

MEDITERRANEAN WATER RESOURCES IN A GLOBAL CHANGE SCENARIO

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Abstract:

Mediterranean areas of both southern Europe and North Africa are subject to dramatic changes that will affect the sustainability, quantity, quality, and management of water resources. Most climate models forecast an increase in temperature and a decrease in precipitation at the end of the 21st century. This will enhance stress on natural forests and shrubs, and will result in more water consumption, evapotranspiration, and probably interception, which will affect the surface water balance and the partitioning of precipitation between evapotranspiration, runoff, and groundwater flow. As a consequence, soil water content will decline, saturation conditions will be increasingly rare and restricted to periods in winter and spring, and snow accumulation and melting will change, especially in the mid-mountain areas. Future land management will be characterized by forest and shrub expansion in most Mediterranean mountain areas, as a consequence of farmland and grazing abandonment, with increasing human pressure localized only in some places (ski resorts, urbanized of valley floors). In the lowlands, particularly in the coastal fringe, increasing water demand will occur as a consequence of expansion of irrigated lands, as well as the growth of urban and industrial areas, and tourist resorts.

Future scenarios for water resources in the Mediterranean region suggest (i) a progressive decline in the average streamflow (already observed in many rivers since the 1980s), including a decline in the frequency and magnitude of the most frequent floods due to the expansion of forests; (ii) changes in important river regime characteristics, including an earlier decline in high flows from snowmelt in spring, an intensification of low flows in summer, and more irregular discharges in winter; (iii) changes in reservoir inputs and management, including lower available discharges from dams to meet the water demand from irrigated and urban areas. Most reservoirs in mountain areas will be subject to increasing water resource uncertainty, because of the reduced influence of snow accumulation and snowmelt processes. Besides, reservoir capacity is naturally reduced due to increasing sedimentation and, in some cases, is also decreased to improve the safety control of

floods, leading to a reduction in efficiency for agriculture. And (iv) hydrological and population changes in coastal areas, particularly in the delta zones, affected by water depletion, groundwater reduction and saline water intrusion. These scenarios enhance the necessity of improving water management, water pricing and water recycling policies, in order to ensure water supply and to reduce tensions among regions and countries.

Key words: climate change, meteorological and hydrological drought, land use changes, land cover changes, snow accumulation, snowmelt, river regime, stream flow decline, reservoir management, Mediterranean region

1. Introduction

Change is an intrinsic characteristic of the Earth's system. During the Quaternary, long cold and dry periods alternated with relatively short warm periods. Each of these was affected by climatic variability at different temporal scales (Alley et al., 1995; Bradley, 1999). Studies of fluvial, lacustrine, and oceanic sediments have demonstrated the occurrence of periodic changes in climate, runoff, flooding, and plant cover (*e.g.*, Ruddiman, 2000; Benito et al., 2003; Valero et al., 2006). The last significant global cold period, the Little Ice Age, finished at the beginning of the 19th century. The Earth's average temperature has subsequently increased by about 1°C (Hansen et al., 2006), and both temperature and precipitation have exhibited varying wet and dry regional cycles that are well represented in the annual streamflow (Benito et al., 1998; Brito-Castillo et al., 1998; Fekete et al., 2002; Kargapalova, 2008). Nevertheless, it is generally agreed that the intensity and rate of recent changes have no precedent since at least the beginning of the Holocene (Mann et al., 1998; Barnett et al., 2001), and reflect natural environmental changes affected by human activities, which can counteract or enhance natural forces (Nepstad et al., 1999; Levitus et al., 2001).

Increasing efforts are being made to understand the consequences of environmental change for society, particularly in the field of water resource management. Changes in water resources are particularly relevant in areas where water availability is a limiting factor for economic development. This is the case in the Mediterranean basin, where both developed and developing countries have a

common dependence on water availability to meet the needs of increasing populations and living standards, development of irrigated agriculture, and increasing industry and tourism activities (Cudennec et al., 2007). Water availability in the Mediterranean basin is scarce, and mainly dependent on runoff from mountain areas (Ives et al., 2003; Viviroli and Weingartner, 2004; De Jong et al., 2009); these supply 20–50% of the total discharge, but in semi-arid areas including the Mediterranean basin runoff can contribute 50–90% of the total supply (Viviroli and Weingartner, 2004; Viviroli et al., 2008). Challenges will be faced in maintaining the quantity and quality of mountain runoff, through preservation of mountain environments, while ensuring sustainable use of the available water resources (Messerli et al., 2004). Water scarcity is particularly intense in the Maghreb countries, including Libya and Egypt, as well as in some sectors of northern Mediterranean countries, such as southeast Spain and the Ebro Depression, where the expansion of irrigated areas and urbanization has caused increasing water supply difficulties. The disjunction between runoff-producing and water-demanding areas is contributing to increasing political tensions, for instance in Spain and the Middle East, and water supply to the large cities (*e.g.*, Barcelona, Madrid, Athens, Jerusalem, Cairo, Casablanca and Marrakech) requires a high level of investment and complex solutions that are, in general, are not designed for a long-term perspective. In the Mediterranean basin precipitation can be subject to high interannual and seasonal variability, with long and intense dry periods (*e.g.*, Lloyd-Hughes and Saunders 2002; Bonaccorso et al., 2003; Picarreta et al., 2004; Van der Schrier et al. 2006; Vicente-Serrano, 2006; Nicault et al., 2008), or extreme rainfall and floods (*e.g.*, Llasat and Puigcerver, 1997; White et al., 1997; García-Ruiz et al., 2000; Brunetti et al., 2002; Peñarrocha et al., 2002; Klein-Tank and Können, 2003; Martius et al., 2006; De Jong et al., 2008; Martín-Vide et al., 2008, Nuissier et al., 2008; Beguería et al., 2009). Consequently, water is relatively scarce throughout most of the year, whereas high flows threaten lives and property on a small number of days per year or decade. Under such conditions, the rising demand for water is met by increasingly expensive and complex infrastructure necessary to store

seasonal or annual water surpluses in reservoirs, to transfer the water from storage to areas of demand, and to pump groundwater reserves (Croke et al., 2000; Ameri, 2002; Ibáñez and Prat, 2003; López-Moreno et al., 2004, 2008). Unfortunately, large infrastructure developments during the 20th century were designed and constructed on the basis that water resources would be relatively stable over time, despite the occurrence of short-term oscillations in supply. However, there is mounting evidence of long-term climatic trends (Giorgi et al., 2004), and changes in land cover have produced marked alterations in hydrological responses at the basin scale. Indeed, the Mediterranean basin is considered to be a global “hot-spot” in terms of climate variability and change, as well as in the rate of land transformation processes (Giorgi, 2006; Rosenzweig et al., 2007).

Future water resource planning decisions should be based not only on water demand, but also on future scenarios of climate and stream flow. Uncertainties include how environmental change will affect the quantity and quality of water resources and the fluvial regimes, and how the new scenarios will affect water management and reservoir operating rules, which were established on the basis of constant water availability. To address these issues, special focus on mountain areas is needed, as these are the main source of water in the region (Beniston, 2003; Viviroli et al., 2003, 2007) and are particularly threatened by environmental change (Beniston, 2003, Nogués-Bravo et al., 2008). Thus, climate scenarios project a greater temperature rise in the high mountains than at lower elevations (Giorgi et al., 1994; Bradley et al., 2004, 2006; Nogués-Bravo et al., 2007). Moreover, the hydrology of snow-fed basins is noticeably more sensitive to climate variability and change, as snow and ice respond rapidly to slight variations in precipitation and temperature (Nesje and Dahl, 2000; Carrivick and Brewer, 2004; López-Moreno and García-Ruiz, 2004). Mountains are also affected by changes in water demand from human activities (new urbanizations, sky resorts and snow making devices etc) and by intense modifications in plant cover and land uses including i) rapid deforestation as a consequence of overexploitation and overgrazing in developing countries,

and forest fires; and, ii) afforestation processes as a consequence of land abandonment and reforestation activities, especially in developed countries. Such changes in vegetation cover affect the water balance because of effects on evapotranspiration and interception rates (Joffre and Rambal, 1993; Llorens et al., 1995, 1997; Cosandey et al., 2004; David et al., 2006; López-Moreno and Latron, 2008), soil moisture dynamics (Correia, 1999; Maestre and Cortina, 2004), and the recharge of aquifers (Callegari et al., 2003). For these reasons, changes in land cover, particularly in the mountains, are as important as climatic variability in explaining the observed hydrological alterations and in assessing future water availability in the region. The present work reviews the main findings on the effects of climate fluctuations and land use changes on water resources of the Mediterranean region. The aim is to provide a comprehensive picture of environmental and human changes in order to underline the main problems derived for water management and to contribute to copy and address the hydrological consequences of such environmental change. This requires a synthesis of results on (i) climate evolution and trend in the last few decades, and future perspectives according projections from climatic models; (ii) land cover and land use changes, particularly the evolution of cultivated areas and forests in mountain areas, and (iii) changes in river discharge and water resources, including trends in discharge, and changes in snow processes and in river regime.

