Global and Planetary Change 148 (2017) 139–152

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Losing water in temporary streams on a Mediterranean island: Effects of climate and land-cover changes

Celso Garcia [a,*], Arnau Amengual [b], Víctor Homar [b], Alberto Zamora [a]

[a] Department of Geography, University of the Balearic Islands, 07122 Palma, Balearic Islands, Spain
[b] Department of Physics, University of the Balearic Islands, 07122 Palma, Balearic Islands, Spain

ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form 6 November 2016
Accepted 16 November 2016
Available online 20 November 2016

Keywords:
Number of days with flow
Temporary streams
Mediterranean climate
Mallorca
Mann-Kendall
Multiple linear regression
Streamflow elasticity
Budyko graph

ABSTRACT

Temporary streams are unique, sensitive and threatened fluvial systems. They periodically dry up and contribute to biodiversity by supporting different species. In Mediterranean regions, human pressures and climate change increase the duration of the dry period for the streams. We analysed the annual and seasonal trends on streamflow data from 14 gauging stations on temporary streams on the island of Mallorca. We used a Mann–Kendall trend test on data from 1977 to 2009 (33 years) to identify trends in discharge, number of days with water, accumulated precipitation, potential evapotranspiration (PET), and land cover change. Results show a general decreasing trend of streamflow during spring and summer, with flows reduced between 4 and 17% in some basins. Although the inter-annual variability is high for both seasons, the decrease in annual precipitation, the increase in temperature, and the effects of colonization and growth of forests explain the reduction in the number of days with running water. Correlation and elasticity analyses show that precipitation is the main driver for streamflow reduction, but the increase in temperature and land-cover changes also play a significant role in the decreasing of flows. These seasonal changes especially affect the headwaters of the basins, which are located in a mountainous area. The Kendall regional test, applied to the 12 basins considered in the Tramuntana range, reveals a significant decreasing annual trend in the number of days with measured flow. The forest expansion and the warmer conditions cause a higher vegetation water demand, increasing the real evapotranspiration and, consequently, reducing the runoff and thus increasing the losses in the water balance. In addition, the increase in the number of days during which channels and parafluvial habitats are disconnected negatively affects the aquatic habitat. This paper provides the first evidence of a consistent long-term reduction in flow in temporary streams in the Mediterranean region. We highlight the ecological implications of losing water in temporary streams across Mallorca, and we argue the urgent need for conservation plans to protect them from present and future changes and challenges.

1. Introduction

Runoff and water quality are influenced by many natural and anthropogenic factors that occur at the basin scale. It is well known that land-cover changes constitute one of these factors (Foley et al., 2005). Land-use activities, primarily agriculture and urban, have caused a net forest loss over the last centuries (Ramankutty and Foley, 1999), affecting surface runoff and river discharge (Costa et al., 2003; Sahin and Hall, 1996). The intensification of agricultural activity has increased erosion and sediment loads (Walling, 1999; Wilkinson and McElroy, 2007). In contrast, afforestation, as a consequence of land abandonment and reforestation activities, also affects the water balance through its effects on evapotranspiration and interception (Cosandey et al., 2005; Llorens et al., 1995). Afforestation is therefore considered to lead to a reduction in runoff (e.g. Bosch and Hewlett, 1982; Jackson et al., 2005; Robinson et al., 1991; Trimble et al., 1987).

Land-cover and land-use change is especially intensive in Mediterranean Europe, where human pressure has modified the landscape (Serra et al., 2008) and transformed the ecosystems over centuries and affected the hydrological response of the drainage basins (Beguería et al., 2003; Buendia et al., 2015; Gallart and Llorens, 2003; Grove and Rackham, 2001; Morán-Tejeda et al., 2010; Sala, 2003). Streams in the Mediterranean basin have a distinct cool and wet season followed by a warm and dry season. However, precipitation possesses a high inter-annual and -seasonal variability, ranging from long and intense dry periods to extreme rainfall and flooding (Alpert et al., 2002; Sumner et al., 2001). Consequently, streams in Mediterranean ecosystems experience sequences of regular and often extreme flooding and drying periods (Gasith and Resh, 1999). Freshwater availability is scarce

* Corresponding author.
E-mail address: celso.garcia@uib.es (C. Garcia).

