Hydrological of Mediterranean catchments: a review

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

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

Caractéristiques se la réponse hydrologique des bassins versants méditerranéens à pas de temps différents

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

Mots-clefs hydrologie; basin versant Méditerranéen ; bilan annuel; pluie-débit; crues; sécheresse; modélisation

1 INTRODUCTION

1.1 The Mediterranean as a focus of research

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

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

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

1.2 Objectives of the review

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

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

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

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

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

2 THE MEDITERRANEAN REGION

2.1 Boundary of the Mediterranean region

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

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

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

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

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

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

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

2.2 Physical characteristics of the Mediterranean region

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

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

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

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

3 REVIEW EXTENT AND DATABASE

3.1 Review information

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

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

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

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

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

(i) Basin location (reference and coordinates)

(ii) Study objectives

(iii) Basin characteristics, such as the area, mean elevation, mean slope, land use, soil classes, geology and the possible presence of karst;

(iv) Hydro-meteorological data characteristics, such as the rainfall-runoff measurement period, the time step of the measurements, the mean annual precipitation, the reference evapotranspiration, the mean annual runoff, the runoff coefficient and the snow contribution; for event-based studies, detailed information on catchment responses (rainfall, runoff, peak discharge) for each event was also extracted when available;

(v) (*v*) Mode characteristics, such as the model name and original reference, the simulated hydrological processes, the spatial resolution (lumped, semi-distributed or distributed), the time step and the model evaluation criteria.

3.2 Annual water balance studies

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

3.3 Rainfall-Runoff event-based studies

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

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

3.4 Drought studies

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

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

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

4 HYDROLOGICAL RESPONSE CHARACTERISTICS

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

4.1 Annual water balance studies

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

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

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

To investigate the climatic features of Mediterranean catchments, a Budyko-type plot (Budyko 1974, Andréassian and Perrin 2012) (Fig. 3) shows the mean annual runoff coefficient MAQ/MAP as a function of the aridity index AI = ET0/MAP. When ET0/MAP<1, wet conditions prevail. When ET0/MAP>1, dry climatic conditions prevail. The lines MAQ/MAP=1 and MAP=MAQ+ET0 represent the water and energy limits. Catchments are expected to fall within these limits for a closed water balance. Otherwise, the catchment is either gaining (catchment with MAQ/MAP>1) or losing (catchment with MAP<MAQ+ET0) water, or there might be errors in the data. Four catchments fall outside the water or energy limits. These catchments are karstic (e.g., Nikolaidis et al. 2013 [Greece], Longobardi and Vallini 2008 [Italy]), which may explain the presence of underground water gain or loss processes. Most catchments (60%) can be considered water-stressed, with an aridity index greater than 1.

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

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

4.2 Rainfall-runoff event-based studies

4.2.1 Rainfall events: amount and duration

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

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

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

4.2.2 Peak discharge

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

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

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

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

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

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

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

4.2.3 Runoff ratio

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

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

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

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

4.3 Drought studies

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

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

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

5 OBJECTIVES AND METHODS OF HYDROLOGICAL STUDIES

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

5.1 Annual water balance studies

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

(1) “simulation”: characterization of hydrological processes, model performance assessment, model uncertainty reduction, development of new models, streamflow simulation with limited data and karstic zone modelling;

(2) “scenario testing”: assessment of the impacts of different scenarios of land use change (LUC) and climate change (CC) on water resources and erosion.

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

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

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

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

5.2 Rainfall-runoff event-based studies

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

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

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

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

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

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

5.3 Drought studies

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

(1) "simulation": characterization of the temporal and spatial variations of droughts and the methods for drought assessment;

(2) "scenario testing": assessment of the impact of different scenarios (climatic, anthropogenic, etc.) on drought characteristics in a catchment or region.

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

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

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

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

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

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

6 DISCUSSION AND PERSPECTIVES

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

6.1 Can we identify regional patterns in the Mediterranean?

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

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

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

6.2 What is required to model Mediterranean catchments?

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

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

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

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

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

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

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

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

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

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

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

Table 2 Summary information of the flood studies on Fig. 1c. Nc: number of catchments; Ne: number of events; Ac: catchment area; X: available data; and (-) not available.

Table 3 Summary information of the chosen droughts studies on Fig. 1d. Nc: number of catchments.