2. Recent environmental change and its hydrological consequences

2.1. Climate evolution

Many studies have assessed whether consistent long-term temporal trends occur within the high natural variability of Mediterranean climatic series. For precipitation, the longest climate records do not show consistent regional patterns (Cudennec et al., 2007). Data from only a few stations cover the entire 20th century, and do not indicate significant trends for the Iberian Peninsula (Esteban-Parra et al., 1998; Rodríguez et al., 1999; Llasat and Quintas, 2004) or the Alpine region (Beniston

et al., 1994; Casty et al., 2005). Auer *et al.* (2005) analysed precipitation and detected two antagonistic centennial precipitation trends: a wetting trend (since the 1860s) in the north-west of the Alps (eastern France, northern Switzerland, southern Germany and western Austria) and a drying trend (since 1800) in the south-east (Slovenia, Croatia, Hungary, south-eastern Austria and Bosnia-Herzegovina). A tendency toward a dryer climate was also detected over the 20th century in other locations including Italy (Brunetti et al., 2004a; Cislighi et al., 2005) and Bulgaria (Alexandrov et al., 2004). During the second half of the 20th century, the number of observatories increased markedly permitting to obtain more robust regional trends. A generalized decrease in annual precipitation has been reported for the whole basin (Bordi and Sutera, 2001; Hoerling et al., 2006; Goubanova and Li, 2007; Alpert et al., 2008). Hassanean (2004) detected a generalized decrease in precipitation in the south, a fall in winter, autumn and annual totals in the northeast, a slight decrease in the central north, and a winter fall in the central west. Such regional studies are supported by numerous studies at finer spatial resolutions, which confirm and reinforce the earlier findings. Sarris et al. (2007) found a recent negative trend in Greece, in line with the results of Feidas et al. (2007) and Kostopoulou and Jones (2005). The latter report also revealed a slight increase in precipitation in western Italy, which represents a local anomaly in the region, as there is general agreement that there is a trend to dryer conditions in the rest of the country (Piervitali et al., 1998; Brunetti et al., 2004; Blasi et al., 2007) as well as in neighboring locations including Malta (Mayes, 2001). A general trend of decreasing precipitation also applies to most of Croatia (Gajić-Čapka, 1993), Serbia (Tosic, 2004) and Romania (Tomozeiu et al., 2005). In Turkey there are spatial differences between the west, where significant trends of decreasing precipitation have been found, some stations in the north, which show the opposite trend, and the southern coast, which also experienced increases in fall and spring. (Tayanç et al., 2009). Decreasing precipitation has also been detected in the eastern Mediterranean (Alpert et al., 2004), in line with a more localized study that also indicated less rainfall in Israel (Krichak et al., 2002). A marked reduction in precipitation

has also been found in north-western Africa (Jacobeit, 2000; Hassanean, 2004), and more specifically in Morocco (Knippertz et al., 2003). In the Iberian Peninsula, a generalized trend to less precipitation is the most common finding (Jacobeit, 2000; Rodrigo and Trigo, 2007). De Luis et al. (2009) reported that annual precipitation has declined over 90.1% of the surface area of the Mediterranean Iberian Peninsula in the last 50 years, with the greatest decreases (-22.5 and -19.3% , respectively) occurring in summer and spring. Nonetheless, the transitional climatic character of the Iberian Peninsula leads to a spatially heterogeneous evolution and strong seasonal contrasts. Thus, areas exposed to Atlantic Ocean conditions tend to show constant annual values, with significantly lower winter precipitation (Jacobeit, 2000; López-Bustins et al., 2008). Finally, in the Alpine region there is a marked contrast between a long-term upward trend in the northwest (less pronounced in the northeast) and a long-term downward trend in the Mediterranean, which is apparent in the southeast but not significant in the southwest (Brunetti et al., 2006). Schmidli et al. (2002) found positive linear trends for precipitation during winter for the northwestern part of the Alps but negative ones for autumn in the southeast of the Alps for the 1901–1990 period. Similarly, Auer and Bohm (1994) indicated a tendency toward drier conditions in eastern Austrian Alps whereas the opposite trend was found toward the west.

In addition to changes in total precipitation, several studies have pointed to alterations in precipitation intensity and drought occurrence, although trends in these parameters are less consistent for the whole basin. Different and even opposing trends have been found at adjacent observatories for precipitation intensity (García-Ruiz et al., 2000; López-Moreno et al., 2009a) and drought (Vicente-Serrano et al., 2004). Nevertheless, most studies have reported an increase in precipitation intensity, in terms of the relationship between the annual precipitation total and the number of rainy days. This applies to the whole basin (Goodess and Jones, 2002; Norrant and Douguedroit, 2006; Goubanova and Li, 2007), the Iberian Peninsula (Rodrigo and Trigo, 2007), the eastern Mediterranean (Alpert et al., 2004), Malta (Mayes, 2001) and Italy (Brunetti et al., 2004b).

In contrast, precipitation intensity in the Spanish Pyrenees has remained stable since 1950 (López-Moreno et al., 2006).

Nicault et al. (2008) analyzed long-term dendrochronological data from the Mediterranean region, and found that the droughts of the second half of the 20th century were the most severe in the last 500 years. Similar results were obtained using the longest available precipitation and temperature series, dating from the early 19th century, in the northern Mediterranean basin (Briffa et al., 2009). In Greece, a drought event at the beginning of the present century killed pine trees more than 80 years old, evidence of the centennial character of such an event (Sarris et al., 2007). Brunetti et al. (2002 and 2004b) found an increase in dry spells in Italy over the period 1951–2000. Some Mediterranean areas did not follow this general pattern; thus no marked trend in drought occurrence was detected for the Iberian Peninsula throughout the 20th century (Vicente-Serrano, 2006).

The Earth's average temperature has tended to increase since the 19th century, particularly since the 1920s (*e.g.*, Folland et al., 2002; Brohan et al., 2006; Hansen et al., 2006). The Mediterranean basin has been no exception, with an increase in average temperature having been observed during the 20th century (Bethoux et al., 1998; Repapis and Philastras, 2004; Camuffo et al., 2010). All studies for the region indicate a trend toward higher temperatures. Thus, reports of the temperature increase over the entire basin in the last 100 years have ranged from 1 to 4.5°C (Brunetti et al., 2004; Alpert et al., 2008; Bertin, 2008). At a more localized scale, warming temperatures have been reported for the Iberian Peninsula (Sanz-Elorza, 2003; Vargas-Yañez et al., 2008), Italy (Brunetti, 2000), Greece (Kostopoulou and Jones, 2005), the eastern Mediterranean (Saaroni et al., 2003, Alpert et al., 2004), the central western Mediterranean (Piervitali et al. 1997), the alpine region (Böhm et al. 2001; Beniston and Jungo, 2002; Casty et al., 2005) and North Africa (Hassanean and Abdel Basset, 2006; El Kenawy et al., 2009). The generalized increase in temperature is particularly evident in summer (Jacobbeit, 2000; Palutikof and Holt, 2004; Ziv et al., 2005; Abaurrea et al., 2007), and in the maximum temperatures attained in the northern Mediterranean basin (Brunetti et al., 2000;

Saaroni et al., 2003; Abaurrea et al., 2007). This contrasts with observations in the southern Mediterranean basin, where the main temperature increase in Egypt (Domroes and El Tantawi, 2005) and Libya (El Kenawy et al., 2009) has occurred in the minimum temperature, whereas the maximum temperature has remained relatively constant. In addition, an increasing occurrence of warm events during winter has been reported in the Iberian Peninsula (Santos and Corte-Real, 2006) and the Alps (Beniston, 2005).

Warming temperatures and a generalized tendency to less precipitation has lead to consistent changes in snowfall and the snowpack extent in mountainous Mediterranean areas. In the northern hemisphere, average snowpack duration fell by 8.8 days per decade between 1971 and 1994 (European Environment Agency, 2004). A decrease in snow accumulation and snowpack duration was reported in the Swiss Alps (Latarnser and Schneebeli, 2003). Marty (2008) found years of unprecedented low snow during the last two decades, with the most recent period differing significantly from previous decades, separated by an abrupt change that occurred around 1980. Less snowfall and snow accumulation was also detected in the Italian Alps (Valt et al., 2005), Slovakia (Vojtek et al., 2003), and northern Greece (Baltas 2007). Brown and Petkova (2007) found a shorter duration of snow cover in Bulgaria in the period 1971–2000, although little evidence of change was detected when the period 1931–2000 was considered. A decrease in the duration of snow cover since the 1940s has been reported for the Iberian Peninsula (Sanz-Elorza et al., 2003), and in the Spanish Pyrenees. López-Moreno (2005) showed a clear trend of decrease from 1950 to 2000, associated with a fall in precipitation and atmospheric circulation changes, during February and March (López-Moreno and Vicente-Serrano, 2007). Changes in snowpack have been noticeably more marked at low altitudes (Beniston 1997; Beniston et al., 2003; Scherrer et al., 2004). For the Alps, a shorter snow cover period has been associated with an earlier melting period, despite the later occurrence of the first snowfall (Latarnser and Schneebeli, 2003).

Figure 1 summarizes the climate evolution in the second half of the 20th century over the Mediterranean region. The data were obtained by the Climate Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/~timm/grid/CRU_TS_2_1.html). The dataset presents terrestrial surface climate for the 1901–2002 period, and is a revised and extended version of an earlier dataset (New et al., 1999, 2000). More details on the methods used and the quality of the data can be found in Mitchell and Jones (2005). Seasonal and annual changes in the magnitude of precipitation and potential evapotranspiration between 1950 and 2002 were calculated by linear regression after filtering the series with a 5-year low-pass filter to reduce high frequency noise and to retain more consistent trends. Potential evapotranspiration was calculated for each grid point at a resolution of 0.5 degrees km²., based on the monthly average temperature and the latitude (Thornwaite, 1948). The statistical significance of trends was checked using the Spearman Rho correlation statistic to compare climate series and time. Despite the large seasonal differences, precipitation showed a generalized decrease across the whole basin. Consistent with local studies, the annual pattern demonstrated a predominance of negative trends over most of the basin, the most extreme occurring in Morocco, Algeria, Italy, the Balkans and some areas of the Iberian Peninsula, where the decrease from 1950 to 2002 was greater than 50 mm. In contrast, in north Turkey, most of the Black Sea basin, France, and northwest Spain, a positive trend was observed.

The general precipitation decrease has been accompanied by a large rise in evapotranspiration rates over the whole Mediterranean basin, the most extreme occurring in the Iberian Peninsula, France, and North Africa. The combination of these two trends is likely to result in decreased moisture availability for crops and natural vegetation.

2.2. Land cover and land use changes

Land cover and land use (LCLU) change is an important feature of environmental alteration. The continental water cycle is highly affected by LCLU change, as vegetation impacts on several

hydrological processes including interception, infiltration, runoff production, and evapotranspiration (Foley et al., 2005; Cosandey et al., 2005).

LCLU change has been a common characteristic of the Mediterranean landscape over the past 10,000 years, as inferred from paleoenvironmental and historical records (Goudie, 1986; Rognon, 1987; Morellón et al., 2008), resulting in incision and accumulation processes on both valley floors and slopes (Gutiérrez and Peña, 1998; Sancho et al., 2008), and different sedimentation rates and sediment characteristics in mountain lakes (Riera et al., 2004; Morellón et al., 2008). However, these changes accelerated during the last three centuries and particularly throughout the 20th century (Wood and Handley, 2001). Population growth, urban and industrial expansion, rural exodus, the development of tourism activities, globalization of markets, increased consumption, more sophisticated technologies, and the availability of financial resources explain the transformation of most Mediterranean landscapes, albeit with variable intensity (García-Ruiz and Valero-Garcés, 1998; Eetvelde and Antrop, 2003; Kizos and Koulouri, 2006; Serra et al., 2008; Hill et al., 2009).

The spatial variability of LCLU changes is affected by the degree of economic development among countries and regions. A clear distinction can be made between the most developed (*e.g.*, Spain, France, Italy, and Greece) and developing countries (*e.g.*, in North Africa), the former having reached a much more advanced stage of economic evolution.

