herschy 2002, Furey and Gupta 2005, Marchi et al. 2010). Figure 6a
311 represents a log-log diagram of the unit peak discharges of our catchment database (for each
312 catchment, the highest peak flow was plotted) with two envelope curves developed by Tarolli et
313 al. (2012) for the NWM (France, Italy and Spain) and for EM (Israel) flash floods.

314 In Mediterranean catchments, unit peak discharges are extremely high. Indeed, values
315 estimated from post-flooding investigations (Gaume et al. 2003, Gaume et al. 2004, Gaume and
316 Bouvier 2004) reached 30 m³/s/km² for the 8-9 September 2002 event for a 15 km² basin,
317 exceeded 15 m³/s/km² in four basins, and exceeded 10 m³/s/km² in six other basins. This finding
318 can be linked to the characterization of extreme flash floods in 60 catchments of five European
319 climate zones (Mediterranean, Alpine-Mediterranean, Alpine, Continental and Oceanic)
320 presented by Marchi et al. (2010). The authors found the highest unit peak flows in the
321 Mediterranean region followed by the Alpine-Mediterranean.

322 In our dataset, the highest unit peak flow was recorded on the Alzon River at the Saint Jean
323 de Pin, southern France (Nguyen et al. 2014), with a value of 33 m³/s/km² (catchment area =
324 30 km²). However, the unit peak discharges decrease rapidly with the increasing catchment
325 area. This rapid decrease in the unit peak discharge with the increase in the catchment area
326 may reflect the high spatial variability in the rainfall events that occurs in the Mediterranean and
327 the high heterogeneity in the hydrological responses of different locations within a catchment
328 (Latron and Gallart 2007, 2008). Thus, for a given catchment and a given rainfall event, the
329 event does not necessarily affect the entire catchment, and the runoff-generating processes are
330 not the same in all parts of the catchment.

331 The differences in catchment responses in terms of unit peak discharges by geographical
332 location are illustrated in Figure 6a. It clearly shows that the highest peak discharges are
333 recorded in the NWM, followed by the SM. The lowest unit peak flows were recorded in the EM.

334 The highest unit peak flows were recorded for the smallest catchments. For large catchments,
335 values from the NWM and SM catchments are within the same range, whereas the EM records
336 the lowest values. Nevertheless, although the NWM region is known for severe rainfall events
337 and catastrophic floods, the highest peak flows may be partly attributed to the relatively denser
338 gauging networks and larger number of research teams investigating post-flood conditions in
339 that region. Hence, information on peak flows in small catchments (on the order of 10 km²) is
340 available. This information is rarely available for other areas of the Mediterranean.

341 Catchment unit peak discharges as a function of event rainfall depth (Fig. 6b) are highly
342 scattered for a given amount of cumulative rainfall. Therefore, no correlation could be found
343 between event rainfall depth and event peak flow, particularly for rainfall depths below 100 mm.
344 However, above a 100 mm rainfall threshold, the unit peak discharge seems to increase
345 continuously with the amount of event rainfall.

346 Another factor that may influence peak flow is the duration of the rainfall event. It is tempting
347 to associate a longer event with a higher unit peak discharge. While this might be the case in
348 humid environments, no obvious relationship exists in Mediterranean catchments. For a given
349 event duration, the unit peak discharges greatly vary (Fig. 6c). However, this relationship is true
350 for relatively short events (event durations of less than 50 hrs), whilst it seems from the analysis
351 of Fig. 6(c) that for longer event durations, a particular pattern exists: the unit peak discharge
352 appears to increase with the increasing event duration. Perhaps for really long events,
353 catchment moisture conditions and runoff generation processes begin to resemble those of
354 humid conditions. In fact, during the wet season, Mediterranean catchments may function
355 similarly to catchments in humid climates (Latron et al. 2009, Gallart et al. 2011).

356 **4.2.3 Runoff ratio**

357 A very important concept for assessing the catchment hydrological response is the event runoff
358 ratio, which is defined as the ratio of the event runoff volume to the event rainfall volume. Figure
359 7 presents the runoff depth (Fig. 7a) and the runoff ratio (Fig. 7b) as a function of the cumulative
360 event rainfall. There is clear scattering in the response. Thus, for a given rainfall depth, both the
361 runoff and runoff ratio may greatly vary.

362 In Mediterranean catchments, event runoff ratios vary over a large range (Fig. 7b). For
363 instance, the ratio varies from 0.01 in the Rafina catchment (Greece; Massari et al. 2014) to 1.2
364 in the Lez catchment (France; Coustau et al. 2012). The mean value of the sample we studied
365 was 0.37, with a standard deviation of 0.27. The median was 0.30, and the interquartile range
366 was 0.14 - 0.51. There are geographical discrepancies in the catchment responses to rainfall
367 events. Figure 7 shows that the highest runoff depth and runoff ratios appear in the NWM
368 catchments. In fact, the median runoff ratios vary between regions, e.g., from 0.40 in the NWM
369 (similar to the values found by Marchi et al. 2010) to 0.36 in the SM and only 0.12 for EM
370 catchments. It is also obvious that for low rainfall depths (particularly below 50 mm), all events
371 are from the EM and SM regions, which may exhibit very high runoff ratios despite low rainfall
372 depths.

373 Extremely high runoff ratios recorded for some events may exceed 1. This finding can be
374 explained by the karstic nature of the catchment, with a runoff-generating area that is much
375 larger than the topographic basin. One example is the Lez catchment in France (Coustau et al.
376 2012). Other high runoff ratios were also estimated for other catchments, such as Merhavia in
377 Israel (Rozalis et al. 2010), Reno River in Italy (Brath et al. 2004) and Mdouar in Morocco
378 (Tramblay et al. 2012). Here, the events triggering such high runoff ratios usually occur after
379 other large events. Thus, the initial moisture conditions influence the generation of important
380 runoff amounts. These physical characteristics of the Mediterranean and the high seasonality of
381 the climatic features may explain the large scattering in the catchment responses both in terms
382 of event runoff ratios and peak discharges.

383 The relatively low dependency of the runoff ratio on the cumulative rainfall depth could be
 384 explained by many factors. First, under Mediterranean climatic conditions, Hortonian flows are
 385 expected to be dominant. Thus, the catchment hydrological response is rather controlled by
 386 rainfall intensity than depth. Moreover, for different events (even with the same amount of
 387 rainfall), the initial moisture conditions are different and trigger different hydrological responses.
 388 Furthermore, the temporal and spatial distributions of a rainfall event certainly play a role in
 389 shaping the catchment hydrological response. In Mediterranean catchments, the temporal and
 390 spatial distributions of rainfall events are highly variable. In addition, the runoff-generating
 391 processes along catchments are heterogeneous, and the percentage of the catchment area that
 392 actually contributes to runoff can vary by event.

393 **4.3 Drought studies**

394 In contrast to studies on the annual water balance and rainfall-runoff events, quantities
 395 comparison is difficult because the authors do not use the same variables to quantify droughts.
 396 Therefore, our analysis is more qualitative, and our conclusions could appear more subjective.

397 Climatic trends in the region show an overall decrease in the available water resources due a
 398 reduction in the annual rainfall and an increase in the annual temperature and reference
 399 evapotranspiration (ET_0) (Vincente-Serrano et al. 2014, Mavromatis and Stathis 2011, Chaouche
 400 et al. 2010, Kafle and Bruins 2009). However, important seasonal discrepancies exist in the
 401 evolution of different components of the water balance equation across areas of the
 402 Mediterranean. Studies show a high spatial and temporal variability of drought events across the
 403 Mediterranean, in the EM, the SM, parts of the Iberian Peninsula, the main islands and
 404 southeastern Italy.

405 Climatic change impact projections for the 21st century in the Mediterranean converge
 406 towards a drier climate by the end of the century (e.g., Capra et al. 2013, Marquez et al., 2013,
 407 Raffaud et al. 2013, Vrochidou et al. 2013, Abuabdillah et al. 2010). The water management
 408 scenarios in different catchments show a large decrease in water availability, particularly during
 409 dry periods due to the large population increase in these catchments. However, important
 410 disparities can exist within the same catchment.

411 **5 OBJECTIVES AND METHODS OF HYDROLOGICAL STUDIES**

412 In this section the main objectives that drove existing hydrological studies in the Mediterranean
 413 region and the most used modelling approaches for annual water balance, rainfall-runoff events
 414 and drought studies are discussed. In each case, the available studies are classified by their
 415 relative objectives or models used, and two main objectives, “simulation” and “scenario testing”,
 416 are then identified. The main objectives behind this analysis is to evaluate whether the
 417 Mediterranean context requires further specific approaches.

418 **5.1 Annual water balance studies**

419 Table 5 gives the list of existing studies. The two main objectives include:

- 420 (1) “simulation”: characterization of hydrological processes, model performance assessment,
 421 model uncertainty reduction, development of new models, streamflow simulation with
 422 limited data and karstic zone modelling;
- 423 (2) “scenario testing”: assessment of the impacts of different scenarios of land use change
 424 (LUC) and climate change (CC) on water resources and erosion.

425 Apart from classical modelling objectives, such as assessing model performances, improving
 426 model predictability or developing and testing new models, continuous streamflow simulation
 427 studies in the Mediterranean regions focus on the impact of global change on hydrological

428 responses. Mediterranean environments are water-stressed, and demands on water are
 429 increasing because of the increasing population and tourist industry. Moreover, the
 430 Mediterranean region is prone to climate change (IPCC 2014), and many studies have projected
 431 an increase in temperature and a decrease in precipitation over the Mediterranean Basin
 432 (Philandras et al. 2011, IPCC 2014, Alpert et al. 2002). Other studies address crucial features of
 433 Mediterranean environments, such as erosion (e.g., Garcia-Ruiz et al. 2013, Shakesby et al.
 434 2011, Lesschen et al. 2009, Raclot and Albergel 2006) and karstic influences (e.g., Touhami et
 435 al. 2013, Doglioni et al. 2012, Coustau et al. 2012).

436 Table 5 also illustrates that the same hydrological model was used for different objectives
 437 (e.g., SWAT or GR). However, some models were developed for a specific purpose: the
 438 HYdrological Land Use Change model (HYLUC) (Delgado et al. 2010) was used to evaluate the
 439 impact of land use change on catchment hydrological responses; and the HYdrological
 440 Modelling for Karst Environment (HYMKE) (Rimmer and Salingar 2006) was built and used for
 441 hydrological simulations in karstic catchments.

442 The model choice seems dependent on the data availability, the experience of the researcher
 443 (especially in terms of computing experience), and the available funding (some models are
 444 expensive). Except for some specific cases (e.g., Delgado et al. 2010 [Spain], Kourgialas et al.
 445 2010 [Greece], Rimmer and salingar 2006 [Israel]), the objective of the study does not
 446 necessarily influence the model choice. These claims are more obvious when we evaluate the
 447 geographical distribution of the models in use. Indeed, complex and data-demanding models
 448 appear to be primarily in use in the Euro-Mediterranean part of the region and in Israel. Most
 449 models were applied in other climatic contexts.

450 **5.2 Rainfall-runoff event-based studies**

451 Like in the case of water balance studies, the two main objectives of rainfall-runoff event-based
 452 studies include (see detailed list in Table 6):

- 453 (1) "simulation": similar objectives, with greater emphasis on runoff generation processes,
 454 wetness impacts on catchment responses and flash flood estimations, and sensitivity of
 455 model performance to data and parameters;
- 456 (2) "scenario testing": similar objectives on LUC and CC impact assessment, as well as
 457 wildfire impact or flood risk mitigation.

458 Regarding event-based studies, the same model can be used for different objectives. These
 459 are classical models that are applied worldwide. There have only been a few attempts to develop
 460 models specifically for the Mediterranean environment (e.g., Manus et al. 2010, Nunes et al.
 461 2011, Roux et al. 2011, Massari et al. 2015). Some authors slightly modified available models to
 462 account for specific features of the Mediterranean (e.g., Rozalis et al. 2010).

463 Modelling the hydrological response of Mediterranean catchments, particularly at the event
 464 level, using classical modelling techniques is somewhat controversial. In fact, the results from
 465 various studies characterizing hydrological responses of these catchments and runoff-generation
 466 mechanisms show that under Mediterranean conditions, runoff-generation mechanisms and
 467 catchment responses are heterogeneous. Hence, the most important rainfall events in terms of
 468 precipitation volume are not necessarily those with the highest runoff ratio or peak flow (Moussa
 469 and Chahinian 2009, Marchi et al. 2010, Tarolli et al. 2012), and different mechanisms can co-
 470 exist (Manus et al. 2010). Furthermore, different parts of the catchments can exhibit different
 471 runoff-generation processes, while some parts of the basin may not contribute at all (Latron and
 472 Gallart 2007). Catchment responses also depend on the initial wetness conditions, and they
 473 greatly fluctuate between seasons (Lana-Renault et al. 2007, Maneta et al. 2007, Huza et al.
 474 2014). However, because of the high intensity of rainfall under Mediterranean conditions,
 475 infiltration excess is often dominant (Manus et al. 2010). The impact of high-intensity rainfall is

476 particularly important for extreme events, where it becomes the sole factor that influences runoff
477 generation (Brath and Montanari 2000, Lana-Renault et al. 2011).

478 Some of the most commonly used models (SCS CN) are threshold models, in which a portion
479 of the precipitation is used to fill soil water content before generating runoff. Other models, e.g.,
480 based on TOPMODEL, were developed for more humid climates. They use saturation excess
481 mechanisms to generate runoff. The limitation of TOPMODEL for Mediterranean catchments
482 was demonstrated by Gallart et al. (2007) in the Vallecebre catchment in Spain. TOPMODEL
483 well simulates the hydrological response in the wet season. However, under dry conditions, the
484 model performance decreases. Moreover, Mediterranean catchment responses at the event
485 scale are very sensitive to the spatial and temporal (within-storm) variation in rainfall (Rozalis et
486 al. 2010). High spatio-temporal resolution rainfall data, which are not available in many parts of
487 the Mediterranean, particularly in North Africa and the Near East, are needed.

488 **5.3 Drought studies**

489 For the existing drought studies (see detailed list in Table 7), the two main objectives include:

- 490 (1) "simulation": characterization of the temporal and spatial variations of droughts and the
491 methods for drought assessment;
- 492 (2) "scenario testing": assessment of the impact of different scenarios (climatic,
493 anthropogenic, etc.) on drought characteristics in a catchment or region.

494 The methods used are also presented in Table 10. A description of the different indices used in
495 these studies and their meanings are available in drought reviews (e.g., Mishra and Singh 2010,
496 2011).