Table 4 Summary statistics of climatic and hydrological variables for the studied catchments (Table 1 and Fig. 1b) for the three Mediterranean sub-regions (NWM, EM and SM). MAP: Mean Annual Precipitation; ET0: reference evapotranspiration; MAQ: Mean Annual Runoff.

Table 5 The main objectives and the models used for continuous streamflow simulation studies in the Mediterranean.

Table 6 The main objectives and the models used for event-based studies in the Mediterranean.

Table 7 The main objectives and methods used for the chosen drought studies in the Mediterranean.

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

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

Fig. 3 Plot of mass balance data from the study catchments on the Budyko diagram: the mean annual runoff coefficient MAQ/MAP function of the aridity index ET0/MAP/ MAP: Mean Annual Precipitation; MAQ: Mean Annual Runoff; ET0: Mean Annual Reference Evapotranspiration for the 3 sub-regions NWM, EM and SM; Plain symbols indicate karstic catchments in each sub-region.

Fig. 4 Monthly distribution of events per geographic region.

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

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).

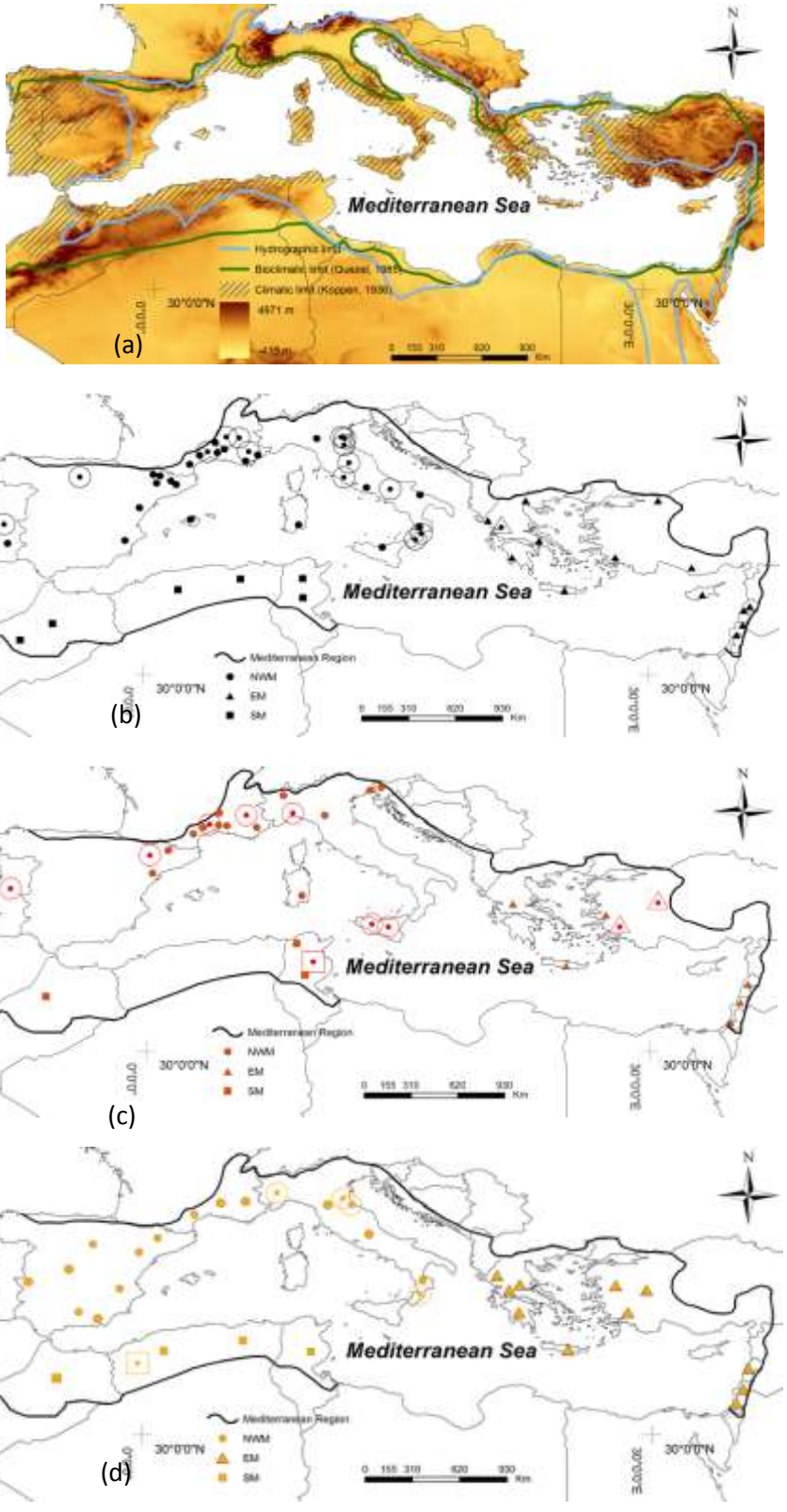


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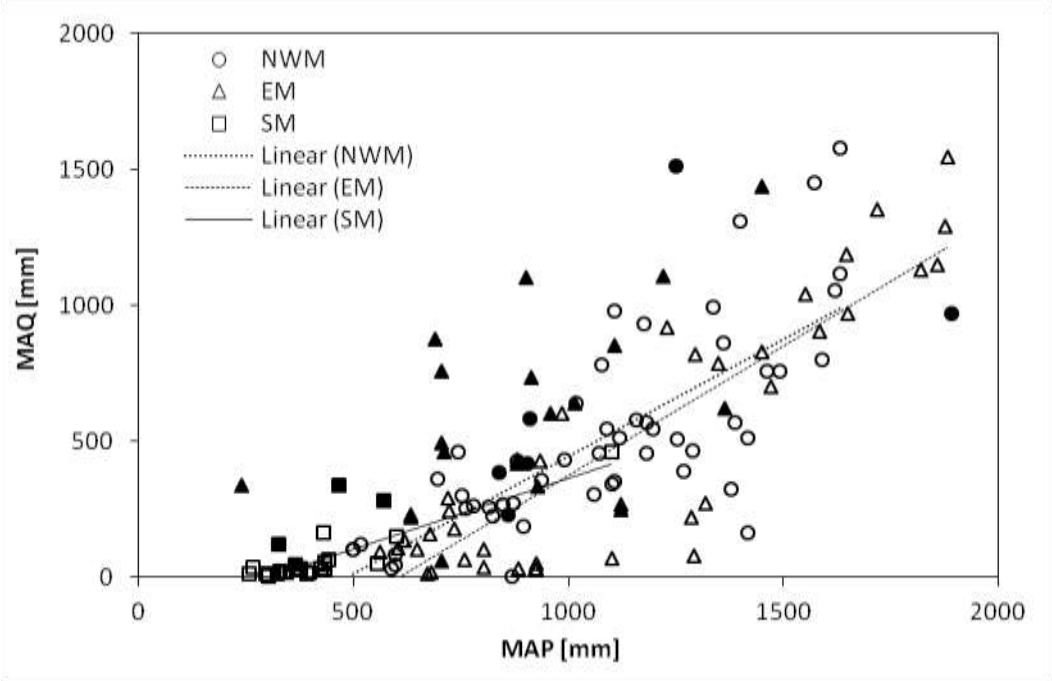


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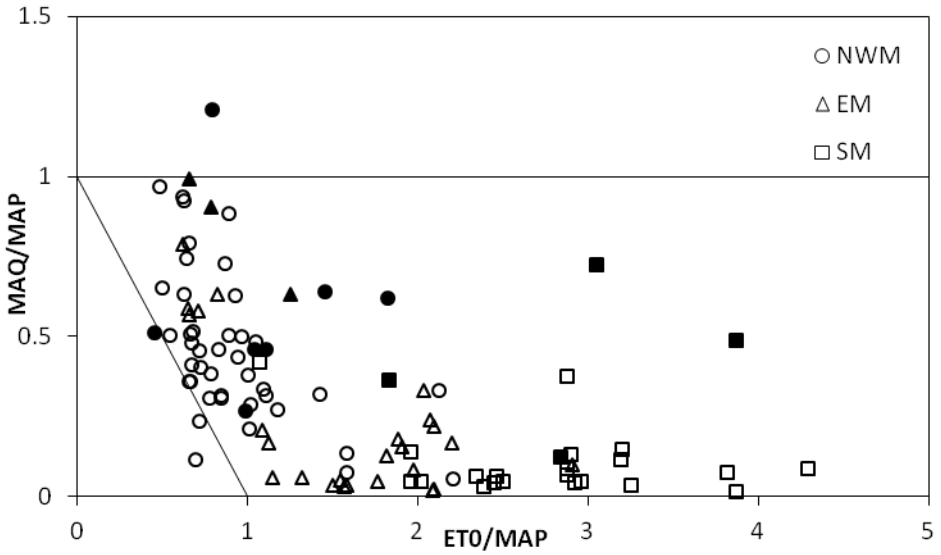