In the case of developed countries in the Mediterranean, the occurrence of high demographic pressures in the middle of the 19th century, resulted in deforestation, farming on steep slopes, overgrazing, soil erosion and the occurrence of torrential rainfall affecting many rivers (García-Ruiz and Valero-Garcés, 1998; Beguería et al., 2006; García-Ruiz, 2010). A subsequent rural exodus to the cities reduced pressure on the less productive areas, first in France and Italy, and later in Spain, Portugal, and Greece, resulting in farmland abandonment, extensification of land management procedures, and a generalized expansion of shrubs and forests, with consequent effects on runoff

generation and soil erosion. At the same time, population and many human activities (tourism, industrial complexes, financial and commercial services, irrigation of productive land, urban growth) were concentrated mainly in coastal regions, but also in small areas in the inner regions (*e.g.*, the Ebro, Guadalquivir, and Po valleys, and big cities like Madrid). Consequently, an increasing contrast between marginal and highly productive areas (*i.e.*, between extensification and intensification) is the most evident characteristic of the spatial organization of population and activities.

A generalized farmland abandonment was reported in mountain and hilly areas of Spain, Italy, France and Greece (García-Ruiz and Lasanta-Martínez, 1990; Ispikoudis et al., 1993; Debussche et al., 1999; Sluiter and De Jong, 2008; García-Ruiz, 2010), caused by both national and international migration, and because market conditions made farming unprofitable under certain environmental conditions (steep slopes, small field size, difficulties in mechanization and accessibility) (Lasanta, 1988; Petanidou et al., 2008). Paralleling this, many slopes were reforested for economic (wood production) and environmental (land reclamation and rehabilitation) purposes (Ortigosa et al., 1990; Bonet et al., 2004; Barberá et al., 2005; Romero-Díaz and Belmonte-Serrato, 2008); this particularly affected Spain (3,383,000 ha were reforested between 1940 and 1984; Castroviejo et al., 1985). Manpower shortages also caused a reduction in livestock pressure and transhumant flocks (Ruiz and Ruiz, 1966; Metailié and Paegelow, 2004; Rescia et al., 2008).

The most important consequence of farmland abandonment and declining livestock pressure in the Mediterranean mountains was the recovery of dense shrubs and young forests (MacDonald et al., 2000; Taillefumier and Piégay, 2003; Roura-Pascual et al., 2005; Vicente-Serrano et al., 2005; Baskent and Kadiogullari, 2007; Chauchard et al., 2007). In the central Spanish Pyrenees most of the abandoned lands (representing 22% of the total area) were turned over to forests (66%), shrubs (27%), and meadows (6%); this, with deliberate reforestation, represented a landscape dominated by generalized plant colonization (Beguería et al., 2003; López-Moreno et al., 2008). The only

remaining cultivated areas, mainly located in the valley floors (fluvial terraces, alluvial plains, and fans), are now occupied by meadows instead of cereal crops. The valley floors are increasingly affected by reservoir construction and the expansion of urbanized areas (García-Ruiz and Lasanta-Martínez, 1990 and 1993). Remote sensing techniques have enabled detection of a widespread increase in vegetation activity in the Iberian Peninsula, as a consequence of rural abandonment combined with local patches of disturbance of vegetation caused by forest fires (Hill et al., 2009).

The opposite has occurred in the Mediterranean European lowlands, with the development of new irrigated lands and crops with high water consumption requirements. The area of irrigated lands in Spain, France, Italy, Greece, and Turkey total 12 million ha, and represent a major increase in area and productivity during the second half of the 20th century (Tanrivermis, 2003; Kilic et al., 2006). It is noteworthy that i) the new irrigated areas represent a change in scale, as they occupy large flat areas away from river valleys, and, ii) crops in the new irrigated areas (mainly maize, lucerne, and rice) consume high volumes of water (up to 10,000 m³ ha⁻¹) in summer, thus forcing the construction of complex and expensive infrastructure (reservoirs, canals) and/or the overexploitation of groundwater. This contrasts with the traditional Mediterranean cereal crops, olive trees and vineyards, which are stress-tolerant and adapted to a long seasonal dry period.

Finally, the coastal lands underwent a large urban expansion because of the concentration of population and human activities (mainly tourism and industry, and some forms of highly productive agriculture including intensive irrigation, greenhouses cultivation, and early fruit production) aimed at national and international markets (Bellot et al., 2007; Sönmez and Sari, 2007; Rico-Amorós et al., 2009). For this reason, areas traditionally farmed or under natural vegetation were replaced by impervious surfaces (buildings, roads, greenhouses) or irrigated lands, causing new land degradation processes (soil salinization and contamination, overexploitation of groundwater resources, and asphaltting of the best agricultural lands) (Kirchmann and Thorvaldsson, 2000; Wissmar et al., 2004; Martínez-Fernández and Esteve, 2005).

In the southern Mediterranean basin intense migration from rural areas to cities started in the last third of the 20th century, but population increase still explains the occurrence of enormous pressures on natural resources in countries including Morocco and Algeria. This is particularly relevant in rural areas of Morocco, where wood is widely used for heating. This is particularly relevant in rural areas of Morocco, where wood is widely used for heating. Farming is generally expanding in response to population increase, progressively occupying more marginal lands on steep slopes or stony, thin soils (Quezel, 1999; Shalaby and Tateishi, 2007), and in extreme cases based on shifting agriculture systems (Margaris et al., 1996; Barrow and Hicham, 2000) or reductions in fallow land. Increasing livestock pressure on natural pastureland has also been detected (Bencherifa and Johnson, 1991), resulting in a decline in primary production from the steppic landscapes in the last 50 years (Puigdefábregas and Mendizábal, 1998). Meanwhile, the enlargement of markets from regional to national and international caused local intensification of irrigated agriculture (Parish and Funnell, 1996 and 1999), with an increasing proportion of products exported to European countries (Barrow and Hicham, 2000; Hervieu et al., 2006). Thus, in the southern Mediterranean basin there is now a generalized increase in pressure on natural resources, caused by population growth and the influence of enlarged markets; this is particularly affecting plant cover in both marginal and intensive high productivity areas.

Figure 2 summarizes the changes in vegetation activity over the Mediterranean region in the last 25 years, based on remote sensing data that can be correlated to well-known changes in land use. The information was derived from analysis of the Global Inventory Modelling and Mapping Studies–Normalized Difference Vegetation Index (GIMMS-NDVI) dataset (<http://www.landcover.org/data/gimms/>), obtained from NOAA-AVHRRR satellite images between 1981 and 2006. Chart A shows the average annual NDVI, in which large contrasts in vegetation activity throughout the basin are clearly evident. Chart B shows the magnitude of change in NDVI values per year between 1981 and 2006, based on linear regression analysis. Chart C shows the

regions that experienced a significant change (positive or negative) in the NDVI based on the non-parametric Rho-Spearman test $\rho < 0.05$). NDVI trends were mostly positive in the European part of the basin, mainly in the Balkan Peninsula, Turkey, Italy, and north of the Iberian Peninsula. Positive trends also dominated in the Atlas mountains. In most of North Africa, the southern Iberian Peninsula, the Middle East, and some regions of Croatia and Montenegro the trends were predominantly negative, although the level of statistical significance was lower. These areas are commonly subject to high aridity, and overgrazing would be expected to result in reduced vegetation cover and primary productivity. Moreover, a climatic component could also be involved, as the western areas affected by a large decrease in NDVI were also affected by precipitation variability, controlled by the North Atlantic Oscillation (NAO) and its trends (Vicente-Serrano and Heredia, 2004).

2.3. Changes in river discharge and water resources

Changes in precipitation, temperature, and plant cover alter the water balance and the partitioning of precipitation between evapotranspiration, surface runoff, and groundwater flow (Foley et al., 2005). A reduction in precipitation and changes in precipitation regime directly affect the quantity of water that reaches the soil, the runoff generation mechanisms, and the magnitude of river discharge. The rise in temperature, together with changes in other parameters, including solar radiation, wind speed, and humidity, increases transpiration processes in plants as well as evaporation from the soil and water bodies. All these changes result in river regime disturbances that may alter the quantity and quality of water resources, and their temporal distribution.

(i) A consistent decrease in water resources because of decreasing precipitation and increasing temperature

A close relationship has typically been observed at all temporal scales (regardless of the basin area studied or geomorphological and geological characteristics) between the temporal evolution of precipitation and river discharge, with correlations higher than 0.8. This is expected, given the extremely high dependence of river discharge on precipitation at annual or longer scales. This is the case for rivers in Thessaly (Greece; Vasiliades and Loukas, 2009), the central and eastern Pyrenees (Beguería et al., 2003; Ludwig et al., 2004; García-Ruiz et al., 2010), the west of the Iberian Peninsula (Trigo et al., 2004; Ceballos et al., 2008), Romania (Stefan et al., 2004), Italy (Fiorillo et al., 2007), Bulgaria (Rivas and Koleva-Lizama, 2005) and Turkey (Kalayci and Kahya, 2006).

The role of temperature in the evolution of water resources is generally more difficult to assess than that of precipitation. However, some studies have confirmed that warming has a role in explaining recent trends in water resources in the Mediterranean basin. Thus, a 10-30% decrease in runoff is projected by climate models in southern Europe (Milly et al., 2005), and perturbations in the water cycle are expected as a consequence of climate warming (Allen and Ingram, 2002). Pandzic et al. (2009) attributed the decrease in discharge since 1950 from the Sava River (Croatia) to a negative trend in soil moisture availability, which is closely related to increased evapotranspiration. In the central Pyrenees, Beguería et al. (2003) demonstrated that temperature did not contribute significantly to explaining the time variation in river discharge, whereas precipitation and land cover change explained 93.9% of the variance. A similar finding was reported by Ludwig et al. (1994) for the Tet river (Southern France), where moisture precedent from the Mediterranean sea seems to be the major driver of hydrological variability of river flows. Nevertheless, in other areas the hydrologic changes are closely related to the recent warming trends. For example, Lespinas et al. (2010) have showed in the coastal rivers of Southern France that the decrease in one third of the watersheds is likely the result of a temperature induced switch of snowfall at high altitudes and the evapotranspiration processes.