http://dx.doi.org/10.1016/j.gloplacha.2016.11.010
0921-8181/

and, in Spain, is mainly dependent on runoff from mountain areas (García-Ruiz et al., 2011; Morán-Tejeda et al., 2010). In contrast, the region has suffered from high demands on water availability to meet the needs of growing populations and living standards, the development of irrigated agriculture, and increasing tourism activities (Cudennec et al., 2007; Garcia and Servera, 2003). Competition for water is often compounded by water pollution, which threatens the existing supplies and exacerbates the damage to stream ecosystems (Gasith and Resh, 1999). Furthermore, large areas of the Mediterranean region are covered by karst or porous terrain formed on carbonate rocks, implying, in general, that streams are groundwater-dominated (Estrany et al., 2009). Transmission losses and cessation of discharge from springs are the predominant mechanisms of water loss in streams (Jourde et al., 2007). Water withdrawals are lowering the groundwater table, which can result in increased transmission losses, intrusion of seawater into coastal aquifers or a modification of the river flow regime (Döll et al., 2009). Therefore, this region is dominated by temporary rivers characterised by intermittence in their surface flow duration. This flow intermittence is a natural phenomenon, although human withdrawals of surface water and groundwater can increase the magnitude or frequency of flow intermittence (Rupp et al., 2008). In recent years, there has been renewed interest in temporary streams, as they are the most common and hydrologically dynamic freshwater ecosystems (Larned et al., 2010). In the Mediterranean, these hydrological characteristics of temporary streams determine the structure and function of invertebrate communities (Álvarez and Pardo, 2009; García et al., 2008). These streams show high natural spatial and temporal variability in their invertebrate assemblages (Álvarez and Pardo, 2007; Munné and Prat, 2011), which makes it necessary to establish a clear distinction between the influence of human impacts and typological differences in order to properly assess the streams' ecological statuses (García et al., 2014).

Streamflow is also influenced by climate change. Precipitation and potential evaporation (PET) are the main climatic drivers controlling freshwater resources. Precipitation tends to decrease in subtropical latitudes, particularly the Mediterranean region, where droughts are projected to become longer and more frequent (Jiménez Cisneros et al., 2015). Global hydrological models project decreases in mean annual discharge in Mediterranean rivers of between 10 and 30% throughout the 21st century (Schewe et al., 2014), and −5% relative change in runoff per °C global warming (Zhang et al., 2014).

The detected trends in streamflow have generally been consistent with observed regional changes in precipitation and temperature since the 1950s. In Europe, streamflow has decreased in the south and east and generally increased elsewhere during the 1962–2004 period (Stahl et al., 2010, 2012). In the western Mediterranean region, seasonal and annual decreasing trends have been reported for rivers in Spain (Beguería et al., 2003; Buendia et al., 2015; Ceballos-Barbancho et al., 2008; Gallart et al., 2011; Lorenzo-Lacruz et al., 2012; Martínez-Fernández et al., 2013; Morán-Tejeda et al., 2011; Salmoral et al., 2015) and France (Lespinas et al., 2010; Ludwig et al., 2004). The main driving factors of streamflow trends in the Mediterranean are climate variability, land-use change, and water management and use strategies (García-Ruiz et al., 2011).

Within this context, we have conducted a thorough examination of the evolution of streamflow data in the gauged basins of Mallorca for the period 1977–2009 (33 years). Specifically, the objectives were to (i) examine the annual and seasonal changes of streamflow, in volume and number of days with flowing water; ii) explore the annual and seasonal changes in precipitation and PET; iii) assess the existence of significant temporal trends; and iv) determine to what extent these changes are attributable to climatic oscillations and land cover change, as well as to evaluate the importance of these changes for water resources management and the ecological status of these temporary streams. This paper provides the first evidence of long term hydrological change in temporary streams in the Mediterranean region.

2. Material and methods

2.1. Study area

Mallorca is the largest of the Balearic Islands, which are located in the Western Mediterranean (Fig. 1). The overall structure of the island comprises a set of NE-SW oriented ranges and basins. The island can be divided into three geomorphological areas: the Tramuntana Range along the NW coast; the Central Zone in the central part of the Island, and the Llevant Ranges along the eastern coast. These zones correspond to uplifted blocks, mainly built of Mesozoic and Tertiary sediments (Jenkyns et al., 1990). The Tramuntana Range is characterised by sharp relief related to the abrupt elevation change that occurs over the 5 km distance separating the highest point (1436 m) from the sea. The Central Zone is composed of subsiding basins, and the Llevant Ranges constitute a series of low mountains (highest point 516 m) mainly made up of Jurassic limestones and dolomites. Therefore, the lithology of the island is mainly composed of permeable carbonate rocks.