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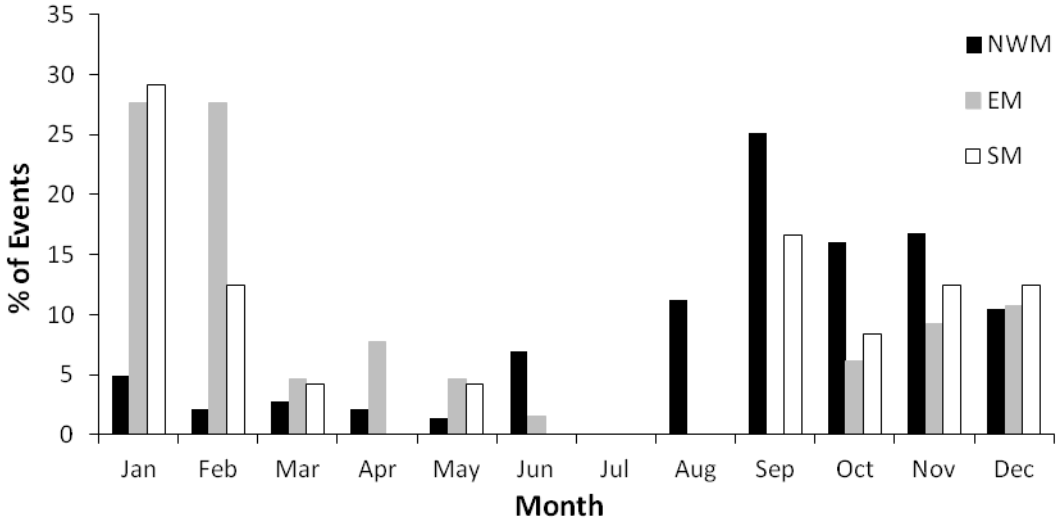


Fig. 4 Monthly distribution of events per geographic region.