Recent analysis has shown that in the last 500 years the Mediterranean river discharges, and the related extreme events: floods and droughts, have been mainly driven by regional climatic forcing (Glaser et al., 2010). As expected from the changes in precipitation and temperature, summarized in Section 2.1, a generalized and consistent decrease in river discharge has been reported in all studies concerning this aspect of the Mediterranean basin in the second half of the twentieth century. This is the case for the Evinos River, Greece, where a long-lasting trend of decreasing runoff, related to a decrease in precipitation in recent decades, has been reported (Giakoumakis and Boloutsos, 1997). In Romania, Carbonnel et al. (1997) showed a negative trend, which began around 1983, in the annual and seasonal discharge of 15 rivers, coinciding with intensification of hydrological drought in the region. The same pattern was observed in Bulgarian rivers and other Balkan countries (including Slovenia and Croatia) between 1952 and 2002, with a sharp decrease in runoff reported after 1981 (Genev, 2003; Rivas and Koleva-Lizama, 2005; Frantar and Hrvatin, 2006), and in the southern basins of Turkey (Kahya and Kayci, 2004). In the western Mediterranean a 25-50% decrease in river discharge has occurred since 1960 in the Duero River basin, in areas not affected by river regulation (Ceballos et al., 2008; Morán-Tejeda et al., 2010), and evidence was found that the changes were particularly related to decreased precipitation and increased temperature in the same period, with a smaller influence of land cover and water management. Unfortunately, no information was found on the hydrological response of those local areas where an increase of annual precipitation has been observed.

The occurrence of severe droughts has affected the duration and severity of low flow periods, which cause significant ecological, economic, and social impact. For instance, Zanchettin et al. (2008) analyzed the evolution of stream flow in the Po River, northern Italy, since the beginning of the 19th century; no changes in average annual discharge during the 20th century were found. Nevertheless, the cited authors found an increase in peak flow discharge in recent decades, and a higher frequency of drought periods since 1940. Similarly, Hisdal et al. (2001) analyzed the

evolution of hydrological droughts between 1962 and 1990, based on 12 gauging stations in Spain, and confirmed a marked increase in the severity of droughts. Renard et al. (2008) also showed a trend toward more severe droughts in rivers of the French Pyrenees.

(ii) Changes in river regimes caused by snow accumulation and melting processes

Snow accumulation and snowmelt play a determining role in the seasonal distribution of river discharge, especially in mountain basins. In general, snow accumulation delays the discharge response to precipitation, resulting in low discharge during winter, independent of the amount of precipitation. This is a well known process in the Alps, the Carpathians, the Balkans, and the Pyrenees. As a consequence, higher discharge is usually expected in spring, when snowmelt and rainfall combine to cause high flows between April and June. This fluvial regime behavior tends to be very regular on an annual cycle, facilitating reservoir management and, in general, the prediction of water resources available during the driest months (July to September).

However, global warming directly affects snow accumulation and snowmelt in two ways: i) increasing temperature progressively elevates the winter 0°C isotherm, such that less snow accumulates in the headwaters and more rain falls in winter; and, ii) snowmelt occurs earlier in the year and is more rapid. Both responses cause major changes in river regimes, including greater and more irregular runoff in winter, and lower discharges during the spring high flows (Beniston et al., 2003; López-Moreno, 2005; Adams et al., 2009). According to Arnell (1999a, b), the rise in temperature is leading to a reduction in the proportion of precipitation falling as snow and, consequently, in the duration of snow cover, progressively shifting the timing of streamflow from spring snowmelt to winter runoff. For instance, López-Moreno and García-Ruiz (2004) and López-Moreno et al. (2008b) reported a large effect of decreasing snowpack on changes in Pyrenean river regimes, particularly a clear decrease in the spring high flows (as snowmelt represents about 40% of total river flows in the region) and the occurrence of the high flows at least 1 month earlier than

heretofore. Figure 3 shows changes in some Pyrenean rivers, with higher discharges in winter and lower high flows in spring. The consequence is an increase in uncertainty concerning availability of water resources and the most appropriate reservoir management regime to ensure water supply. Another important consequence is that water reserves in headwaters are exhausted earlier, with declining summer low flows forcing reservoir managers to reduce the discharge from dams (López-Moreno et al., 2008a). Similar results were found by Shaban (2008) in the El-Kabir River, Lebanon, and by Petrovka et al. (2004) in the Bulgarian Carpathians, where significant decreases in snow cover depth, extent, and duration have occurred.

For the headwaters highest in the Alps, an increase in temperature can result in rises in discharge related to glacier melting, particularly in summer, as was observed in the southern French Alps by Renard et al. (2008), and in the upper Rhone basin, Switzerland, by Collins (2007). Birsan et al. (2005) also found an increase in winter, spring, and summer discharge in Switzerland, as a consequence of increasing precipitation in winter, earlier melting in spring, and a progressive shrinkage in area and volume of the glaciers. These processes affected only small sectors of the river basins, but jeopardize the sustainability of high mountain water resources.

(iii) Changes in river regimes caused by reservoir management

Reservoir management directly affects river regimes during both high and low flows. For instance, López-Moreno et al. (2004) showed that reservoir operation in the central Pyrenees noticeably reduced downstream discharge from the dam, because a part of the flow was diverted to irrigation canals. This increased the duration of the low-flow period, although this was compensated by the establishment of ecological flows during summer. Similarly, construction on the Tagus River of the Alcántara dam (the second biggest reservoir in Europe) affected the downstream propagation of hydrological droughts in the transboundary basin. During the pre-dam period (1943–1969) droughts were longer and more intense in the Spanish part of the basin than in the Portuguese

portion, whereas construction of the dam caused more severe droughts in the latter region, in terms of both magnitude and duration (López-Moreno et al., 2009b).

These results can be extended to the whole Mediterranean region, which is one of the most affected regions in the world by anthropogenic river flow alterations and reservoir management (Döll et al., 2009). Thus, in the Cetina River, Croatia, the average annual discharge has decreased dramatically since 1969, with a reduction of up to 90% at some gauging stations. This is in part related to more severe hydrological droughts, but mainly to the construction of reservoirs and hydroelectric power plants, and flow derivation (Bonacci and Roje-Bonacci, 2003). Batalla et al. (2004) and Skliris et al. (2007) suggested that extensive dam construction, water diversion, and increased water consumption explains the marked downward trend of water release to the Mediterranean Sea from the Ebro River, Spain. López-Moreno et al. (2007) also stressed the key role of dam construction and water transfer in the temporal evolution and downward trend of discharge from the Tagus River, central Iberian Peninsula. Arguably the same reasons explain the dramatic decrease in the annual flow of the Jordan River, from 1,166 Mm³ year⁻¹ in 1926-1945 to 167 Mm³ year⁻¹ in 1978-2000 (Ben-Zvi and Azmon, 2003; Klein, 2005). In some cases annual discharge has declined because of evaporation from the reservoirs, as was demonstrated in Tunisia by Leduc et al. (2007), in the Durance River in the Rhone basin, France, by Warner (2000), and in the Pyrenees by López-Moreno (2008a); wastage represented about 3% of the annual discharge and up to 11% of the summer discharge.

Changes in flood intensity and seasonal distribution are an expected consequence of reservoir construction (Bonacci and Ljubenkov, 2008). An increase in the return period corresponding to any peak flow is the most general effect, as was demonstrated by López Moreno et al. (2002) for the Yesa reservoir (central Pyrenees). Nevertheless, it is interesting to note that the effectiveness of reservoirs in flood protection depends mainly on a combination of the intensity of the peak flow, the infilling state of the reservoir when the flood occurs, and reservoir management.

An analysis of the seasonal distribution of floods before and after construction of the Yesa reservoir (Figure 4) demonstrated that autumn floods were severely attenuated by reservoir management, because of a need to replenish water storage after the summer irrigation campaign; the spring floods were also reduced in number and intensity, to enable complete infilling of the reservoir before summer. However, winter floods were barely affected because the reservoir managers tended to release the resulting water, to keep a safety margin (an empty volume) in the reservoir to receive the snowmelt floods in spring (López-Moreno et al., 2002). At long term, sediment silting in reservoirs reduces their lifetime and creates increasing problems for water management in the future, particularly in semi-arid areas (López-Bermúdez and Gutiérrez-Escudero, 1982), where erosion is still a major problem (López-Bermúdez, 1990). Nevertheless, a decrease in the sedimentation rate has been detected in some reservoirs (Valero-Garcés et al., 1998) due to a decline in soil erosion and transport related to farmland abandonment and forest expansion (Piégay et al., 2004).

(iv) A decrease in water resources attributable to land cover change

In many instances climate evolution and reservoir management do not explain the magnitude of changes in the availability of water resources. Some authors have pointed to other factors that are variable in time, such as LCLU. The hydrological consequences of LCLU change have been the subject of a number of studies. For example, the effects of farmland abandonment and plant recolonization in the Spanish Pyrenees have been comprehensively analyzed by García-Ruiz et al. (1995 and 2008), and Beguería et al. (2006). For instance, using experimental plots, García-Ruiz et al. (1995) confirmed that both cereal crops and fallow lands had increased runoff coefficients and erosion rates relative to a dense shrub cover. In some cases the expansion of shrubs and forests in the abandoned fields has had a greater influence on the availability of water resources than has climate change over large areas (Beguería et al., 2006).

Llorens and Domingo (2007) argued that rainfall partitioning by vegetation plays an important role in water balance at the basin scale, because of the control that canopies exert on evaporation, interception, and redistribution of rainfall in storm runoff and infiltration. These authors reviewed research on rainfall interception in the Mediterranean area of Europe (France, Greece, Italy, Portugal, and Spain) over the last 30 years; the average relative interception under forest cover was 21%. This clearly indicates that changes in plant cover (caused by both reforestation and deforestation) can alter the water balance and ultimately affect the availability of water resources, particularly if these changes affect large areas, as is the case in many mountainous regions.

The majority of studies on the role of land cover change on water resource availability in the Mediterranean basin have been carried out in the Iberian Peninsula, which has been affected by relatively recent changes in vegetation. Gallart and Llorens (2002) found a marked decrease in discharge from the Ebro River as a consequence of rainfall evolution and water consumption, although these authors also pointed to the importance of the expansion of forest cover in headwater areas. The cited authors showed that the overall increase in the forested area between 1970 and 1991 represented 16.7% of the entire basin area, and hypothesized that this in part explained the decreasing correlation between river discharge and climate in the region. This hypothesis was confirmed for the Pyrenees by Beguería et al. (2003 and 2006) and López-Moreno et al. (2008a), who used data from rivers not affected by water extraction or reservoir regulation. Here, natural and human-induced reforestation after farmland abandonment was the only factor explaining the magnitude of the negative trend found in the time series of river discharges. Beguería et al. (2003) estimated that the reduction in streamflow caused by the expansion of forested areas attained 25% for the period 1955-2000. Again, this is a dramatic consequence of farmland abandonment and forest expansion, particularly in mountain areas, which behave as the main runoff source for

Mediterranean rivers. For this reason, some authors defined the mountains as water towers (Viviroli et al., 2003, 2007; Viviroli and Weingartner, 2004).