The island has a warm temperate climate typical of the western Mediterranean. During winter, the island is affected by mid-latitude westerlies, with associated frontal systems that often bring rainfall. During summer, the island lies within the influence of the Azores anticyclone/subtropical belt of high pressure systems, which typically bring dry and sunny weather. During late summer and early autumn, severe local storms generated by local convection are associated with cold water intrusions overlying the relatively warm Mediterranean Sea (Homar et al., 2003; Romero et al., 1998). The closed characteristic of the Mediterranean Sea and the high insolation received during these months lead to high sea surface temperatures, which ensure the strong water vapour availability and frequent convective instability of the Mediterranean air masses. These developments foreshadow the torrential rainfalls during the late summer and autumn. The instability associated with subsynoptic-scale Mediterranean disturbances is eventually released in the form of organized mesoscale convective systems (Amengual et al., 2008; Cohuet et al., 2011; Romero et al., 2014). Most precipitation in the archipelago occurs in autumn and winter, and the wettest months are from September to December (Homar et al., 2010). In addition, there is also a strong regional differentiation in precipitation due to topography. Annual rainfall varies from 300 mm in the southern parts of Mallorca to >1200 mm in the Tramuntana range (Fig. 1), following a NW-SE rainfall gradient.

The permeable rocks and the Mediterranean climate determine the hydrological regime of the streams flowing from the mountains, which is characterised by intermittent flow conditions. As a consequence, the island is drained by temporary streams. Here, we define as temporary a stream with no flowing water along its length for a few months (hydrological disconnectivity) and that consequently dries up. In Mallorca, some of them are groundwater-dominated. The stream is spring-fed and has some baseflow during 6 to 8 months. The other streams are ephemeral and flow briefly following a period of rainfall.

2.2. Database and analyses

In the Balearic Islands, water authorities started streamflow measurement for water management purposes in the late 1960s, deploying a hydrometric network on streams mainly located in the Tramuntana and Llevant ranges. Altogether, 34 streamflow gauging stations (with continuous and partial records) have been active in Mallorca during different periods. After an initial screening, most of the stations were discarded from this study because they receive inflow from sewage treatment plants. A second filter was applied on the basis of: i) a minimum record of 25 years, allegedly long enough to ensure the validity of the trend results (Burn and Hag Elnur, 2002), and ii) no >2 successive years of missing data. As a result, 14 streamflow gauge locations were chosen meeting the above requirements, 12 in the Tramuntana range