497 Precipitation-based indices, such as the standardized precipitation index (SPI) and modified
498 versions of such indices are most popular among meteorological-based indices. These indices
499 are globally relevant and are applicable at different time scales to characterize short- and long-
500 term droughts and their impacts on different components of the water balance. Hence, one must
501 emphasize the importance of the choice of the index time scale. For instance, in the
502 Mediterranean region, time steps that are too long (> 12 months) must not be used due to the
503 high rainfall seasonality (Vincenzo-Serrano and Lopez-Merano 2005). The objective of the index
504 (impact on surface water, reservoirs, etc.) should constrain the choice of the time step.

505 Hydrological indices, such as the Palmer index (e.g., Vasiliades and Loukas 2009) and other
506 hydrological indicators (e.g., Shaban et al. 2009), indices related to soil moisture (Vidal et al.
507 2012) and groundwater indices (Mendicino et al. 2008) have been used. Agricultural drought
508 indices are also prevalent in the Mediterranean literature (Diodato and Bellochi 2008).

509 The models used in drought studies are mainly water management models, such as the
510 Water Evaluation and Planning system (WEAP) (Hamlat et al. 2012, Yilmaz and Hrmancioglu
511 2010) and inVEST model (Terrado et al. 2014, Marquez et al. 2013), or simple water balance
512 models, e.g., the SIERRA model (Ruffault et al. 2013).

513 Moreover, climatic trend analyses are also commonly used to assess the impact of temporal
514 and spatial drought variations.

515 In summary, various methods are used for drought characterization in the Mediterranean.
516 However, climate-based indices (such as the SPI) remain most popular. Moreover, the main
517 concerns that drive drought studies appear to be global change impacts (climatic and
518 anthropogenic pressure).

519 **6 DISCUSSION AND PERSPECTIVES**

520 Sections 4 and 5 presented an overview of the recent studies in the Mediterranean in terms of
521 hydrological response characteristics and modelling approaches at different time scales and for
522 various objectives: annual runoff, floods and drought periods. This section discusses the main
523 results and provides complementary responses to the three questions posed in the introduction.

524 **6.1 Can we identify regional patterns in the Mediterranean?**

525 The comparison of catchments in different Mediterranean areas shows that some regional
 526 tendencies exist. In terms of the annual water balance, catchments from the NWM have a higher
 527 humidity, a relatively low dryness index and higher annual runoff yields. This finding could be
 528 due to the influence of the humidity from the Atlantic Ocean, which modifies the seasonal pattern
 529 of rainfall, i.e., less precipitation in winter and a rainfall peak in autumn and/or spring (McNeill
 530 1992). SM catchments are the driest, with the highest aridity index and lowest annual runoff
 531 yields. The EM proves to be more heterogeneous, with a relatively wide range of values in terms
 532 of both the aridity index and runoff yields (e.g., Rimmer and Salingar 2006, Tzoraki and
 533 Nikolaidas 2007, Kougialas et al. 2010).

534 Regional tendencies also exist in the seasonal distribution and severity of extreme rainfall
 535 events. In fact, rainfall events in the NWM mostly occur in autumn, with a peak in September.
 536 Rainfall in the EM region mostly occurs in winter, with a peak in January and February. In the
 537 SM, the sample is too small to generalize. Moreover, in terms of the event rainfall depth, peak
 538 discharges and runoff ratios, the highest values occur in the NWM. These findings were reported
 539 by other authors who studied floods in the Mediterranean (Marchi et al. 2010, Tarolli et al. 2012,
 540 and Llasat et al. 2013). In fact, the NWM region exhibits extreme rainfall regimes, with rainfall
 541 commonly exceeding 200 mm in 24 hrs. Cortesi et al. (2012) studied the distribution of the daily
 542 precipitation concentration index across Europe. The highest values were computed for the
 543 coastal arc that extends from southeastern Spain to Sicily (Italy). Moreover, Reiser and Kutiel
 544 (2011) compared the rainfall regimes in Valencia (Spain) and Larnaca (Cyprus). The authors
 545 found that in Valencia, the rainfall regimes are more extreme than in Larnaca. Hence, in the
 546 NWM, daily rainfall values that exceed 600 mm have been recorded.

547 However, there is also overlap between morphometric and hydrological characteristics of
 548 particular catchments located in different regions, particularly between the NWM and EM. These
 549 similarities between catchments can highlight twin basins (e.g., basins with similar physiographic
 550 features and/or hydrological responses), for which hydrological responses can be transferred
 551 from gauged to ungauged basins.

552 **6.2 What is required to model Mediterranean catchments?**

553 A difference can be made between continuous streamflow simulations and event-based
 554 simulations. The former is usually applied to quantify water resources in the catchment of
 555 interest, assess land cover and/or climate change impacts, or test new modelling approaches. In
 556 event-based studies, the objectives may vary from flood risk mitigation to understanding flood-
 557 triggering characteristics. For continuous streamflow simulations, daily climatic and hydrological
 558 data are mostly used (sometimes monthly data). The applied models are often lumped as
 559 conceptual models with relatively good results. Nevertheless, modelling the catchment response
 560 at the event scale is a dilemma. The high rainfall intensity and spatial variability within a storm,
 561 along with a catchment's initial wetness conditions, complicate this task. Classical hydrological
 562 models are not well suited to the Mediterranean area. In fact, many of these models assume
 563 precipitation abstraction (such as the widely used SCS CN) or saturated excess mechanisms
 564 (such as the TOPMODEL family), which is not necessarily the case in the Mediterranean.
 565 Moreover, any suitable modelling approach for these catchments is highly demanding in terms of
 566 data. Hence, to account for the variability in the rainfall intensity in a short time, the model should
 567 be applied at the hourly (or shorter) scale for flood studies. Furthermore, this model should be
 568 able to account for any rainfall spatial variability and catchment wetness conditions. Therefore,
 569 information on soil properties and soil moisture conditions is needed.

570 The specificities of the Mediterranean catchment responses explain the large response
 571 heterogeneity in the region and outline the fact that modelling the hydrological behaviour of

572 Mediterranean catchments is difficult (Oudin et al., 2008). In regional studies that involve
 573 catchments from Mediterranean and non-Mediterranean (humid) regions, such as in Goswami et
 574 al. (2007) and Oudin et al. (2008, 2010), the performance of the model-dependent regional
 575 approaches is worse in a Mediterranean climate. High-resolution spatial and temporal rainfall
 576 and soil properties and moisture data may be necessary to accurately simulate the hydrological
 577 behaviour of Mediterranean catchments. However, such data are rarely available. Consequently,
 578 detailed flood studies are usually performed in small, research catchments, with results often
 579 difficult to generalize in space and time (Gallart et al. 2007, Latron and Gallart 2007, Lana-
 580 Renault et al. 2007; Manus et al. 2010, Rozalis et al. 2010, Molina et al. 2014). This finding also
 581 explains why studies in large catchments are usually limited to flood risk mitigation or peak flow
 582 estimation, sometimes using lumped methods only.

583 To overcome the difficulties in modelling hydrological responses of Mediterranean
 584 catchments, particularly in terms of accounting for the high spatial variability in model
 585 parameters, radar rainfall, spatial soil moisture information and remote sensing data are
 586 considered (Tramblay et al. 2010, 2012, Rozalis et al. 2010). New approaches that couple
 587 observations (that are usually obtained on small catchments) and modelling are used to improve
 588 our understanding of flood-triggering processes. For example, recent work was undertaken
 589 within the HyMeX project on two French catchments (Braud et al. 2014). This is a multi-scale
 590 approach that assesses the runoff-generation processes from observations at a small hillslope
 591 scale; the rainfall variability and soil moisture, along with the network organization, were studied
 592 for medium-sized catchments (1 - 100 km²) and for river rooting and flooding at a large scale
 593 (100 - 1000 km²). Data analyses were coupled to modelling techniques, and the results are
 594 promising. However, these approaches are very demanding in terms of instrumentation, data,
 595 and computational efforts; thus, they may be very expensive. Thus, the majority of flood
 596 simulation studies in the Mediterranean are concentrated in the developed countries of the Euro-
 597 Mediterranean region and Israel.

598 **6.3 What are the main challenges for future research in the Mediterranean?**

599 In recent decades, we observed an important change in the scope of hydrological studies in the
 600 Mediterranean zone and consequently in the expected performance of hydrological modelling.
 601 Currently, there remains an important need for research on classical rainfall/runoff hydrological
 602 modelling for engineering applications in water resources management, water supply
 603 infrastructure design, flood and drought prediction, pollution projections and erosion processes.
 604 However, hydrological modelling has become an indispensable tool for many interdisciplinary
 605 projects in the Mediterranean. For example, anthropogenic and climatic change impacts on
 606 environmental variables, such as water, soil, biology, ecology and the socio-economy, can be
 607 assessed. Modelling is data intensive, and improving model performances involves the
 608 acquisition of new data at various spatiotemporal scales. Future research challenges in
 609 Mediterranean hydrology include:

- 610 - *Strengthening the hydrological knowledge in EM and SM*: The majority of studies focuses
 611 on the NWM. There is an urge to conduct more hydrological studies in the EM and SM,
 612 from the plot to the large catchment scales and from short time scales (a few minutes for
 613 flash flood genesis on hillslopes) to decades (impact of land use and climate change);
- 614 - *Improving measurements and data availability*: There is a need to improve
 615 measurements during extreme flash flood events, drought periods (absence of flow) and
 616 long-term land use and climate change. These data can be obtained through the
 617 installation of long-term environmental stations, dense precipitation and streamflow
 618 gauging networks. Radar data and remote sensing approaches are promising.
- 619 - *Conducting large-scale studies under Mediterranean conditions*: There is a need to lead
 620 studies at the scale of the entire Mediterranean region (e.g. Milano et al. 2013,

621 Chenoweth et al. 2011, Garcia-Ruiz et al. 2011, Iglesias et al. 2007 among others). This
 622 would require setting up large datasets through scanning and digitizing old records,
 623 historical data, and previous studies. Thus, the current established database initiated in
 624 this work could be extended to all Mediterranean basins (e.g., the Mediterranean zones
 625 in Australia, California, Chile and South Africa) for a Mediterranean comparative
 626 hydrology. This comparison would provide a common basis for understanding the
 627 hydrological behaviour of catchments and improving regionalization approaches; In terms
 628 of hydrological modelling, models already applied at continental scales (e.g. EFAS, E-
 629 hype) would be good candidates to conduct modelling studies at the Mediterranean
 630 scale;

- 631 - *Studying the Mediterranean under change*: Transferring the results between “similar”
 632 Mediterranean catchments can also be useful for predicting the effects of climate change
 633 or land use change on the hydrological response, following the objectives of the decadal
 634 “Pantha Rei” (2013-2022) of the International Association of Hydrological Sciences
 635 (IAHS) (Hrachowitz et al. 2013).
- 636 - *Improving hydrological modelling on small catchments*: Theoretical developments are
 637 needed, and classical models must be adapted by taking into account the representation
 638 of the main hydrological processes. In large catchments (> 500 km²), spatial rainfall and
 639 hydrographs are smoothed at the daily scale. Consequently, conventional hydrological
 640 models perform well and therefore remain well suited for understanding hydrological
 641 processes, testing hypotheses or simulating missing discharge data series. However,
 642 when moving to small catchments (< 100 km²), many hydrological processes remain
 643 poorly represented or neglected in classical models, e.g., threshold functioning for runoff
 644 genesis and the transfer on hillslopes and through the channel network (e.g., case of
 645 ephemeral and intermittent flows), the importance of flow in non-saturated zone, and the
 646 difficulties in modelling surface-subsurface interactions in dryland regions.
- 647 - *Accounting for variabilities*: New “tailor-made” models need to be developed to consider
 648 specific spatiotemporal heterogeneities of catchment responses in areas with specific
 649 hydrological functions, such as in karstic, urban s and peri-urban zones.

650 We believe that reviews at large regional scales, such as the one presented here, are
 651 essential for advancing our understanding of hydrological behaviour of highly complex areas,
 652 such as the Mediterranean region, in terms of comparative hydrology. Thereof, this review is an
 653 attempt to strengthen the research initiatives at this scale.

654
 655 **Acknowledgments** This research was supported by the Lebanese National Centre for
 656 Remote Sensing and the French National Research Institute of Science and Technology for
 657 Environment and Agriculture (IRSTEA). Part of this research was funded by the CEDRE project
 658 (programme franco-libanais-16ème appel d’offres) entitled «Impact des changements
 659 d’occupation du sol sur les ressources en eau et les crues au Liban».The authors thank Juan
 660 Ignacio López-Moreno and an anonymous reviewer, the Associate Editor Andreas Efstratiadis
 661 for their useful comments, which helped improving the overall quality of the manuscript.

662

663

664

665

666

667 **REFERENCES**

- 668 Abebe, A. and Price, R. K., 2003. Managing uncertainty in hydrological models using
669 complementary models. *Hydrological Sciences Journal*, 48(5), 679-692.
- 670 Abida, H. and Ellouze, M., 2008. Probability distribution of flood flows in Tunisia. *Hydrology and*
671 *Earth System Sciences*, Volume 12, 703-714.
- 672 Abouabdillah, A., Oueslati, O., De Girolama, A. M. and Lo Porto, A., 2010. Modeling the impact
673 of climate change in a Mediterranean catchment (Merguellil, Tunisia). *Fresenius Environmental*
674 *Bulletin*, 19(10a), 2334-2347.
- 675 Adamovic, M., Braud, I., Branger, F. and Kirchner, J. W., 2015. Does the simple dynamical
676 systems approach provide useful information about catchment hydrological functioning in a
677 Mediterranean context: Application to the Ardèche catchment (France). *Hydrology and Earth*
678 *System Sciences*, Volume 19, 2427-2449.
- 679 Albek, M., Ogutveren, U. B. and Albek, E., 2004. Hydrological modeling of Seydi Suyu watershed
680 (Turkey) with HSPF. *Journal of Hydrology*, Volume 285, 260-271.
- 681 Alpert, P. et al., 2002. The paradoxical increase of Mediterranean extreme daily rainfall in spite of
682 decrease in total values. *Geophysical Research Letters*, 29(10).
- 683 Alpert, P. et al., 2008. Climatic trends to extremes employing regional modeling and statistical
684 interpretation over the E. Mediterranean. *Global and Planetary Change*, Volume 63, 163-170.
- 685 Amengual, A. et al., 2006. A Hydrometeorological Modeling Study of a Flash-Flood Event over
686 Catalonia, Spain. *Journal of Hydrometeorology*, Volume 8, 282-303.
- 687 Andréassian, V., Lerat, J., Le Moine, N. and Perrin, C., 2012. Neighbors: Nature's own
688 hydrological models. *Journal of Hydrology* 414–415 (2012) 49–58, Volume 414-415, 49-58.
- 689 Andréassian, V. and Perrin, C., 2012. On the ambiguous interpretation of the Turc-Budyko
690 nondimensional graph. *Water Resour. Res.*, Volume 48, p. W10601.
- 691 Ballesteros-Cánovas, J. A., Sanchez-Silva, M., Bodoque, J. M. and Díez-Herrero, A., 2013. An
692 Integrated Approach to Flood Risk Management: A Case Study of Navaluenga (Central Spain).
693 *Water Resour Manage*, Volume 27, 3051-3069.
- 694 Bangash, R., Passuello, A., Hammond, M. and Schuhmacher, M., 2012. Water allocation
695 assessment in low flow river under data scarce conditions: A study of hydrological simulation in
696 Mediterranean basin. *Science of the Total Environment*, Volume 440, 60-71.
- 697 Benkaci Ali, T. and Dechemi, N., 2004. Modélisation pluie-débit journalière par des modèles
698 conceptuels et à boîte noire; test d'un modèle neuroflou / Daily rainfall-runoff modelling using
699 conceptual and black box models; testing a neuro-fuzzy model. *Hydrological Sciences Journal*,
700 49(5), 919-930.
- 701 Bernal, S., Belillas, C., Ibáñez, J. J. and Àvila, A., 2013. Exploring the long-term response of
702 undisturbed Mediterranean catchments to changes in atmospheric inputs through time series
703 analysis. *Science of the Total Environment*, p. 535–545.
- 704 Blöschl, G., 2005. Rainfall-runoff modeling of ungauged catchments. *Encyclopedia of*
705 *Hydrological sciences*, 2061-2080.