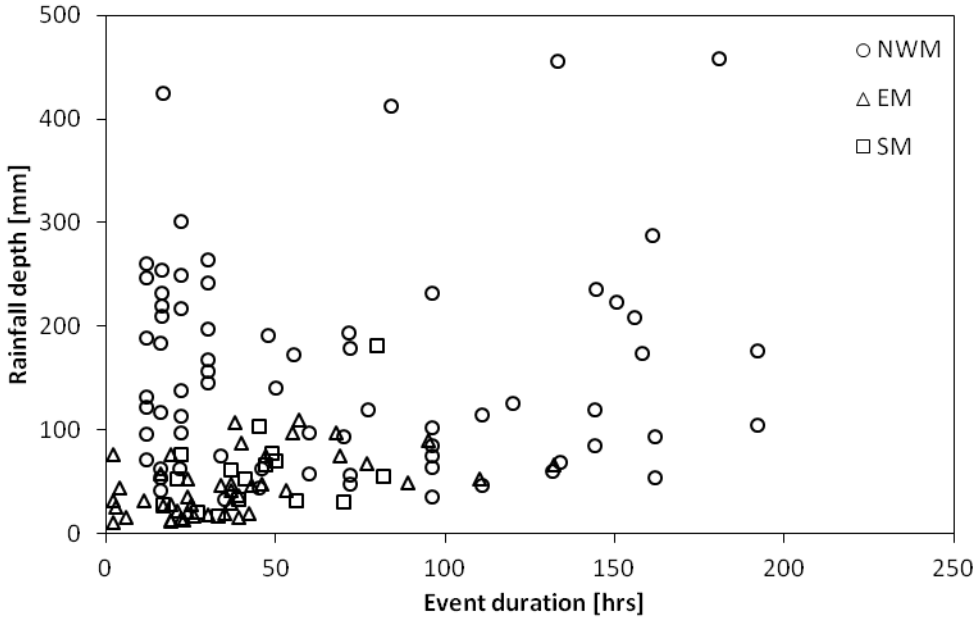
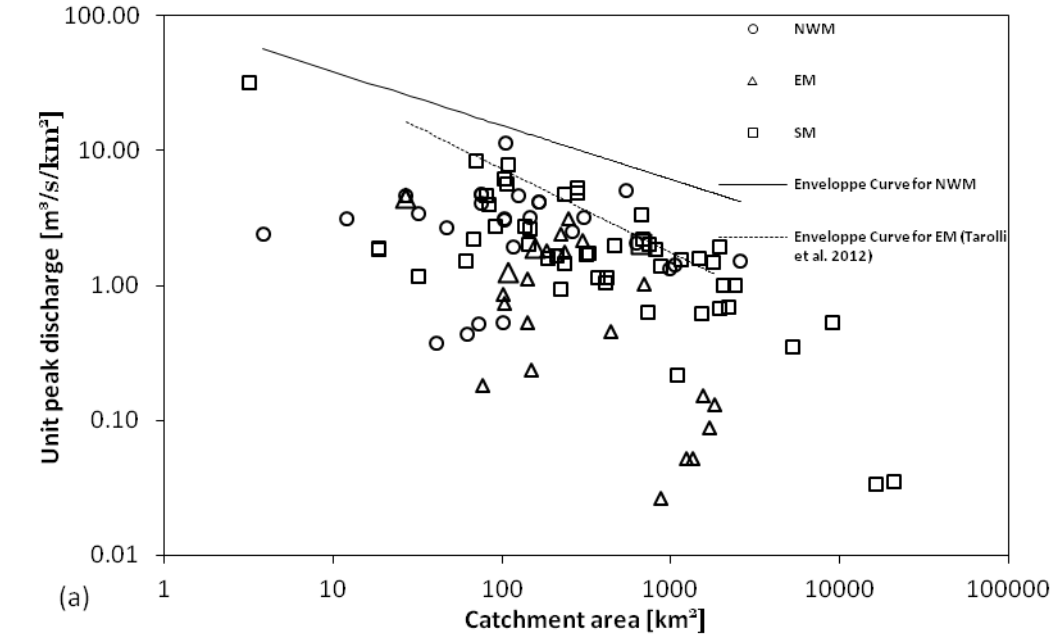
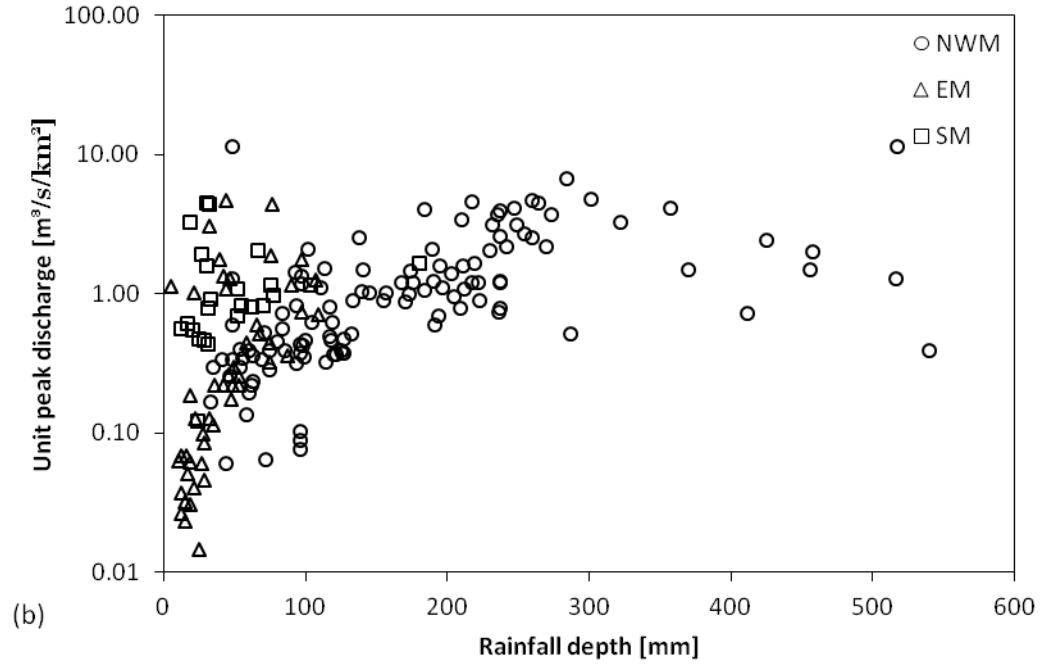


Fig. 5 Relationship between rainfall depth and event duration for the studied events on the three studied sub-regions (NWM, EM and SM).