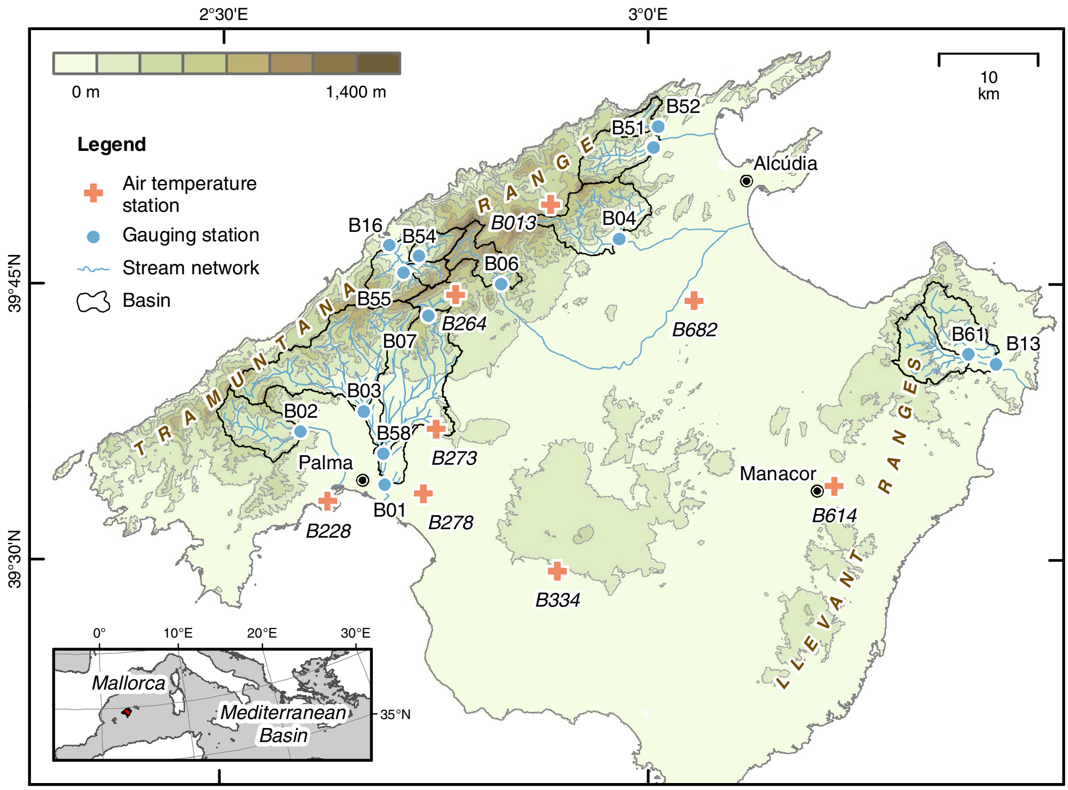

Fig. 1. Location of the studied basins, the gauging stations, and the air temperature stations on the island of Mallorca.

and 2 in the Eastern ranges (Fig. 1 and Table 1) for the period 1977–2009. The drainage areas monitored by the selected stations are typically small, ranging from 8 km^2 to 215 km^2, with an average area of 50 km^2. From these, streamflow and frequency of days with flowing water were derived. The basins, which have not been directly subjected to substantial direct human alteration via the flow regime, may still have been affected by changes in land management and climate. Only the lower parts of the two largest basin outlets (B01 and B58 in Fig. 1) are affected by urban areas.

Table 1 summarises the hydrological characteristics of each basin and, especially, the long-term water balance. The hydrogeological and geomorphological characteristics of the basins determine the interaction of the surface water-groundwater. Consequently, as for the water balance, we compute the amount of precipitation (P) not converted into stream discharge (Q) as water losses (L), and it includes, both, actual evapotranspiration (AET) and percolation or deep groundwater recharge (DP) not returning to the studied basin as Q.

Thus, the main elements of the water balance have been represented in a variant of the Budyko graph (Budyko, 1974; Porporato et al., 2004) for karstic basins. Recall that this hydroclimatological relationship describes the average terrestrial water balance by means of a semi-empirical curve (Fig. 2, discontinuous line), which represents the evaporative

Table 1
Gauging stations used for the analyses and main characteristics of the catchments including the % of rocks with high and medium permeability. Mean discharge, annual rainfall, annual runoff, mean losses, runoff coefficients, and average number of days with water for the period 1977–2009.

ID	Gauging station	Area (km^2)	Medium and high permeability lithologies (%)	mean annual discharge (m^3/s)	Mean annual rainfall (mm)	Mean annual runoff (mm)	Mean losses (mm)	Runoff coeficient	average number of days with water	SD days with water
B01	Gros (outlet)	215	54	0.203	597.1	16.0	581.1	0.03	24.3	26.5
B02	Sa Riera	29	32	0.069	633.0	69.0	564.0	0.11	64.1	61.4
B03	Gros (headwater)	124	49	0.207	655.7	49.3	606.4	0.08	66.1	60.1
B04	Sant Miquel	56	66	0.564	930.2	291.5	638.7	0.31	122.2	71.3
B06	Almedrà	15	71	0.066	1010.5	133.8	876.7	0.13	56.5	43.3
B07	Coanegra (headwater)	11	57	0.024	782.1	66.5	715.6	0.09	142.3	66.7
B13	Canyamel	66	48	0.252	692.1	117.5	574.6	0.17	222.5	127.8
B16	Major de Sóller	50	66	0.426	803.8	261.7	542.2	0.33	120.5	62.9
B51	Sant Jordi	38	47	0.140	967.1	31.0	936.1	0.03	72.9	53.0
B52	Ternelles	10	49	0.061	939.2	188.7	750.5	0.2	89.1	59.2
B54	Fornalutx	13	58	0.106	929.4	249.1	680.2	0.27	124.2	58.8
B55	Biniaraix	8	66	0.107	816.5	407.7	473.4	0.5	132.3	98.3
B58	Coanegra (outlet)	66	50	0.012	562.6	4.7	557.9	0.01	9.3	11.6
B61	Molinet d'Artà	34	42	0.035	682.4	31.6	650.8	0.05	100.5	88.3