- 706 Bloschl, G. et al., 2013. *Runoff prediction in ungauged basins: Synthesis across Processes, Places*
707 *and Scales*. Cambridge: Cambridge University Press.
- 708 Bonada, N. and Resh, V. H., 2013. Mediterranean-climate streams and rivers: geographically
709 separated but ecologically comparable freshwater systems. *Hydrobiologia*, Volume 719, 1-29.
- 710 Borga, M., Boscolo, P., Zanon, F. and Sangati, M., 2007. Hydrometeorological Analysis of the 29
711 August 2003 Flash Flood in the Eastern Italian Alps. *American Meteorological Society*, 1049-
712 1067.
- 713 Bouraoui, F., Benabdallah, S., Brad, A. and Bidoglio, G., 2005. Application of the SWAT model on
714 the Medjerda river basin (Tunisia). *Physics and Chemistry of the Earth*, Volume 30, 497-507.
- 715 Brath, A. and Montanari, A., 2000. The effects of the spatial variability of soil infiltration capacity
716 in distributed flood modeling. *Hydrological processes*, Volume 14, 2779-2794.
- 717 Brath, A., Montanari, A. and Toth, E., 2004. Analysis of the effects of different scenarios of
718 historical data availability on the calibration of a spatially-distributed hydrological model.
719 *Journal of Hydrology*, Volume 291, p. 232–253.
- 720 Braud, I. et al., 2014. Multi-scale hydrometeorological observation and modelling for flash flood
721 understanding. *Hydrology and Earth System Sciences*, Volume 18, p. 3733–3761.
- 722 Brocca, L., Melone, F. and Moramarco, T., 2008. On the estimation of antecedent wetness
723 conditions in rainfall-runoff modeling. *Hydrological Processes*, Volume 22, 629-642.
- 724 Burlando, P. and Rosso, R., 2002. Effects of transient climate change on basin hydrology. 2.
725 Impacts on runoff variability in the Arno River, central Italy. *Hydrological Processes*, Volume
726 16, 1177-1199.
- 727 Byun, H. R. and Wilhite, D. A., 1999. Objective quantification of drought severity and duration.
728 *Journal of Climatology*, Volume 12, p. 2747–2756.
- 729 Candela, L., Tamoh, K., Olivares, G. and Gomez, M., 2012. Modelling impacts of climate change
730 on water resources in ungauged and data-scarce watersheds. Application to the Siurna catchment
731 (NE Spain). *Science of the Total Environment*, Volume 440, 253-260.
- 732 Capra, A., Consoli, S. and Scicolone, B., 2013. Long-Term Climatic Variability in Calabria and
733 Effects on Drought and Agrometeorological Parameters. *Water Resources Management*, Volume
734 27, 601-617.
- 735 Ceballos-Barbancho, A., Moran-Tejeda, E., Luengo-Ugidos, M. A. and Llorente-Pinto, J. M., 2008.
736 Water resources and environmental change in a Mediterranean environment: the south-west
737 sector of the Duero river basin (Spain). *Journal of Hydrology*, Volume 351, 126-138.
- 738 Chahinian, N., Tournoud, M. G., Perrin, J. L. and Picot, B., 2005. Flow and nutrient transport in
739 intermittent rivers: a modeling case study on the Vene River using SWAT. *Hydrological Sciences*
740 *Journal*, 56(2), 268-287.
- 741 Chaouche, K. et al., 2010. Analyses of precipitation, temperature and evapotranspiration in a
742 French Mediterranean region in the context of climate change. *Comptes Rendus Geoscience*,
743 Volume 342, 234-243.

- 744 Chenoweth, J. et al., 2011. Impact of climate change on the water resources of the eastern
745 Mediterranean and Middle East region: Modeled 21st century changes and implications. *Water*
746 *Resources Research*, 47(6).
- 747 Cognard-Plancq, A.-L., Marc, V., Didon-Lescot, J.-F. and Normand, M., 2001. The role of forest
748 cover on streamflow down on sub-Mediterranean mountain watersheds: A modeling approach.
749 *Journal of Hydrology*, Volume 254, 229-243.
- 750 Cortesi, N., Gonzalez-Hidalgo, J. C., Brunetti, M. and Martin-Vide, J., 2012. Daily precipitation
751 concentration across Europe 1971–2010. *Natural Hazards and Earth System Sciences*, Volume
752 12, 2799-2810.
- 753 Cosandey, C. et al., 2005. The hydrological impact of the mediterranean forest: a review of French
754 research. *Journal of Hydrology*, Volume 301, 235-249.
- 755 Coustau, M., Bouvier, C., Borrell-Estupina, V. and Jourde, H., 2012. Flood modeling with a
756 distributed event-based parsimonious rainfall-runoff model: case of karstic Lez river catchment.
757 *Nat. Hazards Earth Syst. Sci.*, Volume 12, 1119-1133.
- 758 Cudennec, C., Leduc, C. and Koutsoyiannis, D., 2007. Dryland hydrology in Mediterranean
759 regions-a review. *Hydrological Sciences Journal*, 52(6), 1077-1087.
- 760 D'Agostino, D. R., Trisorio, L. G., Lamaddalena, N. and Ragab, R., 2010. Assessing the results of
761 scenarios of climate and land use changes on the hydrology of an italian catchment: modeling
762 study. *Hydrological Processes*, Volume 24, 2693-2704.
- 763 De Jong, C., Cappy, S., Finckh, M. and Funk, D., 2008. A transdisciplinary analysis of water
764 problems in the mountainous karst areas of Morocco. *Engeneering Geology*, Volume 99, 228-
765 238.
- 766 De Waele, J. et al., 2010. Flash flood hydrology in karstic terrain: Flumineddu Canyon, central-east
767 Sardinia. *Geomorphology*, Volume 120, 162-173.
- 768 Delgado, J. et al., 2010. Modeling the hydrological response of a Mediterranean medium-sized
769 headwater basin subject to land cover change: The Cardener River basin (NE Spain). *Journal of*
770 *Hydrology*, Volume 383, 125-134.
- 771 Di Castri, F., 1981. *Mediterranean-type shrublands of the world*. Amsterdam: Elsevier.
- 772 Diodato, N. and Bellocchi, G., 2008. Drought stress patterns in Italy using agro-climatic indicators.
773 *Climate Research*, Volume 36, 53-63.
- 774 Dogan, S., Berktaç, A. and Singh, V. P., 2012. Comparison of multi-monthly rainfall-based
775 drought severity indices, with application to semi-arid Konya closed basin, Turkey. *Journal of*
776 *Hydrology*, Volume 470-471, 255-268.
- 777 Efstratiadis, A. et al., 2008. HYDROGEIOS: A semi-distributed GIS-based hydrological model for
778 modified river basins. *Hydrology and Earth System Sciences*, Volume 12, 989-1006.
- 779 Esper, J. et al., 2007. Long-term drought severity variations in Morocco. *Geophysical Research*
780 *Letters*, Volume 34, 1-5.
- 781 Estrany, J., Garcia, C. and Batalla, R. J., 2010. Hydrological response of a small Mediterranean
782 agricultural catchment. *Journal of Hydrology*, Volume 380, 180-190.

- 783 Farquharson, F. A. K., Meigh, J. R. and Sutcliffe, J. V., 1992. Regional flood frequency analysis in
784 arid and semi-arid areas. *Journal of Hydrology*, Volume 138, 487-501.
- 785 Fiorentino, M., Manfreda, S. and Iacobellis, V., 2007. Peak runoff contributing area as hydrological
786 signature of the probability distribution of floods. *Advances in Water Resources*, Volume 30,
787 2123-2134.
- 788 Fiorillo, F., Revellino, P. and Ventafridda, G., 2012. Karst aquifer draining during dry periods.
789 *Journal of Cave and Karst Studies*, 74(2), 148-156.
- 790 Fox, D. M. et al., 2012. A case study of land cover change (1950e2003) and runoff in a
791 Mediterranean catchment. *Applied Geography*, Volume 32, 810-821.
- 792 Franchini, M. and Pacciani, M., 1991. Comparative Anaysis of several conceptual rainfall runoff
793 models. *Journal of Hydrology*, Volume 122, 161-219.
- 794 Franchini, M., Wendling, J., Obled, C. and Todini, E., 1996. Physical interprestation and senitivity
795 analysis of TOPMODEL. *Journal of Hydrology*, Volume 175, 293-338.
- 796 Fujihara, Y. et al., 2008. Assessing the impacts of climate change on the water resources of the
797 Seyhan River Basin in Turkey: Use of dynamically downscaled data for hydrologic simulations.
798 *Journal of Hydrology*, Volume 353, 33-48.
- 799 Gage, S. H. and Mukerji, M. K., 1977. A perspective of grasshopper population distribution in
800 Saskatchewan and interrelationships with weather. *Environ Entomol*, Volume 6, 469-479.
- 801 Gallart, F. et al., 2011. Analysing the effect of global change on the historical trends of water
802 resources in the headwaters of the Llobregat and Ter river basins (Catalonia, Spain). *Physics and*
803 *Chemistry of the Earth*, Volume 36, 655-661.
- 804 Gallart, F., Latron, J., Llorens, P. and Beven, K., 2007. Using internal catchment information to
805 reduce the uncertainty of discharge and baseflow predictions. *Advances in Water Resources*,
806 Volume 30, 808-823.
- 807 Gallart, F. and Llorens, P., 2004. Observations on land cover changes and water resources in the
808 headwaters of the Ebro catchment, Iberian Peninsula. *Physics and Chemistry of the Earth*,
809 Volume 29, 769-773.
- 810 Garambois, P. A. et al., 2014. Analysis of flash flood triggering rainfall for a process-oriented
811 hydrological model. *Atmospheric Research*, Volume 137, 14-24.
- 812 Garambois, P. A. et al., 2013. Characterization of process-oriented hydrologic model behavior with
813 temporal sensitivity analysis for flash floods in Mediterranean catchments. *Hydrol. Earth Syst.*
814 *Sci.*, Volume 17, 2305-2322.
- 815 Garcia-Ruiz, J. M. et al., 2011. Mediterranean water resources in a global change scenario. *Earth-*
816 *Science Reviews*, Volume 105, 121-139.
- 817 Garcia-Ruiz, J. M., Nadal-Romero, E., Lana-Renault, N. and Begueria, S., 2013. Erosion in
818 Mediterranean landscapes: Changes and future challenges. *Geomorphology*, Volume 198, 20-36.
- 819 Gathara, S. T. et al., 2002. *Report of the CAgM working group on the impacts of desertification and*
820 *drought and of other extreme meteorological events*. Geneva, s.n.

- 821 Gaume, E. et al., 2003. A compilation of data on European flash floods. *Journal of Hydrology*,
822 367(1-2), 70-78.
- 823 Gaume, E. and Bouvier, C., 2004. Analyse hydro-pluviométrique des crues du Gard et du Vidourie
824 des 8 et 9 septembre 2002. *La Houille Blanche*, Volume 6, 99-106.
- 825 Gaume, E., Livet, M. and Desbordes, M., 2003. Study of the hydrological processes during the
826 Avene River extraordinary flood (south of France). *Physics and Chemistry of the Earth*, Volume
827 28, 263-267.
- 828 Gaume, E., Livret, M., Desbordes, M. and Villeneuve, J.-P., 2004. Hydrological analysis of the
829 river Aude, France, flash flood on 12 and 13 November 1999. *Journal of Hydrology*, Volume
830 286, 135-134.
- 831 Gibbs, W. J. and Maher, J. V., 1967. Rainfall Deciles as Drought Indicators. *Bureau of*
832 *Meteorology Bull*, Volume 48.
- 833 Gomez Gomez, C. M. and Perez Blanco, C. D., 2012. Do drought management plans reduce
834 drought risk? A risk assessment model for a Mediterranean river basin. *Ecological Economics*,
835 Volume 76, 42-48.
- 836 Grove, A. T. and Rackham, O., 2001. The nature of Mediterranean Europe: an ecological history..
837 *Journal of Mediterranean Ecology*, Volume 3, 65-68.
- 838 Gul, G. O., Harmancioglu, N. and Gul, A., 2010. A combined hydrologic and hydraulic modeling
839 approach for testing efficiency of structural flood control measures. *Natural Hazards*, Volume 54,
840 245-260.
- 841 Hartmann, A. et al., 2012. A multi-model approach for improved simulations of future water
842 availability at a large Eastern Mediterranean karst spring. *Journal of Hydrology*, Volume 468-
843 469, 130-138.
- 844 Hessling, M., 1999. Hydrological modeling and pair basins studies of Mediterranean catchments.
845 *Physics and Chemistry of the Earth (B)*, Volume 24, 59-63.
- 846 Hooke, J. M., 2006. Human impacts on fluvial systems in the Mediterranean region.
847 *Geomorphology*, Volume 79, 311-335.
- 848 Hrachowitz, M. et al., 2013. A decade of Predictions in Ungauged Basins (PUB)—a review.
849 *Hydrological Sciences Journal*, 58(6), 1198-1255.
- 850 Hreiche, A., Najem, W. and Bocquillon, C., 2007. Hydrological impact of climate change on
851 Lebanese coastal rivers/ simulation des impacts hydrologiques du changement climatique sur les
852 fleuves cotiers libanais. *Hydrological Sciences Journal*, 52(6), 1119-1133.
- 853 Huza, J. et al., 2014. Precipitation, soil moisture and runoff variability in a small river catchment
854 (Ardèche, France) during HyMeX Special Observation Period 1. *Journal of Hydrology*, Volume
855 516, 330-334.
- 856 Iglesias, A., Garrote, L., Flores, F. and Moneo, M., 2007. Challenges to Manage the Risk of Water
857 Scarcity and Climate Change in the Mediterranean. *Water Resources Management*, Volume 21,
858 775-788.