100.00
10.00
1.00
0.10
0.01
Unit peak discharge [m³/s/km²]
NWM
EM
SM
Enveloppe Curve for NWM
Enveloppe Curve for EM (Tarolli et al. 2012)
(a)
1
10
100
1000
10000
100000
Catchment area [km²]

1220


100.00
10.00
1.00
0.10
0.01
Unit peak discharge [m³/s/km²]
NWM
EM
SM
(b)
0
100
200
300
400
500
600
Rainfall depth [mm]

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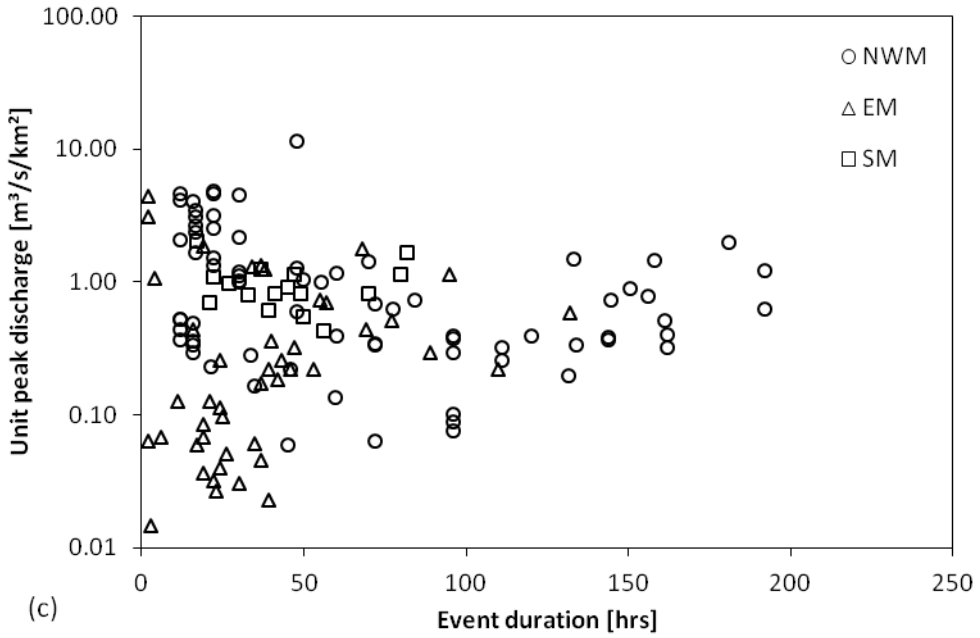
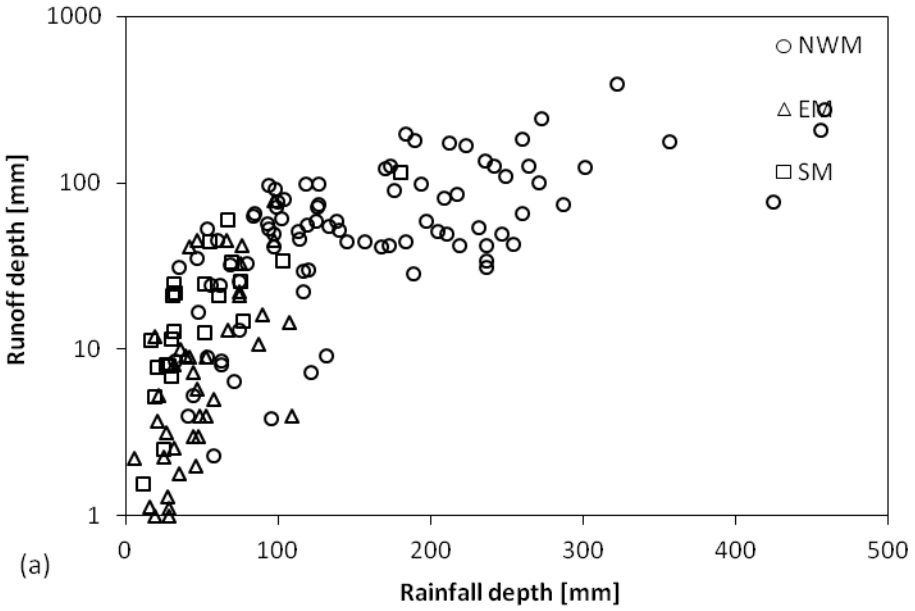


Fig. 6 Relationship between unit peak discharge and (a) catchment area, (b) rainfall depth and (c) event duration.