Experimental studies in monitored catchments in the central Pyrenees and southern France demonstrated that forests noticeably reduce runoff coefficients (Cosandey et al., 2005; García-Ruiz et al., 2008), reinforcing the idea that the establishment of forest cover may be another factor explaining the decline in water resources in the Mediterranean basin. Using an Hydrological Land Use Change model, Delgado et al. (2010) have simulated the consequences of land cover changes in a river basin of NE Spain, showing a consistent decrease in the summer low flows under forest recovering of old agricultural fields. Serrano-Muela et al. (2008) studied the hydrological behavior of a densely forest covered catchment in the Pyrenees, and found that i) the catchment had both smaller peak flows and smaller low flows than had a neighboring non-forested catchment, ii) most rainstorm events produced almost no discharge response, and, iii) the intensity of precipitation had no influence on the magnitude of peak flow. García-Ruiz et al. (2008) also stressed that catchments affected by extensive human activity respond to almost any precipitation, whereas forested catchments react only a few times per year, particularly in periods when the water table is close to the surface.

3. Projected environmental change for the 21st century, and hydrological implications

3.1 Projected climatic change

Projections of future evolution of climate are always subject to uncertainty (Räisänen, 2007). However, the scenarios projected by the best available models of the climate system and the prognostics of socioeconomic development in the Mediterranean region have major implications for the hydrological cycle and water resources.

There is consensus that projections of the future evolution of temperature (error $\pm 1^\circ\text{C}$) are more reliable than for precipitation (error $\pm 25\%$) (Giorgi et al., 2004b; Dequé et al., 2005; López-

Moreno et al., 2008b). Despite these uncertainties, existing models reproduce quite realistically the main climatic features of the Mediterranean region (Gibelin and Dequé, 2003). For temperature, all models project a consistent tendency toward warmer conditions (Gibelin and Dequé 2003; Giorgi, 2006; Goubanova and Li, 2007; Alpert et al., 2008; Hertig and Jacobeit, 2008, Sánchez-Gómez et al., 2009). The predicted magnitude of change for the next century varies between 1°C and 6°C, depending on the model and the greenhouse gas emission scenario used (Nogués-Bravo et al., 2007 and 2008). In addition to average temperature increase, a greater occurrence of extreme hot events is expected (Beniston, 2004; Diffenbaugh et al., 2007; Giorgi and Lionello, 2008), which could lead to the development of tropical cyclones over the Mediterranean (Gaertner et al., 2007).

For precipitation, most studies project a general tendency toward less precipitation in the next century (Ragab and Prudhome, 2002; Gibelin and Dequé, 2003; Giorgi et al., 2004; Goubanova and Li, 2007; Giorgi and Lionello, 2008; Evans, 2009). Projected changes show greater spatial variability than for temperature (López-Moreno et al., 2008b). In some areas, like the Alps, projected changes in precipitation are moderate in terms of the yearly total, but show noticeable seasonal differences (EEA, 2009). In northern Mediterranean area the common pattern shows an increase of the winter precipitation is a common result (Giorgi et al. 2004b; Giorgi and Lionello, 2008; Hertig and Jacobeit, 2008)

Some studies also point to a likely increase of precipitation intensity in the region (Gaertner et al., 2007; Goubanova and Li 2007; López-Moreno and Beniston, 2009), and increases in both the interannual variability of precipitation (Giorgi et al., 2004; Alpert et al., 2008) and the length of the dry season (Ragab and Prudhome, 2002; Palutikof and Holt, 2004; Evans, 2009). With respect to drought occurrence, droughts of a severity expected every 100 years will recur every 10 years in the northern Mediterranean, but will be less frequent in North Africa by the end of the 21st century (Weiß et al., 2007). For southern Europe, Blenkinsop and Fowler (2007) project an increase in the frequency of long-duration droughts, but the magnitude of this change is not certain. Overall,

Diffenbaugh et al. (2007) have shown that by the end of the 21st century the Mediterranean region may experience a substantial increase in the northward extension of dry and arid lands, caused by a large increase in warming and a pronounced decrease in precipitation, especially during spring and summer. Areas expected to be particularly affected include the central and southern portions of the Iberian, Italian, Greek, and Turkish peninsulas, parts of southeastern Europe (*e.g.*, Romania and Bulgaria), and the Middle East, northern Africa, and the major Islands (Corsica, Sardinia, and Sicily).

Figure 5 summarizes average climate change for the Mediterranean region for the period 2040-2070 in comparison to 1960-1990, as projected by a set of nine general circulation models (GCMs) under IPCC emission scenario A1B. A marked decrease in annual precipitation is evident, affecting the entire Mediterranean basin. The south of Spain, North Africa, and the Middle East are areas where a greater decrease is expected (around -15%). A substantial decrease in precipitation (around 10%) is also projected for southern Italy, Greece, and south of Turkey. Northern Spain,

most of Italy, and north of the Balkans show a slight decrease in annual precipitation, whereas in the northern Alps values are expected to remain constant or perhaps to increase. For temperature, an increase ranging from 2°C to 3°C is projected. The greatest increase is expected in the northern Balkans, Turkey and generally in areas far away from the Mediterranean coastland. As for the observed trends, the combination of warmer temperatures and less precipitation leads to projections of significant decreases in moisture availability that are particularly problematical in the southern part of the basin.

In winter a marked decrease in precipitation is expected in northern Africa, but also in the Middle East and southeastern Spain. On the other hand, stable or increasing precipitation is projected to the north of the Balkans, northwest of the Iberian Peninsula, and in the alpine region. An increase in temperature is also evident for the whole basin, although less intense than the annual values. The projected warming generally varies between 1.8°C and 2.6°C, but this may be exceeded

in North Africa and the northern Balkans. The magnitude of the temperature increase may severely affect snow accumulation and melting processes in all mountain ranges within the Mediterranean region. Snowpack in the Atlas Range (Morocco), the Lebanon mountains, and the Sierra Nevada (southern Spain) is likely to be particularly affected, as suggested from the combined precipitation and temperature projections. The observed trends in snowpack and streamflow timing (earlier, and less spring melting) are indicative of future changes: model simulations suggest that these trends will continue and accelerate (Stewart, 2009). At the same time, water reserves in mountains will become exhausted before the beginning of summer, exacerbating summer low flows (Frederick, 1997). This is extremely important for the Mediterranean region, where snow accumulation and snowmelt processes retard the discharge and make the spring and summer discharges more reliable (Viviroli et al., 2003). In addition, more frequent and intense winter floods are expected, particularly in middle- altitude mountains, where soil will be free of snow for longer periods, thus favoring immediate storm runoff, particularly in the late autumn and winter (Arnell, 1999a). Moreover, snowfall in low- and middle-altitude mountains will be increasingly unpredictable in the coming decades (Burki et al., 2003), affecting the reservoir operating rules (López-Moreno et al., 2008a) and winter tourism (Uhlmann et al., 2009). Thus, López-Moreno et al. (2008c and 2009b) found large reductions in snow volume with increased temperature in the Spanish Pyrenees, but the effect was subject to strong vertical gradients and the emission scenario chosen, with the expected decrease ranging from 90% at low altitudes and high emission levels to less than 10% at high altitudes and low emission levels. This problem has also been reported in other European mountains. For instance, an increase of 1°C will reduce the duration of the snowpack by 4-6 weeks (Hantel et al., 2000), even at high altitudes. In Switzerland, an increase of 4°C would reduce the snowpack duration by 90% at 1000 m a.s.l., and by 30-40% at 3000 m (Beniston et al., 2003).

3.2 Projected changes in river flows

Climate change projected for the region will severely impact river discharge and water resource availability. Even if precipitation remains stable, an increase of 2-4°C in the average temperature could result in a decline of 4-21% in stream flow (Nash and Gleick, 1993). This is because of enhanced evapotranspiration and the reduced possibility of saturation excess runoff. It is to be expected that the additional decrease in precipitation projected for most of the Mediterranean basin will reinforce the likely effects of warming temperatures in reducing water resources, with losses of up to 30% forecasted for the Mediterranean region (Allen and Ingram, 2002; Milly et al., 2005).

All these changes will have significant consequences for river regimes and flood magnitude. Thus, Nohara and co-workers (2006) projected a decrease in Mediterranean river flows and earlier melting under the A1B emission scenario. Similarly, Manabe et al. (2004) predicted less runoff and soil moisture in the Mediterranean basin. In a global study, Wetherald and Manabe (2002) showed that the Mediterranean is a region where some of the most substantial decreases in soil moisture and runoff are expected as a consequence of global change processes. Arnell (1999b) used four climate change scenarios and each one indicated a general reduction in the annual runoff in southern Europe, where percentage decreases could be as great as 50%. Regarding to hydrological extremes, Lehner et al. (2006) used the WaterGAP model to calculate relative changes in flood and hydrological drought frequencies in Europe. These authors showed that, independent of the climate model used, southern and southeastern Europe are likely to be subject to a significant increase in drought frequency. In these regions the current 100-year droughts may recur every 10-50 years by 2070. In any case, it is necessary to bear in mind that for extreme values the uncertainties associated to climatic and hydrological projections are much larger.

Local studies point to similar results throughout the Mediterranean basin, some based on hydrological models and the outputs from different scenarios obtained from climate change models. Nunes et al. (2008) showed that runoff and subsurface runoff in Portugal are expected to decrease

as a consequence of less precipitation and higher temperatures. Younger et al. (2002) suggested that climate change could reduce groundwater recharge in Spain by around 16% by the middle of the 21st century. Fujihara et al. (2008) have shown that the drought return period for the Sayehan River basin (Turkey) will change from 5.3 years under present conditions to 2.0 years under future conditions; that is, critical hydrological drought events will occur more frequently as a consequence of climate change. Using scenario B2 from the ECHAM4 model, Kunstmann et al. (2006) have shown a decrease of 23% in the total runoff at the outlet of the upper Jordan catchment, accompanied by a significant decrease in groundwater recharge. Similarly, in the Aliakmon River basin (Greece), hydrological models applied under climate change conditions indicate a reduction of average runoff from winter to summer, and a reduction in soil moisture (Baltas and Mimikou, 2005; Baltas, 2007). A decrease in runoff of about $11\pm 8\%$ is expected for the Adour River (French Pyrenees, Garonne basin) by 2050-2060, as a consequence of increased temperature and decreased summer precipitation (Caballero et al., 2007). Overall, climate scenarios suggest a marked increase of water resource stress in the Mediterranean and the Middle East (Arnell, 2004). Finally, in the Alps a decrease in snow pack and changes in glacier surface could lead to an increase in alpine winter runoff of up to 19 % with a reduction in spring runoff of up to – 17 %. For the southern and central Alps decrease in summer runoff is predicted as being up to – 55 % by the end of the 21st century (EEA, 2009).