- 859 Javelle, P., Fouchier, C., Arnaud, P. and Lavabre, J., 2010. Flash flood warning at ungauged
860 locations using radar rainfall and antecedent soil moisture estimation. *Journal of Hydrology*,
861 Volume 394, 267-274.
- 862 Kafle, H. K. and Bruins, H. J., 2009. Climatic trends in Israel 1970–2002: warmer and increasing
863 aridity inland. *Climatic Change*, Volume 96, 63-77.
- 864 Koutroulis, A. G. and Tsanis, I. K., 2010. A method for estimating flash flood peak discharge in a
865 poorly gauged basin: Case study for the 13-14 January 1994 flood, Giofiros basin, Crete, Greece.
866 *Journal of Hydrology*, Volume 385, 150-164.
- 867 Koutroulis, A. G., Tsanis, I. K., Daliakopoulos, I. N. and Jacob, D., 2013. 2013. *Journal of*
868 *Hydrology*, Volume 479, 146-158.
- 869 Lacombe, G., Cappelaere, B. and Leduc, C., 2008. Hydrological impact of water and soil
870 conservation works in the Merguellil catchment of central Tunisia. *Journal of Hydrology*,
871 Volume 359, 210-224.
- 872 Lana-Renault, N. et al., 2011. Differences in streamflow in relation to changes in land cover: A
873 comparative study in two sub-Mediterranean mountain catchments. *Journal of Hydrology*, Volume
874 411, 366-378.
- 875 Lana-Renault, N., Latron, J. and Regues, D., 2007. Streamflow response and water-table dynamics
876 in a sub-Mediterranean research catchment (Central Pyrenees). *Journal of Hydrology*, Volume
877 347, 497-507.
- 878 Lana-Renault, N. et al., 2014. Comparative analysis of the response of various land covers to an
879 exceptional rainfall event in the central Spanish Pyrenees, October 2012. *Earth Surface Processes*
880 *and Landforms*, Volume 39, 581-592.
- 881 Latron, J. and Gallart, F., 2007. Seasonal dynamics of runoff-contributing areas in a small
882 Mediterranean research catchment (Vallecebre, Eastern Pyrenees). *Journal of Hydrology*, Volume
883 335, 194-206.
- 884 Latron, J. and Gallart, F., 2008. Runoff generation processes in a small Mediterranean research
885 catchment (Vallecebre, Eastern Pyrenees). *Journal of Hydrology*, Volume 358, 206-220.
- 886 Lespinas, F., Ludwig, W. and Heussner, S., 2014. Hydrological and climatic uncertainties
887 associated with modeling the impact of climate change on water resources of small Mediterranean
888 coastal rivers. *Journal of Hydrology*, Volume 511, 403-422.
- 889 Lesschen, J. P., Schoorl, J. M. and Cammeraat, L. H., 2009. Modeling runoff and erosion for a
890 semi-arid catchment using a multi-scale approach based on hydrological connectivity.
891 *Geomorphology*, Volume 109, 174-183.
- 892 Llasat, M. C. et al., 2013. Towards a database on societal impact of Mediterranean floods within
893 the framework of the HYMEX project. *Natural Hazards and Earth System Sciences*, Volume 13,
894 1337-1350.
- 895 Llasat, M. C., Llasat-Botija, M., Rodriguez, A. and Lindbergh, S., 2010. Flash floods in Catalonia:
896 a recurrent situation. *Advances in Geosciences*, Volume 26, 105-111.
- 897 Llorens, P. and Domingo, F., 2007. Rainfall partitioning by vegetation under Mediterranean
898 conditions. A review of studies in Europe. *Journal of Hydrology*, Volume 335, 37-54.

- 899 Longobardi, A. and Vallini, P., 2008. Baseflow index regionalization analysis in a Mediterranean
900 environment and data scarcity context: role of the catchment permeability index. *Journal of*
901 *Hydrology*, Volume 355, 63-75.
- 902 Lopez-Bustins, J. A., Pascual, D., Pla, E. and Retana, J., 2013. Future variability of droughts in
903 three Mediterranean catchments. *Natural Hazards*, Volume 69, 1405-1421.
- 904 López-Moreno, J. I., Beniston, M. and García-Ruiz, J. M., 2008. Environmental change and water
905 management in the Pyrenees facts and future perspectives for Mediterranean mountains. *Global*
906 *Planet. Change* 61, 300–312., Volume 61, 300-312.
- 907 Lorenzo-Lacruz, J. et al., 2010. The impact of droughts and water management on various
908 hydrological systems in the headwaters of the Tagus River (central Spain). *Journal of Hydrology*,
909 Volume 386, 13-26.
- 910 Makropoulos, C. et al., 2008. A multi-model approach to the simulation of large scale karst flows.
911 *Journal of Hydrology*, 348(3-4), 412-424.
- 912 Maneta, M. P. et al., 2007. Temporal instability of parameters in an event-based distributed
913 hydrologic model applied to a small semiarid catchment. *Journal of Hydrology* , Volume 341,
914 207-221.
- 915 Manus, C. et al., 2009. A modeling approach to assess the hydrological response of small
916 Mediterranean catchments to the variability of soil characteristics in a context of extreme events.
917 *Hydrology and Earth Syst Sciences*, 13(2), 79-97.
- 918 Marchi, L., Borga, M., Preciso, E. and Gaume, E., 2010. Characterisation of selected extreme flash
919 floods in Europe and implications for flood risk management. *Journal of Hydrology*, 394(1-2),
920 118-133.
- 921 Marquès, M. et al., 2013. The impact of climate change on water provision under a low flow
922 regime: A case study of the ecosystems services in the Francoli river basin. *Journal of Hazardous*
923 *Materials*, Volume 236, 224-232.
- 924 Massari, C. et al., 2014. Using globally available soil moisture indicators for flood modelling in
925 Mediterranean catchments. *Hydrology and Earth System Sciences*, Volume 18, 839-853.
- 926 Massari, C. et al., 2015. The use of H-SAF soil moisture products for operational hydrology: flood
927 modelling over Italy. *Hydrology*, 2(1), 2-22.
- 928 Mavromatis, T. and Stathis, D., 2011. Response of the water balance in Greece to temperature and
929 Precipitation trend. *Theor Appl Climatol*, Volume 104, 13-24.
- 930 Mayor, A. G., Bautista, S., Llovet, J. and Bellot, J., 2007. Post-fire hydrological and erosional
931 responses of a Mediterranean landscape: Seven years of catchment-scale dynamics. *Catena*,
932 Volume 71, 68-75.
- 933 McKee, T. B., Doesken, N. J. and Kleist, J., 1993. *The Relationship of Drought Frequency and*
934 *Duration to Time Scales*. Anaheim, CA, s.n.
- 935 McNeill, J. R., 1992. *The mountains of the Mediterranean world: an environmental history*.
936 s.l.:Cambridge University Press; Studies in Environment and History.

- 937 Megnounif, A., Terfous, A., Ghenaim, A. and Poulet, J. B., 2007. Key processes influencing
938 erosion and sediment transport in a semi-arid Mediterranean area: the Upper Tafna catchment,
939 Algeria. *Hydrological Sciences Journal*, 52(6), 1271-1284.
- 940 Mehaiguene, M., Meddi, M., Longobardi, A. and Toumi, S., 2012. Low flows quantification and
941 regionalization in North West Algeria. *Journal of Arid Environments*, Volume 87, 67-76.
- 942 Milano, M. et al., 2012. Facing climatic and anthropogenic changes in the Mediterranean basin:
943 What will be the medium-term impact on water stress?. *Comptes Rendus Geoscience*, Volume
944 344, 432-440.
- 945 Milella, P. et al., 2012. Diagnostic analysis of distributed input and parameter datasets in
946 Mediterranean basin streamflow modeling. *Journal of Hydrology*, Volume 472–473, p. 262–276.
- 947 Mimikou, M. A., Baltas, E., Varanou, E. and Pantazis, K., 2000. Regional impacts of climate
948 change on water resources quantity and quality indicators. *Journal of Hydrology*, Volume 234, p.
949 95–109.
- 950 Mishra, A. K. and Singh, V. P., 2010. A review of drought concepts. *Journal of Hydrology* ,
951 Volume 391, 202-216.
- 952 Mishra, A. K. and Singh, V. P., 2011. Drought modeling – A review. *Journal of Hydrology* ,
953 Volume 403, 157-175.
- 954 Molina, A. J. et al., 2014. Spatio-temporal variability of soil water content on the local scale in a
955 Mediterranean mountain area (Vallcebre, North Eastern Spain). How different spatio-temporal
956 scales reflect mean soil water content. *Journal of Hydrology*, Volume 516, 182-192.
- 957 Moran-Tejeda, E., Ceballos-Barbancho, A. and Llorento-Pinto, J. M., 2010. Hydrological response
958 of Mediterranean headwaters to climate oscillations and land-cover changes: The mountains of
959 Duero River basin (Central Spain). *Global and Planetary Change*, Volume 72, 39-49.
- 960 Moran-Tejeda, E. et al., 2012.) The contrasted evolution of high and low flows and precipitation
961 indices in the Duero basin (Spain). *Hydrological Sciences Journal*, 57(4), 591-611.
- 962 Moran-Tejeda, E. et al., 2014. Streamflow timing of mountain rivers in Spain: Recent changes and
963 future projections. *Journal of Hydrology*, Volume 517, 1114-1127.
- 964 Moussa, R. and Boucquillon, C., 2009. On the use of the diffusive wave for modeling extreme
965 flood events with overbank flow in the floodplain. *Journal of Hydrology*, Volume 374, 116-135.
- 966 Moussa, R., Chahinian, N. and Boucquillon, C., 2007. Distributed hydrological modelling of a
967 Mediterranean mountainous catchment – Model construction and multi-site validation. *Journal of*
968 *Hydrology*, Volume 337, 35-51.
- 969 Mueller, E. N., Francke, T., Batalla, R. J. and Bronstert, A., 2009. Modelling the effects of land-use
970 change on runoff and sediment yield for a meso-scale catchment in the Southern Pyrenees.
971 *Catena*, Volume 79, 288-296.
- 972 Nalbantis, I. and Tsakiris, G., 2009. Assessment of hydrological drought revisited.. *Water*
973 *Resources Management*, Volume 23, 881-897.
- 974 Nguyen, C. C., Gaume, E. and Payrastre, O., 2014. Regional flood frequency analyses involving
975 extraordinary flood events at ungauged sites: further developments and validations. *Journal of*
976 *Hydrology*, Volume 508, 385-396.

- 977 Niadas, I. A., 2005. Regional flow duration curve estimation in small ungauged catchments using
 978 instantaneous flow measurements and a censored data approach. *Journal of Hydrology*, Volume
 979 314, 48-66.
- 980 Nikolaidis, N. P., Bouraoui, F. and Bidoglio, G., 2013. Hydrologic and geochemical modeling of a
 981 karstic Mediterranean watershed. *Journal of Hydrology*, Volume 477, 129-138.
- 982 Nunes, J. P., Seixas, J. and Keizer, J. J., 2013. Modeling the response of within-storm runoff and
 983 erosion dynamics to climate change in two Mediterranean watersheds: A multi-model, multi-
 984 scale approach to scenario design and analysis. *Catena*, Volume 102, 27-39.
- 985 Oudin, L. et al., 2008. Spatial proximity, physical similarity, regression and ungauged catchments: A
 986 comparison of regionalization approaches based on 913 French catchments. *Water Resources
 987 Research*, Volume 44, 1-15.
- 988 Oudin, L., Kay, A., Andréassian, V. and Perrin, C., 2010. Are seemingly physically similar
 989 catchments truly hydrologically similar?. *Water Resources Research*, p. W11558.
- 990 Ozturk, M., Coptu, N. K. and Saysel, A. K., 2013. Modeling the impact of land use change on the
 991 hydrology of a rural watershed. *Journal of Hydrology*, Volume 497, 97-109.
- 992 Perrin, J. L. and Tournoud, M. G., 2009. Hydrological processes controlling flow generation in a
 993 small Mediterranean catchment under karstic influence. *Hydrological Sciences Journal*, 54(6),
 994 1125-1140.
- 995 Petroselli, A., Grimaldi, S. and Romano, N., 2013. Curve-Number/Green-Ampt mixed procedure
 996 for net rainfall estimation: a case study of the Mignone watershed, IT.. *Procedia Environmental
 997 Sciences*, Volume 19, p. 113 – 121.
- 998 Philandras, C. M. et al., 2011. Long term precipitation trends and variability within the
 999 Mediterranean region. *Natural Hazards and Earth System Sciences*, Volume 11, p. 3235–3250.
- 1000 Pisinaras, V. et al., 2010. Hydrological and water quality modeling in a medium-sized basin using
 1001 the Soil and Water Assessment Tool (SWAT). *Desalination*, Volume 250, 274-286.
- 1002 Post, D. A., 2009. Regionalizing rainfall-runoff model parameters to predict the daily streamflow
 1003 of ungauged catchments in the dry tropics. *Hydrological Resources*, Volume 40, 433-444.
- 1004 Quézel, P., 1985. *Definition of the Mediterranean region and the origin of its flora*. Dordrecht: Plant
 1005 Conservation in The Mediterranean area.
- 1006 Raclot, D. and Albergel, J., 2006. Runoff and water erosion modeling using WEPP on a
 1007 Mediterranean cultivated catchment. *Physics and Chemistry of the Earth*, Volume 31, 1038-
 1008 1047.
- 1009 Ramadan, H. H., Beighley, E. R. and Ramamurthy, A. S., 2012. Modeling streamflow trends for a
 1010 watershed with limited data: case of the Litani basin, Lebanon. *Hydrological Sciences Journal*,
 1011 57(8), 1516-1529.
- 1012 Reiser, H. and Kutiel, H., 2011. Extreme Rainfall Events and Uncertainty in the Mediterranean
 1013 Region. In: *Survival and Sustainability*. s.l.:Springer-Verlag Berlin Heidelberg 2011, 1439-1448.
- 1014 Rimmer, A. and Salingar, Y., 2006. Modelling precipitation-streamflow processes in karst basin:
 1015 The case of the Jordan River sources. *Journal of Hydrology*, Volume 331, 524-542.