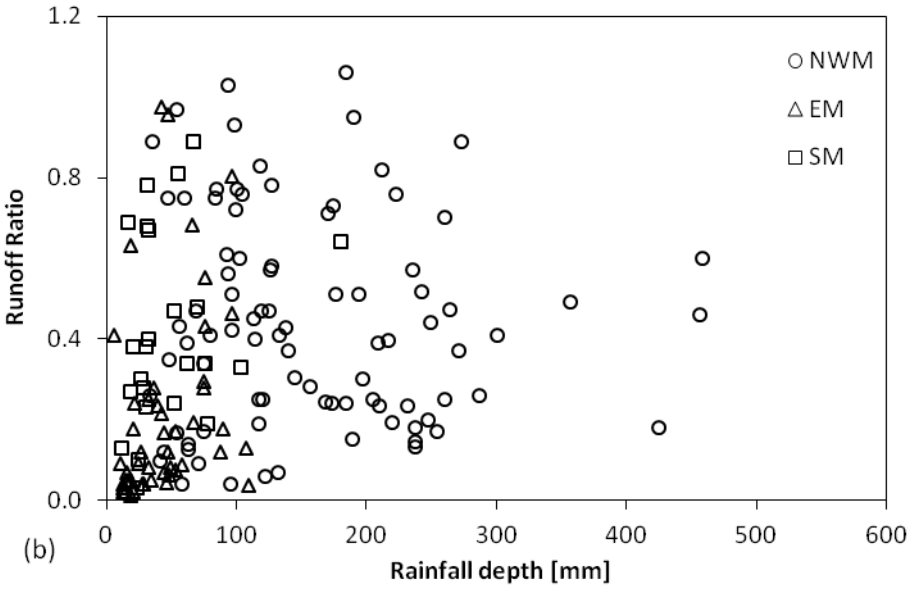


Fig. 7 Relationship between runoff depth and rainfall depth (a), and between runoff ratio and rainfall depth (b).

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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
		Tramblay 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	Raclot and Albergel 2006	1	2.45	-	1995 - 2002
		Bouraoui et al. 2005	1	16000	132 - 1373	1988 - 1999

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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

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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
		EM	Hreiche et al. 2005	MEDOR
	Streamflow simulation with limited data	EM	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 kartic 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	ln-STRHym
			Burlando and Russo 2002	PRMS
		EM	Hreiche et al. 2007	MEDOR
		SM	Bakreti et al. 2013	Hydrological indices
			Bouabid and Chafai ELalaoui 2010	IHACRES, HEC-HMS
	LUC & CC impact	NWM	Collet et al. 2013	GR4J
			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
	Erosion	NWM	Lesschen et al. 2009	LAPSUS
		SM	Raclot and Albergel 2006	WEPP

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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

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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

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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 (km²)	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	-

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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

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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

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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

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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	Vincento-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
				Turkes and Tutli 2009	SPI & modified SPI
Scenarios testing	Water resources management	NWM	Spain	Terrado et al. 2014	InVEST model
				Bangash et al. 2012	MIKE BASIN model
				Gomez and Blanco 2012	Risk Assessment model
		EM	Turkey	Yilmaz and Harmancioglu 2010	WEAP model
		SM	Algeria	Hamlat et al. 2012	WEAP model
	Climatic trends	NWM	France	Chaouche et al. 2010	Climatic trends
			Spain	Vincento-Serrano et al. 2014	12 methods for ET0 estimation
		EM	Greece	Mavromatis and Stathis 2011	Trends in Hydrological parameters
			Israel	Kafle and Bruins 2009	Climatic trends
	CC Impact	NWM	France	Ruffault et al. 2013	SIERRA model
			Italy	Capra et al. 2013	SPI
			Spain	Lopez-Bustins et al. 2013	SWAT model; SPI & SPEI
				Marquèz et al. 2013	InVEST model
				Lorenzo-Lacruz et al. 2010	SPI and SPEI
		EM	Greece	Vrochidou et al. 2013	IHMS-HBV model
		SM	Tunisia	Abouabdillah et al. 2010	SWAT model

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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
Vezza 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

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