3.3. Scenarios of future vegetation cover and land use changes

It is more difficult to project changes in land cover and vegetation over the coming decades. There is strong evidence that the process of revegetation of abandoned farmland and overgrazed areas is far from complete, even in the most developed countries. A large proportion of land abandoned several decades ago is still in the primary stages of revegetation, covered by sparse shrub that should evolve into more developed stands of forest (Vicente-Serrano et al., 2005;

Baskent and Kadiogullori, 2007). Moreover, forests are able to spread as a consequence of the abandonment of subalpine summer pastures, and a warming climate will lead to an upward shift in the upper limit of forests (Essery, 1998; Beniston, 2003). Thus, Gaucherel et al. (2008) indicated that the warming temperatures projected for Mediterranean France under scenario B2 (medium-low emission of greenhouse gases) would increase the optimum altitude for pine production by 300 m, representing a significant potential for forests to expand in both extent and elevation. Logically, the magnitude of change in vegetation in developing countries should noticeably exceed that expected in developed regions. Although traditional agriculture is still practiced in large parts of southern Mediterranean countries and in the mountain areas of Turkey and the Middle East, technological improvements and migratory fluxes from rural to urban areas suggest that human pressure in headwaters of the Atlas, Rift, Taurus, Lebanon, and Anti-Lebanon mountains in coming decades are likely to undergo a similar process to that observed in the Iberian Peninsula, southern France, and Italy. Thus, the decreased generation of runoff produced by projected climatic change may be enhanced by initiation of revegetation schemes over large areas. Moreover, an increase of 2°C in coming decades could introduce changes in vegetation that would be independent of the evolution of precipitation (Cheddadi et al., 2001). If precipitation is maintained there will be spread of evergreen forest in the western Mediterranean, conifers in Turkey, and woody xerophytes in northwestern Africa. A reduction in land suitable for cultivation as a consequence of climate change is also predicted (Schröter et al., 2005), and this could extend areas of degraded xeric vegetation and denuded soil, with marked hydrological consequences. In any case, the expected response of the Mediterranean vegetation and forests to the warming processes and the reduction of precipitation probably will be very complex in the space. Some factors will play a large role in the changes, being necessary to take into account the capacity of adaptation of the species and the diversity of the climatic and environmental conditions. Thus, in neighbor areas can be expected a

very different evolution in the expected forest growth as a function of the aridity conditions (Vicente-Serrano et al., 2010).

4. Discussion: will current water management strategies be adequate to address the consequences of environmental change?

Many studies have revealed a consistent decrease in river discharge over almost the entire Mediterranean basin. The occurrence of significant and positive trends in temperature has been confirmed, as have long-term trends in precipitation during the last six decades. This climate evolution is consistent with the response of river discharges, but most studies have indicated that climate alone does not fully account for the magnitude of the observed hydrological changes. Two additional reasons have generally been proposed to explain the decline in water resource availability: i) an increase in water consumption for urban, agriculture, industry, and tourism purposes; and, ii) an increase in water consumption by natural vegetation that expanded in areas where human pressure has decreased, and grazing and cultivation has disappeared. It is noteworthy that such changes in land cover have occurred mainly in mountain headwaters, where most of the water resources of the Mediterranean basins are generated. The effect of vegetation on runoff generation is unclear, as this changes markedly between sites in response to climatic conditions and vegetation type (Andréassian, 2004; Cosandey et al., 2005). However, it has consistently been concluded that deforestation causes an increase in the average annual discharge (Bosch and Hewlett, 1982; Andréassian, 2004), which is directly attributable to changes in evapotranspiration and infiltration rates (Calder, 1992; Fohrer et al., 2001). In contrast, afforestation causes a decrease in runoff generation and an attenuated response to rainstorm events. At the regional scale, most studies have identified the important role of land cover change, although it is dependent on the type

of change and the final structure of the landscape (Ranzi et al., 2002; Beguería et al., 2003; Gallart and Llorens, 2003).

In addition to changes in the annual amount of water, noticeable alterations have been detected in seasonality of river flows. A generalized decrease in snow accumulation during winter, and earlier melting, are the main causes of decreasing spring peak flows and soil moisture exhaustion, resulting in more marked summer low flows. It is noteworthy that in areas where the density of vegetation is increasing, the greatest evapotranspiration demand occurs in spring and summer, which might exacerbate the hydrological changes associated with changes in snow cover.

Predictions for coming decades suggest a marked intensification of recent trends in environmental variables. Climate projections point to a potential acceleration of climatic trends, with temperatures rising 1-6°C and decreasing precipitation in the 21st century. Under these conditions the snowpack would be severely affected, particularly at low and middle altitudes. In addition to climatic change, intensification of revegetation is likely to occur in most headwater areas, continuing the trends occurring in most of the European sector of the basin. There may also be a reversal of the current trend in North Africa, the Middle East, and sectors of Turkey, as a consequence of the expected progressive abandonment of the most marginal croplands and grazing areas. Thus, in most of the Mediterranean mountain areas the recent and future evolution of plant cover will reinforce the consequences of foreseen climatic trends, resulting in a general decrease in the availability of water resources.

The exploitation (or overexploitation) of surface and groundwater resources has to date enabled increasing water demand to be met despite declining water availability caused by environmental change, and hydraulic infrastructure including reservoirs, canals, groundwater pumping, and treatment plants have played key roles. These expensive, complex, and long-term approaches were designed to store large volumes of water and, in some cases, transport the water for hundreds of kilometers, including among basins. This allowed creation of large irrigation areas,

improvement in the quality of drinking water, and ensured the production of energy in hydropower and nuclear plants. The benefits of water resource management are evident; the production of food and energy has increased exponentially, the quality and quantity of the water supply to cities has been assured, and the magnitude and frequency of floods on densely populated floodplains have been reduced (Gleick, 2003). However, the social and environmental costs have also been very high and include i) the construction of large reservoirs, which have necessitated population displacement (McCully, 2001) or have transformed the management systems in mountainous areas (García-Ruiz and Lasanta, 1993); ii) the deviation of large quantities of water from the main channel, including interbasin transfers, which has affected ecosystems in the flood plain and the land-sea ecotone (Pircher, 1990; Zsuffa, 1999; López-Moreno et al., 2002; Batalla et al., 2004); and, iii) the trapping of sediment in reservoirs, which has reduced nutrient transport and decreased productivity in both rivers and deltas downstream of dams (Brune, 1953; Verstraeten, 2000; Maneux et al., 2001), reduced the life expectancy of reservoir (López-Bermúdez and Gutiérrez-Escudero, 1982), activated processes of channel incision and lateral erosion (Andrews, 1986; Beguería et al., 2006), subsequently changed the hydrological functioning of the floodplain (*i.e.*, by lowering the water table), and threatened the sustainability of deltas (*e.g.*, the Ebro River Delta; Sanz-Montero et al., 1999).

Water policy based on the construction of large reservoirs and canals is now unsustainable and no longer advisable in the Mediterranean region. The main reasons are that, from a topographical and geological point of view, there are few adequate places left to construct new dams, at least in the most developed countries of the basin, and there is also increasing community opposition to the construction of new reservoirs in Mediterranean mountain areas. Prior to construction of new dams it is necessary to address the key question: what is the future of the reservoir? The life span of reservoirs is probably hundreds of years under ocean-dominated climatic conditions and in forest-covered areas, where soil erosion is a relatively minor problem. However,

soil erosion is a first-order problem in semi-arid areas under a Mediterranean climate, where high levels of suspended sediment and bedload transport cause a rapid reduction in reservoir capacity and lifespan. Some reservoirs in semi-arid Mediterranean areas are now ineffective after a few decades of use in the 20th century (McCully, 2001). These issues highlight the difficult compromises to be made among financial costs, social and environmental problems, the lifespan of the reservoir, and societal benefits.

Worldwide, the planning and management of reservoirs was premised on the assumption that annual water resources and the fluvial regimen would be relatively stable through time. The evidence presented here and in other studies shows that this is not the case. Several authors have demonstrated that small changes in water inputs can induce major alterations in reservoir functioning (Nemec and Schaake, 1982). Thus, a runoff reduction of 20% can cause a decline of 60-70% in the annual water storage, and 60% less power production (Nash and Gleick, 1993). A study of four multipurpose reservoirs in the Acheloos River, central Greece, indicated that the reservoirs were more sensitive to decreased precipitation than to a temperature increase (Mimikou et al., 1991), with respect to the risks to power production and water storage.

Reservoir management schemes have to take account of very complex interacting variables related to reservoir size, the influence of snow in the fluvial regime, trends in precipitation and discharge within the basin, and the use of the water stored in the reservoir (López-Moreno and García-Ruiz, 2007). The infilling regime for a reservoir is the result of a tradeoff between the fluvial regime characteristics and water demand. Thus, changes in annual discharge or in river regimes require delicate adjustments to the management pattern, including i) if discharge increases in winter (as a result of higher temperatures and less snow accumulation), then more water will need to be stored in the reservoir in winter, because of an expected decrease in spring high flows; and, ii) if average annual discharge declines (caused by a reduction in average precipitation or to land cover changes including reforestation), adjustment is possible but invariably reduces river discharge

downstream the dam. In such cases, reservoir managers try to maintain the same level of flow to irrigation canals to supply irrigated areas; this is compensated by reducing discharge to the river, thus threatening ecological flows (López-Moreno et al., 2004) and confirming the existence of opposing interests related to water sharing, whose solution would need the management of water demand rather than use. Also, even if these adjustments are adopted, a shorter snowmelt season results in an earlier start to the dry season, and consequently presents more difficulties in meeting the water demand in summer, and a greater chance that the reservoir will be completely exhausted by the beginning of autumn. This scenario highlights the need to increase the rate of reservoir infilling throughout autumn and winter (López-Moreno et al., 2004).