- 1016 Roux, H. et al., 2011. A physically-based parsimonious hydrological model for flash floods in
 1017 Mediterranean catchments. *Nat. Hazards Earth Syst. Sci.*, 11, 2567–2582, 2011. *Natural Hazards*
 1018 *and Earth System Sciences*, Volume 11, 2567-2582.
- 1019 Rozalis, S., Morin, E., Yair, Y. and Price, C., 2010. Flash flood prediction using an uncalibrated
 1020 hydrological model and radar rainfall data in a Mediterranean watershed under changing
 1021 hydrological conditions. *Journal of Hydrology* 394 (2010) 245–255. *Journal of Hydrology*,
 1022 Volume 394, 245-255.
- 1023 Rozos, E., Efstratiadis, A., Nalbantis, I. and Koutsoyiannis, D., 2004. Calibration of a semi-
 1024 distributed model for conjunctive simulation of surface and groundwater flows. *Hydrological*
 1025 *Sciences Journal*, 49(5), 819-842.
- 1026 Rozos, E. and Koutsoyiannis, D., 2006. A multicell karstic aquifer model with alternative flow
 1027 equations. *Journal of Hydrology*, 325(1-4), 340-355.
- 1028 Ruffault, J., Martin-StPaul, N. K., Rambal, S. and Mouillot, F., 2013. Differential regional
 1029 responses in drought length, intensity and timing to recent climate changes in a Mediterranean
 1030 forested ecosystem. *Climatic Change*, Volume 117, 103-117.
- 1031 Ruiz-Sinoga, J. D., Garcia-Marin, R., Gabarron-Galeote, M. A. and Martinez-Murillo, J. F., 2012.
 1032 Analysis of dry periods along a pluviometric gradient in Mediterranean southern Spain.
 1033 *International Journal of Climatology*, Volume 32, p. 1558–1571.
- 1034 Ruiz-Villaneuva, V. et al., 2013. Characterisation of flash floods in small ungauged mountain
 1035 basins of Central Spain using an integrated approach. *Catena*, Volume 110, 32-43.
- 1036 Salinas, J. L. et al., 2014a. Regional parent flood frequency distributions in Europe – Part 1: Is the
 1037 GEV model suitable as a pan-European parent?. *Hydrol. Earth Syst. Sci.*, Volume 18, 4381-4389.
- 1038 Salinas, J. L. et al., 2014b. Regional parent flood frequency distributions in Europe – Part 2:
 1039 Climate and scale controls. *Hydrol. Earth Syst. Sci.*, 18, 4391-4401, 2014, Volume 18, 4391-
 1040 4401.
- 1041 Sangati, M., Borga, M., Rabuffetti, D. and Bechini, R., 2009. Influence of rainfall and soil
 1042 properties spatial aggregation on extreme flash flood response modelling: An evaluation based on
 1043 the Sesia river basin, North Western Italy. *Advances in Water Resources*, Volume 32, 1090-
 1044 1106.
- 1045 Selek, B. and Tuncok, I. K., 2013. Effects of climate change on surface water management of
 1046 Seyhan basin, Turkey. *Environ Ecol Stat.*
- 1047 Sellami, H., La Jeunesse, I., Benabdallah, S. and Vanclooster, M., 2013. Parameter and rating curve
 1048 uncertainty propagation analysis of the SWAT model for two small Mediterranean catchments.
 1049 *Hydrological Sciences Journal*, 58(8), 1635-1657.
- 1050 Senatore, A., Mendicino, G., Smiatek, G. and Kunstmann, H., 2011. Regional climate change
 1051 projections and hydrological impact analysis for a Mediterranean basin in Southern Italy. *Journal*
 1052 *of Hydrology*, Volume 399, 70-92.
- 1053 Shaban, A., 2009. Indicators and Aspects of Hydrological Drought in Lebanon. *Water Resources*
 1054 *Managment*, Volume 23, p. 1875–1891.

- 1055 Shakesby, R. A., 2011. Post-wildfire soil erosion in the Mediterranean: Review and future research
1056 directions. *Earth-Science Reviews*, Volume 105, 71-100.
- 1057 Silvestro, F. et al., 2013. Exploiting remote sensing land surface temperature in distributed
1058 hydrological modelling: the example of the Continuum model. *Hydrology and Earth System
1059 Sciences*, Volume 17, 39-62.
- 1060 Stern, R., Dennett, M. and Dale, I., 1982. Analysing daily rainfall measurements to give
1061 agronomically useful results. I. Direct methods. *Experimental Agriculture*, Volume 18, 223-236.
- 1062 Tarolli, P., Borga, M., Morin, E. and Delrieu, G., 2012. Analysis of flash flood regimes in the
1063 North-Western and South-Eastern Mediterranean regions. *Natural Hazards and Earth System
1064 Sciences*, Volume 12, 1255-1265.
- 1065 Tayfur, G., Zucco, G., Brocca, L. and Moramarco, T., 2014. Coupling soil moisture and
1066 precipitation observations for predicting hourly runoff at small catchment scale. *Journal of
1067 Hydrology* 510 (2014) 363–371. *Journal of Hydrology*, Volume 510, 363-371.
- 1068 Terrado, M. et al., 2014. Impact of climate extremes on hydrological ecosystem services in a
1069 heavily humanized Mediterranean basin. *Ecological Indicators*, Volume 37, 199-209.
- 1070 Thornthwaite, C. W., 1948. An approach toward a rational classification of climate. *Geographical
1071 Reviews*, Volume 38, 55-94.
- 1072 Tigkas, D., Vangelis, H. and Tsakiris, G., 2012. Drought and climatic change impact on streamflow
1073 in small watersheds. *Science of the Total Environment*, Volume 440, 33-41.
- 1074 Tramblay, Y. et al., 2012. Estimation of antecedent wetness conditions for flood modeling in
1075 northern Morocco. *Hydrology and Earth System Sciences*, Volume 16, 4375-4386.
- 1076 Tramblay, Y. et al., 2010. Assessment of initial soil moisture conditions for event-based rainfall-
1077 runoff modeling. *Journal of Hydrology*, Volume 387, 176-187.
- 1078 Tramblay, Y. et al., 2013. . High-resolution Med-CORDEX regional climate model simulations for
1079 hydrological impact studies: a first evaluation of the ALADIN-Climate model in Morocco.
1080 *Hydrology and Earth System Sciences*, Volume 17, 3721-3739.
- 1081 Tsakiris, G., 2004. *Meteorological Drought Assessment. Paper prepared for the needs of the
1082 European Research Program MEDROPLAN*. Zaragosta, Spain, s.n.
- 1083 Tsakiris, G., Pangalou, D. and Vangelis, H., 2007. Regional Drought Assessment Based on the
1084 Reconnaissance Drought Index (RDI). *Water Resources Management*, Volume 21, p. 821–833.
- 1085 Turkes, M. and Tatli, H., 2009. Use of the standardized precipitation index (SPI) and a modified
1086 SPI for shaping the drought probabilities over Turkey. *International Journal of Climatology*,
1087 Volume 29, 2270-2282.
- 1088 Vafeidis, A. T., Drake, N. A. and Wainwright, J., 2007. A proposed method for modelling the
1089 hydrologic response of catchments to burning with the use of remote sensing and GIS. *Catena*,
1090 Volume 70, 396-409.
- 1091 Vangelis, H., Spiliotis, M. and Tsakiris, G., 2011. Drought severity assessment based on bivariate
1092 probability analysis. *Water Resources Management*, 25(1), 357-371.

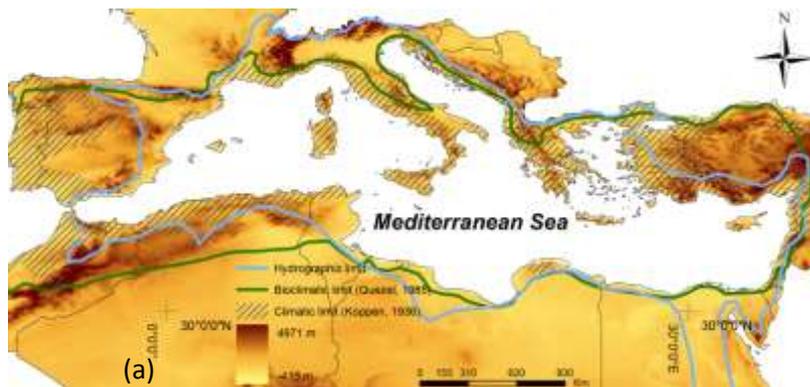
- 1093 Vasiliades, L. and Loukas, A., 2009. Hydrological response to meteorological drought using the
1094 Palmer drought indices in Thessaly, Greece. *Desalination* , Volume 237, 3-21.
- 1095 Vicente-Serrano, S., 2006. Spatial and temporal analysis of droughts in the Iberian Peninsula
1096 (1910-2000). *Hydrological Sciences Journal*, 51(1), 83-97.
- 1097 Vicente-Serrano, S. M. and Lopez-Moreno, J. I., 2005. Hydrological response to different time
1098 scales of climatological drought: an evaluation of the Standardized Precipitation Index in a
1099 mountainous Mediterranean basin. *Hydrology and Earth System Sciences*, Volume 9, 523-533.
- 1100 Vidal, J. P. et al., 2012. Evolution of spatio-temporal drought characteristics: validation,
1101 projections and effect of adaptation scenarios. *Hydrology and Earth System Sciences*, Volume 16,
1102 p. 2935–2955.
- 1103 Vincendon, B. et al., 2010. Benefit of coupling the ISBA land surface model with a TOPMODEL
1104 hydrological model version dedicated to Mediterranean flash-floods. *Journal of Hydrology*,
1105 Volume 394, 256-266.
- 1106 Vincente-Guillen, J. et al., 2012. Performance of a Monthly Streamflow Prediction Model for
1107 Ungauged Watersheds in Spain. *Water Resources Management*, Volume 26, 3767-3784.
- 1108 Vincente-Serrano, S. M. et al., 2014. Reference evapotranspiration variability and trends in Spain,
1109 1961–2011. *Global and Planetary Change*, Volume 121, 26-40.
- 1110 Viola, F., Noto, L. V., Canarozzo, M. and La Loggia, G., 2011. Regional flow duration curves for
1111 ungauged sites in Sicily. *Hydrology and Earth System Sciences*, 15(1), 323-331.
- 1112 Viviroli, D., Mittelbach, H., Gurtz, J. and Weingartner, R., 2009. Continuous simulation for flood
1113 estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation
1114 and flood estimation results. *Journal of Hydrology*, Volume 377, 208-225.
- 1115 Vrochidou, A.-E. K., Tsanis, I. K., Grillakis, M. G. and Koutroulis, A. G., 2013. The impact of
1116 climate change on hydrometeorological droughts at a basin scale. *Journal of Hydrology*, Volume
1117 476, 290-301.
- 1118 Wagener, T. and Wheater, H. S., 2006. Parameters estimation and regionalization for continuous
1119 rainfall-runoff models including uncertainty. *Journal of Hydrology*, Volume 320, 132-154.
- 1120 Wainwright, J. and Thornes, J. B., 2004. *Environmental issues in the Mediterraeaan*. London:
1121 Routledge.
- 1122 Yilmaz, B. and Harmancioglu, N. B., 2010. An Indicator Based Assessment for Water Resources
1123 Management in Gediz River Basin, Turkey. *Water Resources Management*, Volume 24, p. 4359–
1124 4379.
- 1125 Young, A. R., 2006. Stream flow simulation within UK ungauged catchments using a daily
1126 rainfall-runoff model. *Journal of Hydrology*, Volume 320, 155-172.
- 1127 Zanon, F. et al., 2010. Hydrological analysis of a flash flood across a climatic and geologic
1128 gradient: The September 18, 2007 event in Western Slovenia. *Journal of Hydrology*, Volume
1129 394, 182-197.
- 1130
1131
1132

- 1133
1134
1135
1136
1137
1138
1139 **Table 1** Characteristics of the annual water balance studies in Mediterranean catchments. Nc:
1140 number of catchments; Ac: catchment area; Zc: catchment mean elevation; Period: period or
1141 number of years used to calculate the water balance components.
1142
1143 **Table 2** Summary information of the flood studies on Fig. 1c. Nc: number of catchments; Ne:
1144 number of events; Ac: catchment area; X: available data; and (-) not available.
1145
1146 **Table 3** Summary information of the chosen droughts studies on Fig. 1d. Nc: number of
1147 catchments.
1148
1149 **Table 4** Summary statistics of climatic and hydrological variables for the studied catchments
1150 (Table 1 and Fig. 1b) for the three Mediterranean sub-regions (NWM, EM and SM). MAP: Mean
1151 Annual Precipitation; ET0: reference evapotranspiration; MAQ: Mean Annual Runoff.
1152
1153 **Table 5** The main objectives and the models used for continuous streamflow simulation studies
1154 in the Mediterranean.
1155
1156 **Table 6** The main objectives and the models used for event-based studies in the Mediterranean.
1157
1158 **Table 7** The main objectives and methods used for the chosen drought studies in the
1159 Mediterranean.
1160
1161
1162
1163
1164 **Fig.1** The Mediterranean region: (a) Relief and different limits; (b) Annual water balance studies;
1165 (c) Event-based studies and (d) Drought studies. Small symbols (o, □ and ◻) represent individual
1166 catchment studies and large symbols (O, □ and ◻) represent regionalization studies.
1167
1168 **Fig. 2** Relationship between the Mean Annual Runoff (MAQ) and the Mean Annual Precipitation
1169 (MAP) for the three studied sub-regions (NWM, EM and SM). Plain symbols indicate karstic
1170 catchments in each sub-region.
1171
1172 **Fig. 3** Plot of mass balance data from the study catchments on the Budyko diagram: the mean
1173 annual runoff coefficient MAQ/MAP function of the aridity index ET0/MAP/ MAP: Mean Annual
1174 Precipitation; MAQ: Mean Annual Runoff; ET0: Mean Annual Reference Evapotranspiration for
1175 the 3 sub-regions NWM, EM and SM; Plain symbols indicate karstic catchments in each sub-
1176 region.
1177
1178 **Fig. 4** Monthly distribution of events per geographic region.
1179
1180 **Fig. 5** Relationship between rainfall depth and event duration for the studied events on the three
1181 studied sub-regions (NWM, EM and SM).
1182

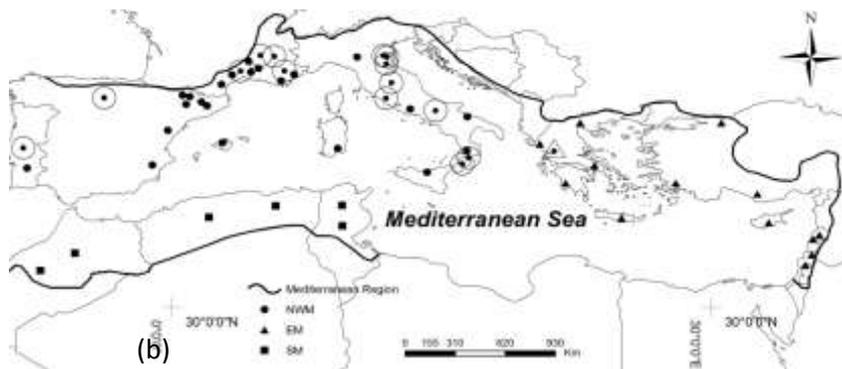
1183 **Fig. 6** Relationship between unit peak discharge and (a) catchment area, (b) rainfall depth and
1184 (c) event duration.

1185 **Fig. 7** Relationship between runoff depth and rainfall depth (a), and between runoff ratio and
1186 rainfall depth (b).

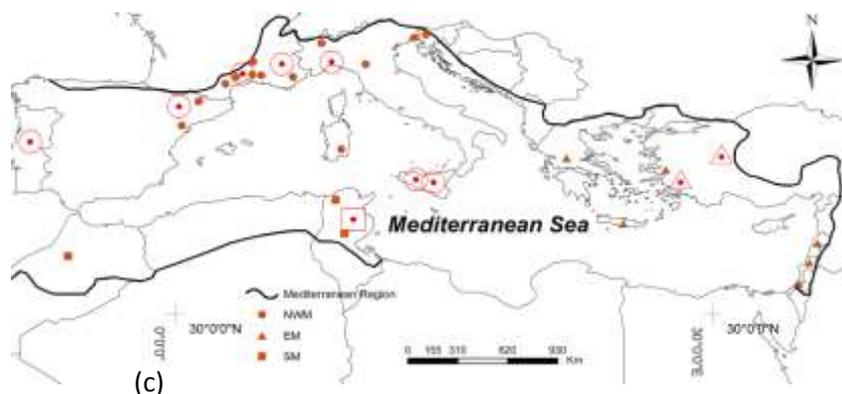
1187



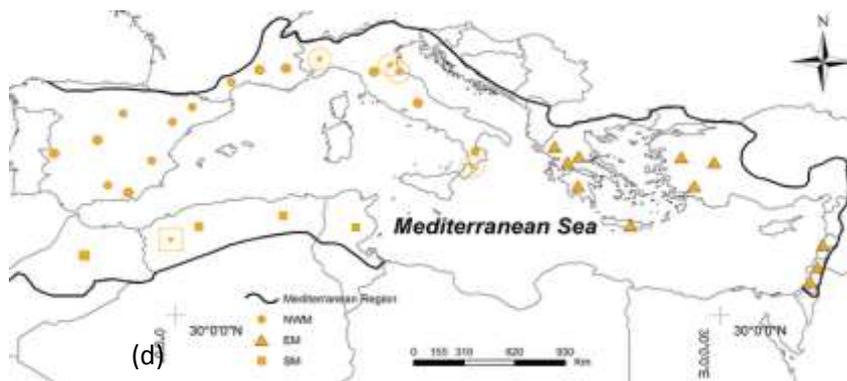
1188



1189

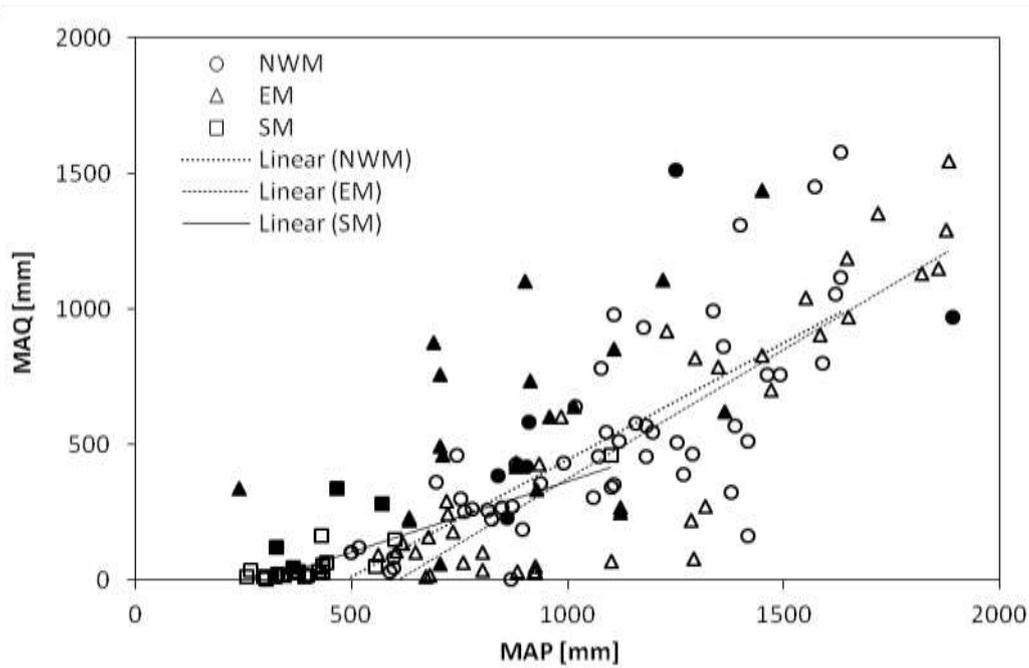


1190



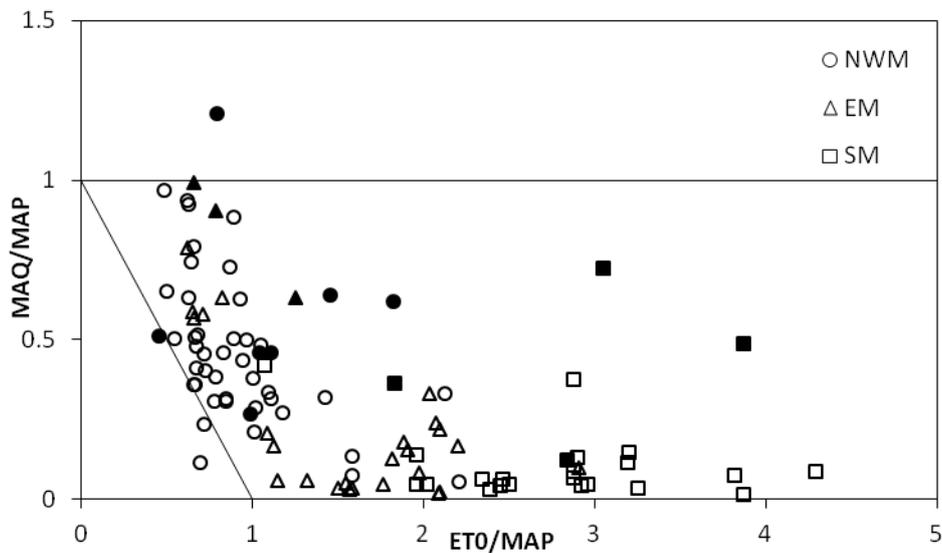
1191 **Fig.1** The Mediterranean region: (a) Relief and different limits; (b) Annual water balance
 1192 studies; (c) Event-based studies and (d) Drought studies. Small symbols (o, Δ and □)
 1193 represent individual catchment studies and large symbols (O, Δ and □) represent
 1194 regionalization studies.

1195



1196

1197 **Fig. 2** Relationship between the Mean Annual Runoff (MAQ) and the Mean Annual
 1198 Precipitation (MAP) for the three studied sub-regions (NWM, EM and SM). Plain symbols
 1199 indicate karstic catchments in each sub-region.



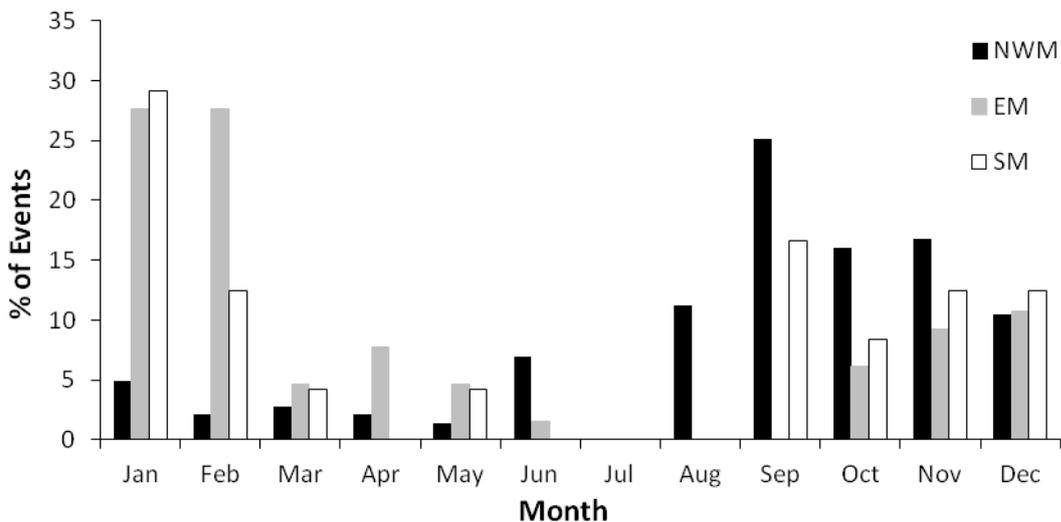
1200

1201

1202 **Fig. 3** Plot of mass balance data from the study catchments on the Budyko diagram: the
 1203 mean annual runoff coefficient MAQ/MAP function of the aridity index $ET_0/MAP / MAP$: Mean
 1204 Annual Precipitation; MAQ: Mean Annual Runoff; ET_0 : Mean Annual Reference
 1205 Evapotranspiration for the 3 sub-regions NWM, EM and SM; Plain symbols indicate karstic
 1206 catchments in each sub-region.

1207

1208

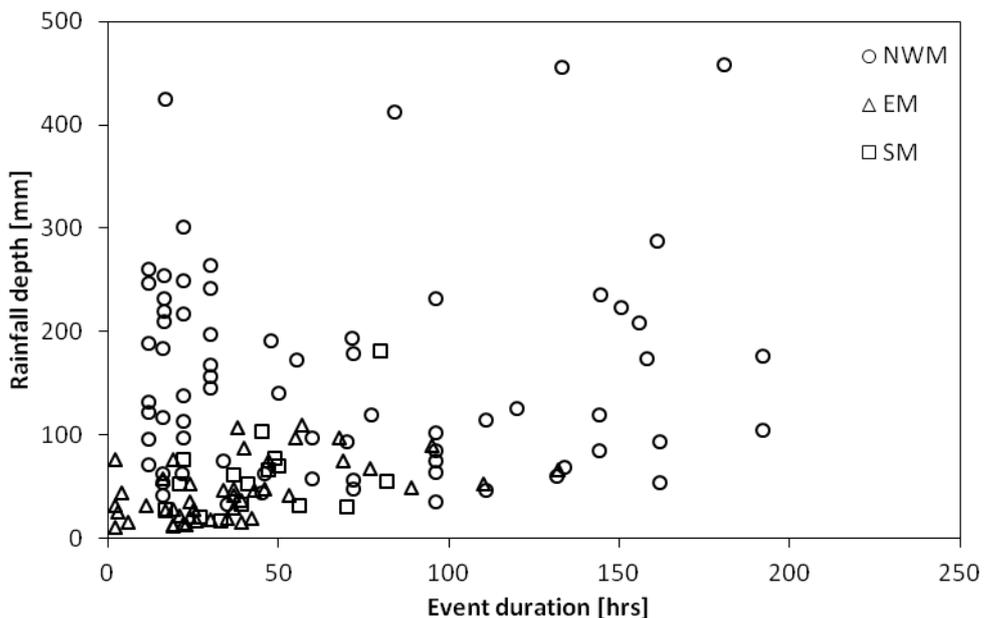


1209

1210 **Fig. 4** Monthly distribution of events per geographic region.

1211

1212



1213

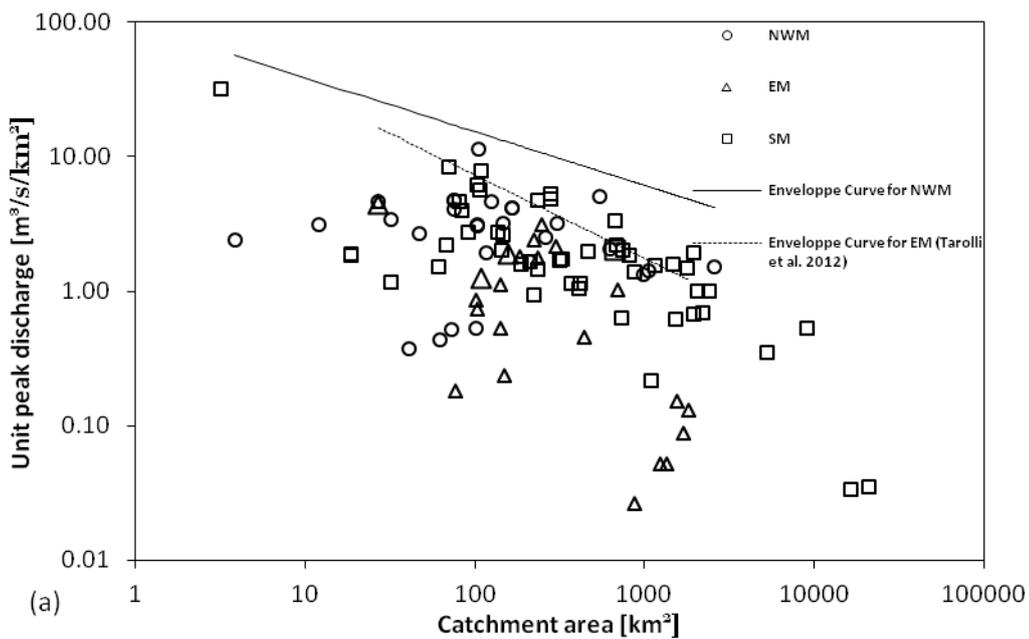
1214

1215

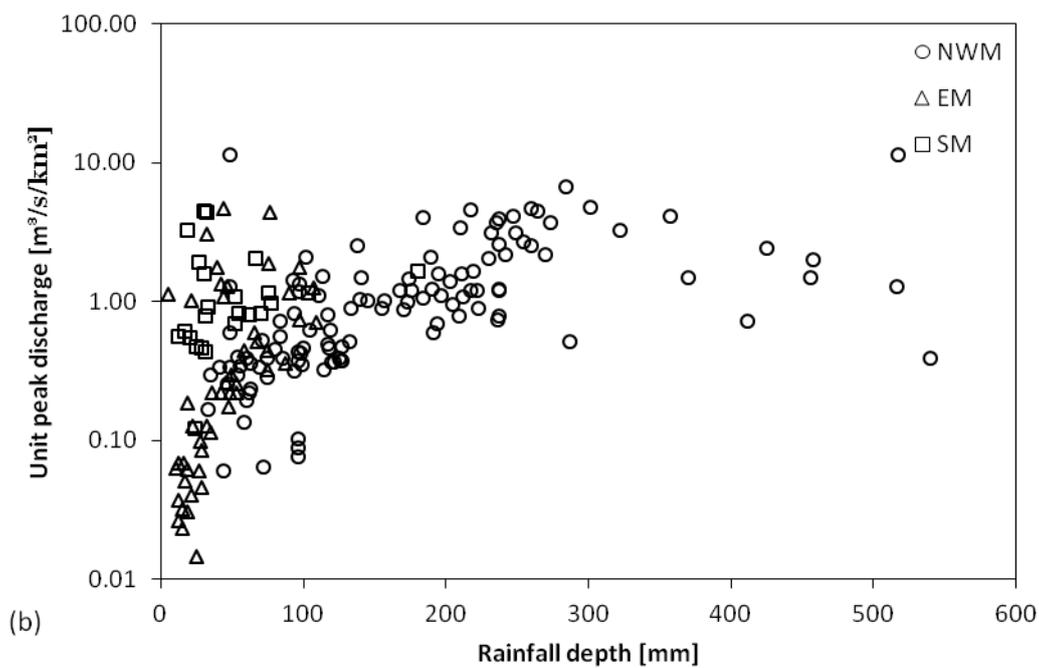
1216 **Fig. 5** Relationship between rainfall depth and event duration for the studied events on the
1217 three studied sub-regions (NWM, EM and SM).