Several predictions about the future of water resource management in the Mediterranean are possible. i) Fewer reservoirs will be developed in the north of the basin, where current water policies reflect the notion that human well-being depends more on water economy than water consumption. Some decades ago planners assumed a continued exponential growth in total water demand (Gleick, 2003), which is no longer tenable because of environmental change and the high cost of infrastructure. The suggestion that water demand be satisfied by the construction of new infrastructure is increasingly being abandoned. ii) Some indispensable new reservoirs will be constructed in seasonally challenged countries, where water supply now depends mainly on very irregular stream flows, limiting the possibilities for assuring supply and increasing crop production under irrigation. iii) New adjustments between water resources and reservoir management will be needed to enable adaptation to changing river regimes and water availability. iv) New policies on water recycling and desalinization will be needed, involving technological improvements and new water pricing formulae to achieve water conservation. In most developed countries water demand tends to be saturated in the domestic and industrial sectors (Alcamo et al., 2003), and to be declining in irrigated lands, because of constant improvements in water efficiency. Pyrenean studies reveal that adjustments already introduced to reservoir management strategies cannot be further

improved (López-Moreno et al., 2008a), and many warn that current levels of groundwater exploitation are unsustainable (Croke et al. 2000; Leduc et al. 2007; Shaban, 2008). In this respect it is not an exaggeration to conclude that, on a worldwide basis, Mediterranean countries are among the most threatened by water stress, because of extreme natural inter-annual variability, seasonality of water resources, and decreasing stream flows forecast in coming decades.

Conclusions

Water resource availability in the Mediterranean has already been affected by environmental change, and is seriously jeopardized in future environmental, economic, and demographic scenarios. Most global hydrological models are based on expected trends in precipitation and temperature. However, a number of studies have demonstrated the influence of land cover on river discharge and water resources. Climate and land cover change (artificial and natural reforestation, deforestation, expansion of farming areas) are likely to amplify water stress in the Mediterranean region, caused by a combination of decreased water resource availability (lower precipitation and increased evapotranspiration) and increased water use pressure resulting from economic growth and urban expansion. The effects of increasing water demand exceed those of global warming (Vörösmarty et al., 2000). Some areas with scarce water resources will be particularly at risk, above all if they are subject to strong population growth, as is the case for the Maghreb region (Algeria, Tunis, and Morocco).

Special attention to mountain areas is required, as they are the most important sites for water resource generation worldwide, and particularly in temperate and semi-arid areas including the Mediterranean basin. However, mountain areas are facing increasing hydrological stress caused by a combination of i) increasing temperature and decreasing precipitation, exceeding that in the lowlands; ii) land use change, including natural and deliberate reforestation of abandoned farmland, thus increasing evapotranspiration and water consumption (although deforestation and expansion of

agricultural areas are expected in some marginal and less developed areas); and, (iii) increasing pressures on surface and groundwater resources, thus reducing river discharge and lowering the depth of the water table in groundwater-dependent areas. In coastal areas, overexploitation of groundwater resources and a depletion of river flows in the Delta areas may enhance saline intrusion in the lower reaches of rivers and into the groundwater reserves. It affects negatively to water quality which impact to agriculture and domestic water use (Oki and Kanae, 2006).

Of particular interest will be the changing role of snow, and the ratio between precipitation and snow. Snowfall and snow accumulation are declining in Mediterranean mountain regions, thus increasing the probability of winter floods, reducing the intensity of spring high flows, and causing an earlier occurrence of these high flows. This will lead to changes in river regimes, and the need to adjust reservoir operating rules to adapt to increasing water scarcity in summer.

Future scenarios for water resource management will be characterized by increasing demand in developing countries and, in part, developed countries, and by the short-term unsustainability of many reservoirs in the Mediterranean basin. Changing water resources and demand will necessitate improved management, water economy, and water recycling policies. Continued monitoring of climatic trend and land cover will be necessary for adjustment of water management strategies and water demand with respect to the temporal variability of water resources. Climate and land use change scenarios clearly suggest an increase in water resources stress and a shortage of water availability in the Mediterranean region. This will possibly increase regional and national tensions over the control and use of water at transboundary basins. Strong institutional frameworks will be needed to develop socially, economically, and environmentally sustainable water management. Such an extremely complex problem will need the development of interdisciplinary teams to work on climate change, river regimes, snow accumulation and melting, reservoir management and land use changes, with the participation of engineers, climatologists, hydrologists, human and physical geographers and general environmentalists.

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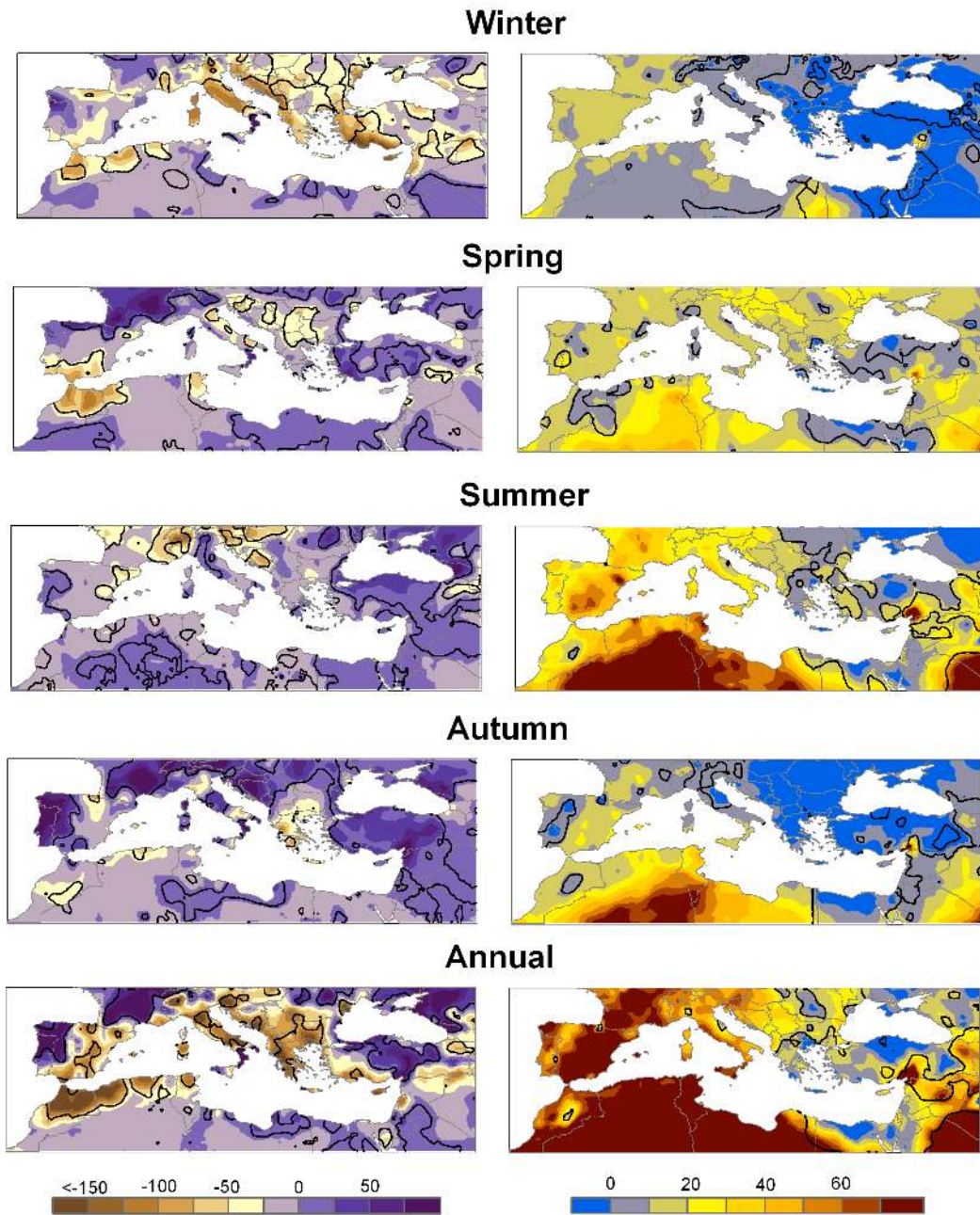


Figure 1. Seasonal and annual climate evolution in the Mediterranean region between 1950 and 2002. Colors show the magnitude of changes in precipitation (left) and potential evapotranspiration (right), in mm. Black isolines: areas with significant trends ($p < 0.05$).

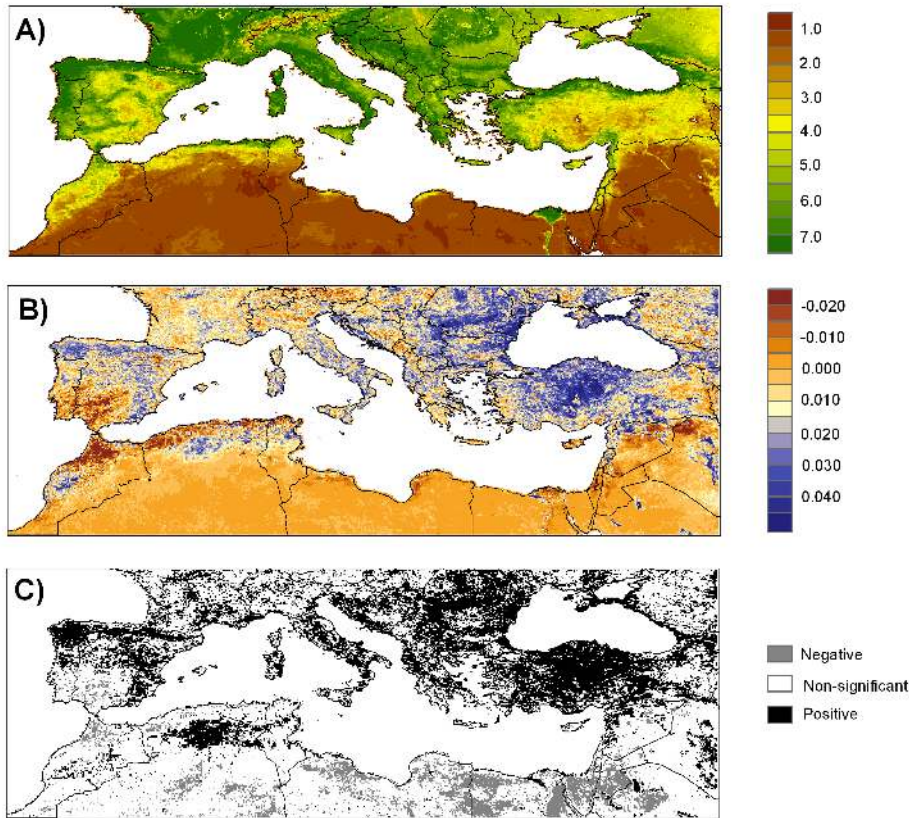


Figure 2. Evolution of the normalized difference vegetation index (NDVI) in the Mediterranean basin for the period 1980–2006. A: mean annual NDVI; B: annual change in the NDVI (slope of the linear regression); C: significant changes in the NDVI values according to Spearman's rho test ($\rho < 0.05$)