1218

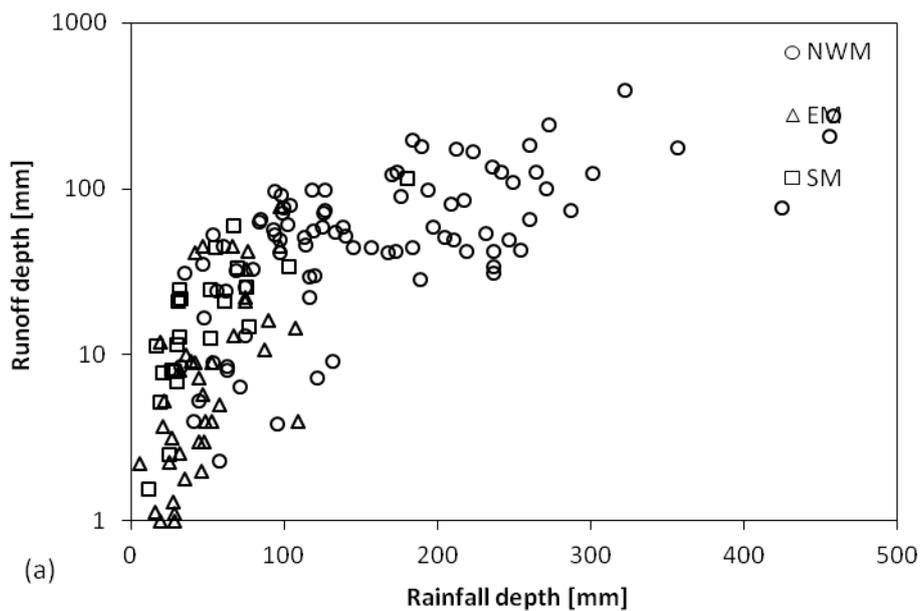
1219



1220

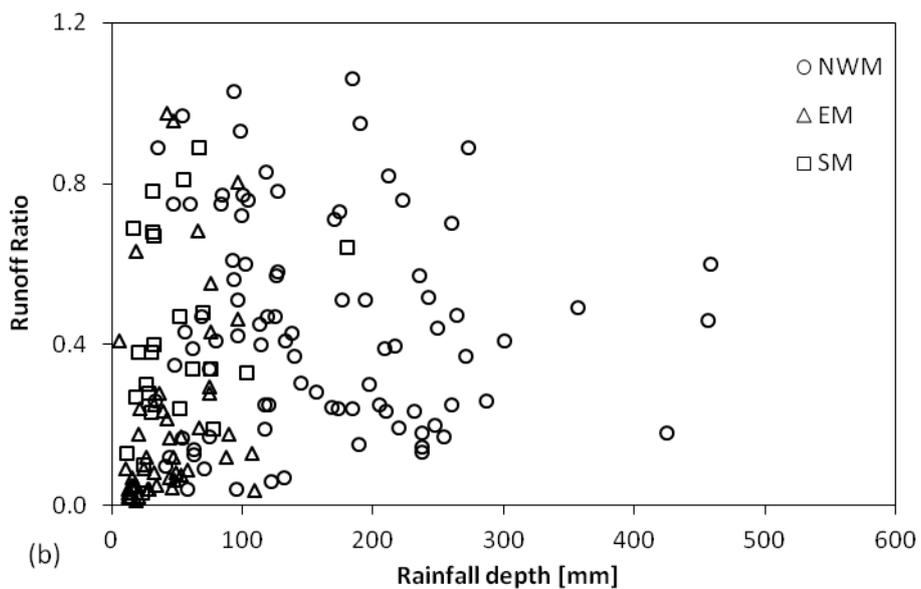


1221



1241

1242



1243

1244 **Fig. 7** Relationship between runoff depth and rainfall depth (a), and between runoff ratio and
1245 rainfall depth (b).

1246

1247

1248

1249

1250 **Table 1** Characteristics of the annual water balance studies in Mediterranean catchments.
 1251 Nc: number of catchments; Ac: catchment area; Zc: catchment mean elevation; Period:
 1252 period or number of years used to calculate the water balance components.

Region	Country	Study	Nc	Ac range (km ²)	Zc range (m)	Period/Number of years	
NWM	France	Adamovic et al. 2014	4	16.7 - 103	892 - 1142	2000 - 2008	
		Lespinas et al. 2014	6	130 - 4957	367 - 1076	1960 - 2004	
		Trambly et al. 2013	1	1808	-	1984 - 2010	
		Coustau et al. 2012	1	114	-	1994 - 2008	
		Fox et al. 2012	1	234	0 - 144	1950 - 2003	
		Goswami et al. 2007	3	150-291	79 - 850	1995 - 2003	
		Moussa et al. 2007	1	545	123 - 1567	1975 - 1984	
	Italy	Tayfur et al. 2014	1	137	250 - 887	1989 - 2010	
		Pumo et al. 2013	1	9.5	792	1957 - 2004	
		De Giroloma and La Porto 2011	1	488	70 - 960	1996 - 2007	
		Longobardi and Vallini 2008	28	18 - 5586	240 - 1397	6 - 65	
		Fiorentino et al. 2007	2	462 - 511	-	1951 - 1961	
		Burlando and Russo 2002	1	4000	1000	1953 - 1992	
		Brath and Montanari 2000	1	1294	20 - 2121	1923 - 1970	
	Portugal	Nunes et al. 2011	1	290	-	1961 - 1990	
		Spain	Bernal et al. 2013	1	2.05	650-1343	1983 - 2010
			Candela et al. 2012	1	615	20-1200	1984 - 2008
			Gallart et al. 2011	2	504-1386	-	1940 - 2000
		Delgado et al. 2010	1	256	-	1940 - 2001	
		Estrany et al. 2010	1	1.03	0-144	1974 - 2006	
		Lana-Renault et al. 2007	1	2.84	910-1340	1999 - 2005	
		Ceballos and Schnabel 1998	1	0.35	378	1991 - 1997	
Pinol et al. 1997		2	0.38-0.51	680-1084	1981 - 1988		
EM		Cyprus	Hessling 1999	5	23 - 234	115 - 1400	1989 - 1994
	Greece		Koutroulis et al. 2013	15	22-1294	-	1970 - 1999
		Nikolaidis et al. 2013	1	132	0 - 2120	1973 - 2010	
		Vasiliades and Loukas 2007	7	133 - 6591	415 - 1400	1960 - 2002	
		Tzoraki and Nikolaidis 2007	1	149	0 - 2356	-	
		Naidas 2005	12	154 -1118	565-1509	5 - 10	
	Israel	Rimmer and Salingar 2006	1	783	-	1969 - 2004	
	Lebanon	Sene et al. 2001	16	77 - 1815	-	1967 - 1974	
	Turkey	Kukul et al. 2007	1	17200	220	-	
		Fujihara et al. 2008	1	21700	-	1990 - 2004	
	SM	Algeria	Bakreti et al. 2013	5	236 - 1819	205 - 760	1975 - 2006
Mehaiguene et al. 2012			24	95 - 2526	153 - 1139	30	
Benkaci Ali and Dechemi 2004			1	575	-	1979 - 1989	
Morocco		Bouabid and Chafai Elalaoui 2010	4	-	-	1959 - 2009	
		De Jong et al. 2008	1	1239	1500 - 4071	1963 - 1998	
Tunisia	Raotlot and Albergel 2006	1	2.45	-	1995 - 2002		
	Bouraoui et al. 2005	1	16000	132 - 1373	1988 - 1999		

1253

1254

1255

1256

1257

1258 **Table 2** Summary statistics of climatic and hydrological variables for the studied catchments
 1259 (Table 1 and Fig. 1b) for the three Mediterranean sub-regions (NWM, EM and SM). MAP:
 1260 Mean Annual Precipitation; ET0: reference evapotranspiration; MAQ: Mean Annual Runoff.

		MAP (mm)	ET0 (mm)	MAQ (mm)	ET0/MAP (-)	MAQ/MAP (-)
NWM	Min-Max	589 -1892	775 -1617	33 -1579	0.45 - 2.21	0.06 - 1.21
	Median	1113	933	485	0.84	0.46
	Interquartile range	891 -1366	868 - 990	319 - 763	0.67 -1.04	0.32 - 0.62
EM	Min-Max	428 -1718	957 - 1517	12 - 1437	0.62 - 2.91	0.02 - 0.99
	Median	924	1391	105	1.56	0.17
	Interquartile range	713 -1294	1120 -1444	105 - 649	1.02 - 1.99	0.06 - 0.57
SM	Min-Max	257 -1100	519 - 2382	4 - 460	1.07 - 4.29	0.01 - 0.73
	Median	376	1157	33	2.88	0.08
	Interquartile range	327 - 433	811 - 1272	15 - 56	2.39 - 3.19	0.05 - 0.14

1261
 1262
 1263
 1264
 1265
 1266
 1267
 1268
 1269
 1270
 1271
 1272
 1273
 1274
 1275
 1276
 1277
 1278
 1279
 1280
 1281
 1282
 1283
 1284
 1285

1286 **Table 3** The main objectives and the models used for continuous streamflow simulation
 1287 studies in the Mediterranean.

Theme	Objectives	Region	Study	Model	
Simulation	Assessment of model performance	NWM	Delgado et al. 2010	HYLUC	
			Franchini and Pacciani 1991	STANFORD IV;TANK; APIC; SACRAMENTO; SSARR; XINANJIANG ; ARNO	
		EM	Pisinaras et al. 2010	SWAT	
			Hessling 1999	PHASE	
		SM	Raclot and Albergel 2006	WEPP	
			Bouraoui et al. 2005	SWAT	
			Benkaci Ali and Dechemi 2004	GR3J, CREC, ARMAX	
		Improve model performance and reduce uncertainty	NWM	Tayfur et al. 2014	GRNM
				Milella et al. 2012	DREAM
				Loiaza Uzuga and Pauwels 2008	TOPLATS
	Gallart et al. 2007			TOPMODEL	
	New model development	NWM	Silvestro et al. 2013	Continuum model	
			Moussa et al. 2007	ModSpa	
	Streamflow simulation with limited data	EM	Hreiche et al. 2005	MEDOR	
			Ramadan et al. 2012	HRR	
	Karstic catchment	EM	Hartmann et al. 2013	Conceptual reservoirs models	
			Nikolaidis et al. 2013	Modified SWAT	
			Kourgialas et al. 2010	HSPF coupled to a snowmelt model and a conceptual Karstic reservoir and a karstic channel model	
			Tzoraki and Nikolaidas 2007	HSPF coupled to a 2-reservoirs karstic model	
			Rimmer and Salingar 2006	HYMKE	
Scenario testing	LUC impact	NWM	De Girolama and La Porto 2012	SWAT	
			Estrany et al. 2010	Thornwaite-Mather model	
	CC impact	NWM	Candela et al. 2012	HEC-HMS coupled to VisualBALAN	
			Nunes et al. 2008, 2011	SWAT	
			Senatore et al. 2011	In-STRHym	
			Burlando and Russo 2002	PRMS	
			Hreiche et al. 2007	MEDOR	
	LUC & CC impact	NWM	Bakreti et al. 2013	Hydrological indices	
			Bouabid and Chafai ELalaoui 2010	IHACRES, HEC-HMS	
			Collet et al. 2013	GR4J	
	Erosion	NWM	D'Agostino et al. 2012	DiCaSM	
			Gallart et al. 2011	SACRAMENTO ; Zhang Eq.	
			Ceballos-Barbancho et al. 2008	Statistical Analysis	
			Gallart and Llorens 2004	Annual Water balance (Dooge et al. 1999)	
			EM	Albek et al. 2004	HSPF
SM			Lesschen et al. 2009	LAPSUS	
			Raclot and Albergel 2006	WEPP	

1289 **Table 4** Summary of existing regionalization studies for continuous runoff simulation in the
 1290 Mediterranean. Statistical evaluation indicates the leave-one-out assessment of the regionalization
 1291 approach performance with the Nash-Sutcliffe (NSE) efficiency criterion. Nc: total number of
 1292 catchments and the number in brackets represents the number of Mediterranean catchments in the
 1293 larger dataset. Methods used for transfer of hydrologic model parameters include: SP: physical
 1294 similarity; S: similarity; MA: model averaging; R: two-step parameter regression; and RC: regional
 1295 calibration. The performances of the regionalization approaches are not reported when they were
 1296 available for the whole set of catchments and not particularly for the Mediterranean cases.