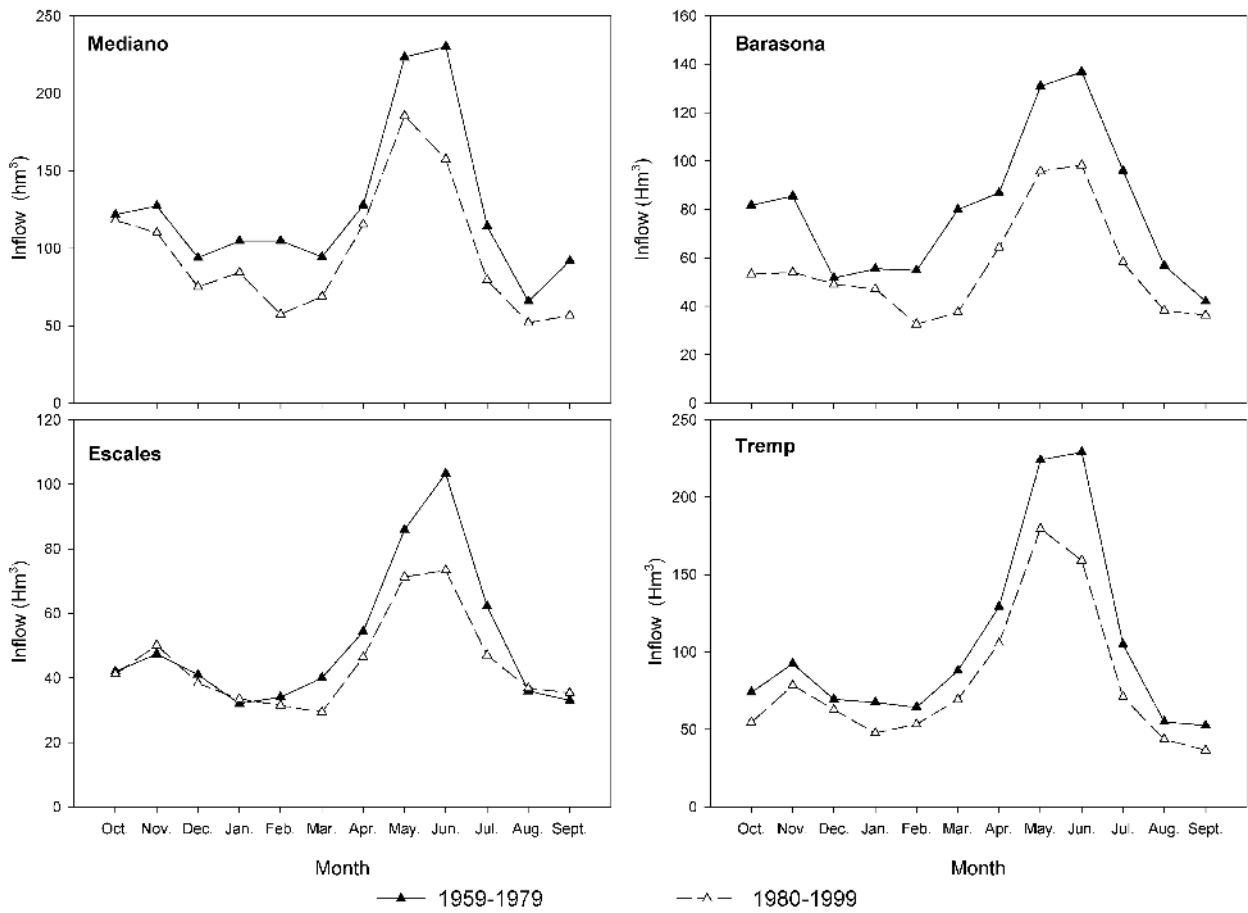


Figure 3. Mean monthly discharge into different Pyrenean rivers for the periods 1959-1979 and 1980-1999 (López-Moreno and García-Ruiz, 2004).

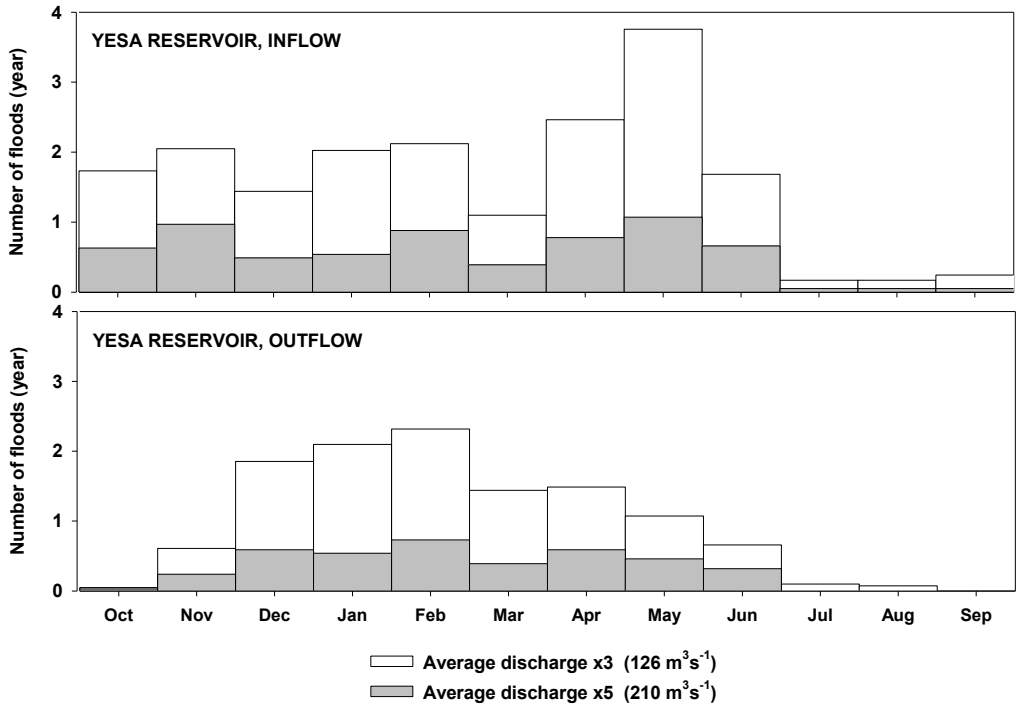


Figure 4. Number of floods that exceed three- and five-fold the mean annual runoff upstream and downstream of the Yesa reservoir.

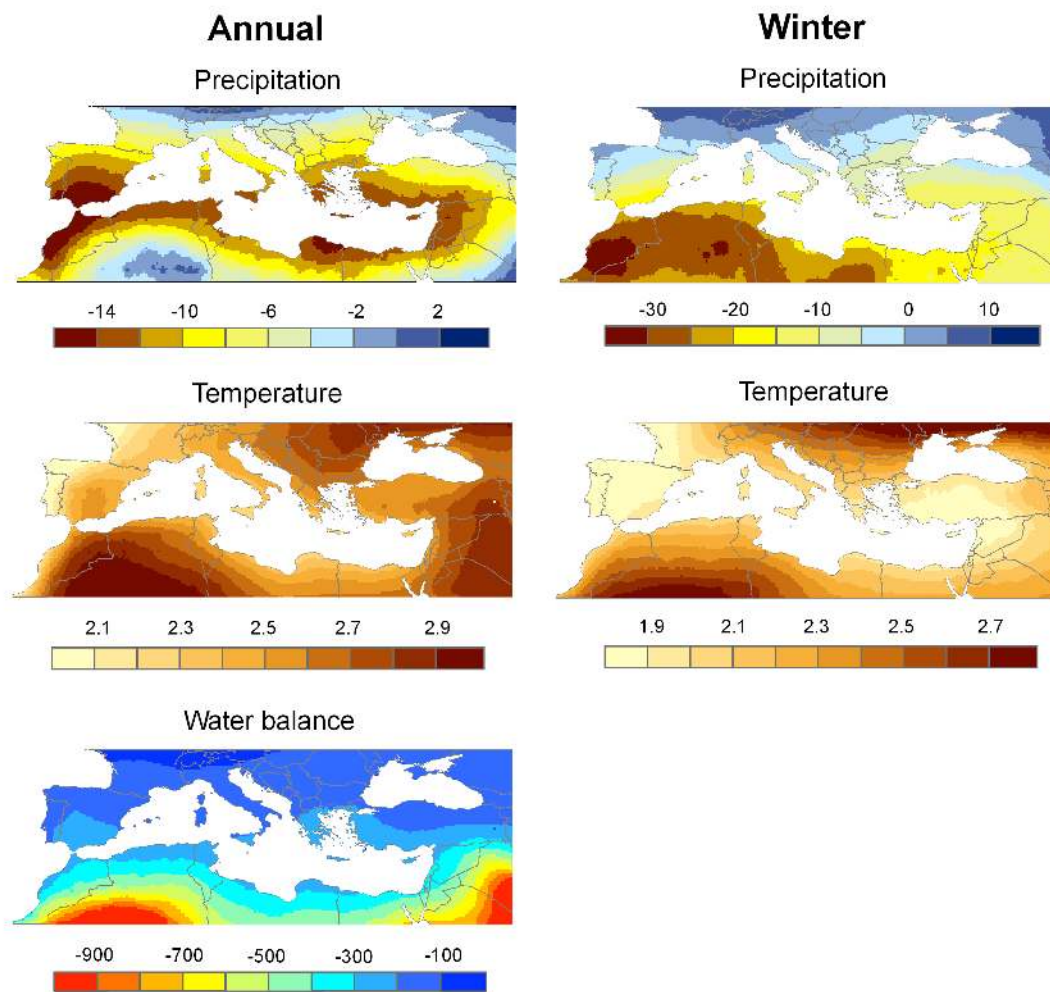


Figure 5. Mean annual and winter climate change, precipitation (P; %), temperature (T, °C) and water balance (P-T, mm) projected for the Mediterranean region between 2040 and 2070 in comparison to 1960-1990 by nine general circulation models. BCCR: BCM2, CCMA: CGMA3T3, UKMO: HADCM3, NIES: MIROC3HI, CNRM: CM3, CSIRO: MK3, NCAR: CCSM3, CNRM: CM3, and MPIM: ECHAM5.