Study	Country	Nc	Hydrologic model	Time step	Regionalization method	Performance (NSE)
Castiglioni et al. 2010	Italy (Central)	52	HYMOD	Daily	R	0.53
Cutore et al. 2007	Italy (Eastern Sicily)	9	Regression-based RR model	Monthly	R; RC	0.59; 0.66
Oudin et al. 2010	France	850	GR4J; TOPMO	Daily	S	-
Oudin et al. 2008	France	913 (162)	GR4J; TOPMO	Daily	SP, S, R	-
Goswami et al. 2007	France	12 (3)	Combination of models	Daily	MA, RP	-
Vicente-Guillen et al. 2012	Spain	8	Exponential model	Monthly	R	0.9

1297

1298 **Table 5** Summary assessment of existing regionalization studies for Flow Duration Curve (FDC) in
 1299 the Mediterranean. Statistical evaluation indicates the leave-one-out assessment of the regionalization
 1300 approach. NSE: Nash-Sutcliffe efficiency criterion; MSE: mean square error; RMSE: root mean square
 1301 error;

Study	Country	Nc	FDC approach	Predicted variable	Performance criterion	Performance
Sellami et al. 2014	France (South)	10	Modelling	FDC	NSE	-
Longobardi and Vallini 2013	Italy (South)	28	Statistical	FDC	RMSE	0.014 - 0.498
Mendicino and Senatore 2013	Italy (South)	19	Statistical Parametric	FDC	NSE	>0.75 for more than 78% of cases for all models; >0.75 for more than 52% of cases for all models
Rianna et al. 2011	Italy (Lazio)	28	Statistical	FDC	NSE	>0.95 for 54% of cases
Viola et al. 2011	Italy (Sicily)	53	Parametric	FDC	RMSE	0.24 – 0.38
Castellarin et al. 2007	Italy (Eastern Central)	18	Statistical	FDC	NSE	As figure
Castellarin et al. 2004	Italy (Eastern Central)	51	Statistical Parametric Graphical	FDC	NSE	>0.75 for 29 % of cases; >0.75 for 31% of cases; >0.75 for 22% of cases
Franchini and Suppo 1996	Italy (Molise)	16	Parametric	FDC	-	-
Croker et al. 2003	Portugal	67	Statistical	FDC	BIAS (%)	12 sites with BIAS > 75%
Mimikou and Keamaki 1985	Greece	11	Parametric	FDC	MSE (%)	3 - 10

1302

1303

1304

1305

1306 **Table 6** Summary information of the flood studies on Fig. 1c. Nc: number of catchments; Ne:
 1307 number of events; Ac: catchment area; X: available data; and (-) not available.

Region	Country	Study	Nc	Ne	Ac (km ²)	Available data			
						Peak Discharge	Rainfall Depth	Runoff Depth	Event duration
NWM	France	Nguyen et al. 2014	18	13	6 - 2240	X	-	-	-
		Garambois et al. 2013	6	9	144 - 619	X	X	-	-
		Artigue et al. 2012	1	4	222	X	X	-	-
		Coustau et al. 2012	1	21	114	X	X	X	-
		Tramblay et al. 2010	1	20	3.83	X	X	X	X
		Vincendon et al. 2010	4	4	1090 - 1910	X	X	-	X
	Italy	De Waele et al. 2010	1	1	105	X	X	-	-
		Sangati et al. 2009	6	3	75 - 2586	X	X	X	X
		Borga et al. 2007	10	1	23.9 - 1843	X	X	X	X
		Brath et al. 2004	1	15	1050	X	X	X	X
	Slovenia	Zanon et al. 2010	4	1	31.8 - 211.9	X	X	X	X
Spain	Lana-Renault et al. 2014	2	5	3340 - 4915	X	X	X	-	
	Amengual et al. 2007	5	1	0.12 – 2.84	X	X	-	X	
EM	Greece	Massari et al. 2014	1	16	109	X	X	X	X
		Koutroulis and Tsanis 2010	1	9	158	X	X	X	X
	Israel	Rozalis et al. 2010	1	20	27	X	X	X	X
	Lebanon	Sene et al. 2001	16	16	102 - 1345	X	-	-	-
NWM & EM	NWM & Israel	Tarolli et al. 2012	12	12	12 - 699	X	X	X	X
SM	Morocco	Tramblay et al. 2012	1	16	665	X	X	X	X
	Tunisia	Abida and Ellouze 2008	42	-	3.2 - 16330	X	-	-	-
		Nasri et al. 2004	2	4	3.16 – 18.1	X	X	X	-

1308

1309

1310

1311

1312

1313

1314

1315

1316

1317

1318

1319

1320

1321

1322

1323

1324 **Table 7** The main objectives and the models used for event-based studies in the
 1325 Mediterranean.

Theme	Objectives	Region	Study	Model	
Simulation	Catchment characteristics and wetness conditions impact on catchment response	NWM	Huza et al. 2014	Field data analysis	
			Molina et al. 2014	Field data analysis	
			Manus et al. 2010	Tailor model in LIQUID	
			Tramblay et al. 2010	SCS CN	
			Brocca et al. 2008	A water balance	
			Fiorentino et al. 2007	DREAM	
			Brath and Montanari 2000	SCS CN	
		EM	Massari et al. 2014	MISD & SCRRM	
		SM	Tramblay et al. 2012	SCS CN	
	Runoff generation processes and catchment hydrological response	NWM	Gallart et al. 2007, 2008, 2011	Rainfall-Runoff relationships, Water table dynamics; TOPMODEL	
			Lana-Renault et al. 2007	Rainfall-Runoff relationships, Water table dynamics	
	Peak flood estimation and flash floods characterization	NWM	Roux et al. 2011	MARINE	
			Gaume and Bouvier 2004	SCS CN	
			Gaume et al. 2003, 2004	SCS CN ;	
EM		Koutroulis and Tsanis 2010	Empirical Eq.		
		Rozalis et al. 2010	Modified SCS		
	SM	Nasri et al. 2004	A Geomorphological model		
Impact of data and parameters input on model performance	NWM	Maneta et al. 2005	5-parameters overland flow model		
		Brath et al. 2004	SCS CN		
Scenario Testing	Land cover impact of floods	NWM	Cosandey et al. 2005	HRR	
			Lana-Renault et al. 2011	Paired catchments	
	Climate Change impact	NWM	Mediero et al. 2014	MEFIDIS	
			Nunes et al. 2011	Trend Analysis	
	Fire impact on floods	NWM	Mayor et al. 2007	Paired catchments	
		EM	Vafeidis et al. 2007	Paired catchments	
	Flood risk mitigation	NWM	Ballestros-Canevos et al. 2013	HEC-HMS	
			EM	Kumuscu and Celik 2013	Hydro-meteorological analysis
			Gul et al. 2010	HEC-HMS	

1326

1327

1328

1329

1330

1331

1332

1333

1334 **Table 8** Summary of existing regionalization studies for floods in the Mediterranean.
 1335 Statistical evaluation indicates the leave-one-out assessment of regionalization approach.
 1336 Methods used include: IM: Index Methods; PB: Process based methods; RR: Regional
 1337 Regression models (RR). Notations: Nc : number of catchments ; Q(2, 10, 100) : flood of 2,
 1338 10 and 100 years return period; Q100/Qm : Q100 normalized by the mean annual flow ;
 1339 MAF : maximum annual flow; (-): information not retrievable.

Study	Country	Nc	Regionalization method	Predicted Variable	Performance criterion	Performance
Artigue et al. 2012	France (South)	1	PB	Peak flow	NSE & % of Peak Discharge	-
Javelle et al. 2010	France (South)	160	PB	Peak flow	Peak Error	-
Shentsis et al. 1997	Israel	67	RR	Peak flow	RMSE	-
Bocchiola and Rosso 2009	Italy (Northwest)	16	IM	Peak flow	Dimensionless MSE (%)	8 - 69
Aronica and Candela 2007	Italy (Sicily)	6	IM	Peak flow	Comparison with observed	-
Ferro and Porto 2006	Italy (Sicily)	43	IM	MAF	MSE	-
Portela and Dias 2005	Portugal	120	IM	Q2	Correlation coefficient	0.774 - 0.929
Mediera and Kjeldsen 2014	Spain	93	IM	Q(2, 10, 100)	RMSE	-
Cherif and Bargaoui 2013	Tunisia	32	IM	Q100	RMSE	0.29 - 0.46
Saf 2009	Turkey (West)	47	IM	Q100/Qm	RMSE	0.43
Topaloglu 2005	Turkey	50	IM	MAF	Prediction Error (%)	49 - 56

1340

1341

1342

1343

1344

1345

1346

1347

1348

1349

1350

1351

1352

1353

1354

1355

1356

1357

1358

1359

1360 **Table 9** Main objectives, methods and periods of the chosen droughts studies. Nc: number of
 1361 catchments.

Region	Country	Study	Nc	Period
NWM	France	Ruffault et al. 2013	-	1971 - 2006
		Vidal et al. 2012	-	1957 - 2007
		Chaouche et al. 2010	13	1970 - 2006
	Italy	Capra et al. 2013	-	1921 - 2007
		Diodato and Bellocchi 2008	-	1961 - 2006
		Mendicino et al. 2008	16	1957 - 2007
	Spain	Terrado et al. 2014	1	1951 - 2000
		Vincento-Serrano et al. 2014	-	1961 - 2011
		Lopez-Bustins et al. 2013	3	1984 - 2008
		Marquèz et al. 2013	1	1971 - 2100
		Bangash et al. 2012	1	2002 - 2006
		Gomez and Blanco 2012	1	1941 - 2009
		Ruiz-Sinoga et al. 2012	-	1964 - 2008
		Lorenzo-Lacruz et al. 2010	3	1961 - 2006
		Vincento-Serrano and Lopez-Merano 2005	1	1950 - 2000
	Spain & Portugal	Vicento-Serrano 2006	-	1910 - 2000
EM	Greece	Vrochidou et al. 2013	1	1974 - 1999
		Tigkas et al. 2012	6	1970 - 1997
		Mavromatis and Stathis 2011	-	1961 - 2006
		Vasiliades and Loukas 2009	7	1960 - 2002
		Tsakiris et al. 2007	2	1962 - 2001
	Israel	Aviad et al. 2009	-	1960 - 1990
		Kafle and Bruins 2009	-	1970 - 2002
	Lebanon	Shaban et al. 2009	-	1963 - 2007
	Turkey	Dogan et al. 2012	1	1972 - 2009
		Yilmaz and Harmancioglu, 2010	1	1995 - 2003
		Turkes and Tutli 2009	-	1929 - 1993
SM	Algeria	Hamlaoui-Moulai et al. 2013	4	1914 - 2004
		Hamlat et al. 2012	4	2006 - 2030
	Morocco	Esper et al. 2007	-	1050 -2000
	Tunisia	Abouabdillah et al. 2010	1	1992 - 1996

1362

1363

1364

1365

1366

1367

1368

1369

1370

1371

1372

1373

1374

1375 **Table 10** The main objectives and methods used for the chosen drought studies in the
 1376 Mediterranean.

Theme	Objectives	Region	Country	Study	Methods		
Simulation	Drought Analysis	NWM	France	Vidal et al. 2012	ISBA model; SPI & SWI		
			Italy	Diodato and Bellocchi 2008	Cy; HPR; MCDI		
			Spain	Ruiz-Sinoga et al. 2012	DDSLR index		
			Spain, Portugal	Vicento-Serrano 2006	SPI		
		EM	Greece	Tsakiris et al. 2007	RDI; SPI		
				Tigkas et al. 2012	RDI & SDI & Medbasin model		
			Lebanon	Shaban et al. 2009	Hydrological Drought indices		
			Israel	Aviad et al. 2009	DDSLR		
			SM	Algeria	Hamlaoui-Moulai et al. 2013	Trend analysis, PCA	
		Morocco		Esper et al. 2007	PDSI & Cedar Trees ring width		
		Efficacy of Drought indices	NWM	Italy	Mendicino et al. 2008	GRI	
				Spain	Vicento-Serrano and Lopez-Merano 2005	SPI	
			EM	Greece	Vasiliades and Loukas 2009	PDI & UTHBAL model	
				Turkey	Dogan et al. 2012	PN-Mean; RDDI; Z-score; CZI; SPI; EDI	
			Scenarios testing	Water resources management	NWM	Spain	Turkes and Tutli 2009
Terrado et al. 2014	InVEST model						
Bangash et al. 2012	MIKE BASIN model						
Gomez and Blanco 2012	Risk Assessment model						
Climatic trends		EM	Turkey	Yilmaz and Harmancioglu 2010	WEAP model		
			SM	Algeria	Hamlat et al. 2012	WEAP model	
		NWM		France	Chaouche et al. 2010	Climatic trends	
			Spain	Vicento-Serrano et al. 2014	12 methods for ET0 estimation		
		CC Impact		EM	Greece	Mavromatis and Stathis 2011	Trends in Hydrological parameters
					Israel	Kafle and Bruins 2009	Climatic trends
NWM	France				Ruffault et al. 2013	SIERRA model	
	Italy			Capra et al. 2013	SPI		
SM	Spain			Lopez-Bustins et al. 2013	SWAT model; SPI & SPEI		
		Marquèz et al. 2013	InVEST model				
	EM	Greece	Lorenzo-Lacruz et al. 2010	SPI and SPEI			
			Vrochidou et al. 2013	IHMS-HBV model			
SM	Tunisia	Abouabdillah et al. 2010	SWAT model				

1377

1378

1379

1380

1381

1382

1383 **Table 11** Summary of existing regionalization studies for low flows in the Mediterranean.
 1384 Statistical evaluation indicates the leave-one-out assessment of the regionalization approach.
 1385 Methods used include: PSBI: Physiological Space-Based Interpolation; G: Geo-statistical
 1386 methods; GR: Global Regression; and RR: Regional Regression. Notations: Nc: number of
 1387 catchments; BFI: baseflow index; Q355: discharge associated with duration of 355 days;
 1388 Q95%: discharge equalled or exceeded 95% of the time.

Study	Country	Nc	Regionalization method	Predicted Variable	Performance criterion	Performance
Mehaiguene et al. 2012	Algeria (Northwest)	24	GR RR	BFI	R ²	0.32; 0.82 - 0.92; 0.70 - 0.99
Castiglioni et al. 2011	Italy (Centre)	51	PSBI G	Q355	NSE	0.78 - 0.83 0.89
Veza et al. 2010	Italy (Northwest)	41	GR RR	Q95%	R ²	0.657 0.531 - 0.687
Castiglioni et al. 2009	Italy (Centre)	51	D G GR	Q355	NSE	0.64 - 0.65 0.31 - 0.81 0.72
Longobardi and Vallini 2008	Italy (South)	28	GR	BFI	R ²	0.230 - 0.678

1389

1390

1391

1392

1393