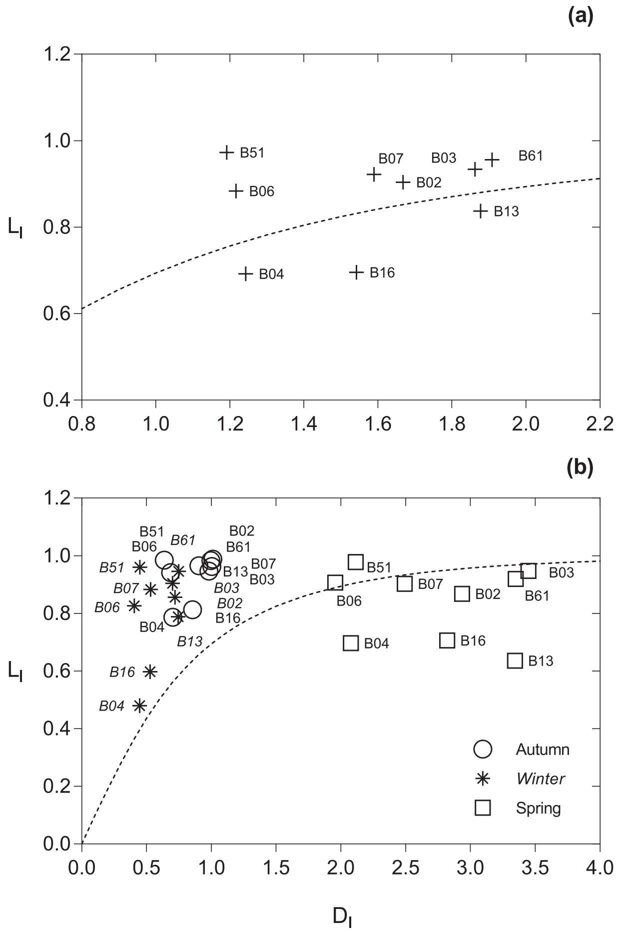

Fig. 2. Annual (a) and seasonal (b) water balance for the largest basins and the period 1977–2009 represented in a variant of the Budyko graph. For the long-term water balance in karstic basins, the evaporative index was substituted by the losses index (L_I).

index (E_I) as a nonlinear function of the dryness index (D_I):

$$E_I = \sqrt{D_I\left[1-e^{(-D_I)}\right]\tanh\left(\frac{1}{D_I}\right)} \tag{1}$$

where $E_I = \frac{AET}{P}$ and $D_I = \frac{PET}{P}$, and PET denotes the potential evapotranspiration. For the long-term water balance in karstic areas, E_I is substituted by L_I, a loss index defined as:

$$L_I = \frac{(AET+DP)}{P} = E_I + \frac{DP}{P} \tag{2}$$

The modification of the Budyko graph for the computation of actual losses reduces the significance of this plot as a representation of the climatic conditions (water supply-limited versus energy supply-limited basins), but not undermines its use as a graphical tool to represent the main components of the water balance and their changes with time. A result of summing up AET and DP (Eq. (2)) is that a number of basins fall above the oblique segment of the envelope of the Budyko plot (Fig. 2b). In the original version of the Budyko plot this cannot occur because the ratio of actual evapotranspiration to precipitation cannot exceed the ratio of potential evapotranspiration to precipitation.

We use monthly precipitation accumulation derived from the raingauge network measurements compiled by the Spanish Meteorological Agency (AEMET) to examine the temporal and spatial trends at each basin for the period 1977–2009. Monthly accumulations are computed from a gridded analysis dataset of daily rainfall derived from all of the stations compiled by AEMET on a regular basis. Daily precipitation measurements are expressed as anomalies with respect to the annual mean calculated over the entire observation record for each station. Then, a standard kriging interpolation method, with a specific exponential variogram for each day, is applied to the irregularly distributed daily anomalies to compute the analysed values over a 100 m grid-size mesh. The resulting gridded field of daily anomalies and the corresponding variances are used to derive the absolute daily accumulations and the respective error estimate. Areal accumulated values of monthly precipitation for each drainage basin of the considered gauged streams are then computed.

Daily maximum and minimum 2-m temperatures from 7 stations with complete data series for the 1977–2009 period have been obtained from AEMET in order to compute the potential evapotranspiration (Fig. 1 and Table 2). PET is calculated by applying the Hargreaves-Samani equation (Hargreaves and Samani, 1985; Allen et al., 1998; in mm day^{-1}):

$$PET = 0.0023 R_a \sqrt{\delta_T}(T+17.8) \tag{3}$$

Where T is the daily mean air temperature (°C); δ_T is the daily air temperature range (°C); and R_a is the water equivalent extraterrestrial radiation (mm day^{-1}). Note that the Hargreaves-Samani equation was originally developed for semi-arid and arid climates and, although being solely temperature-based, it accounts for effects of cloudiness through δ_T. Furthermore, the daily temperature range also correlates positively with relative humidity and vapour pressure, and negatively with wind speed (Hargreaves and Allen, 2003). In fact, after testing several evapotranspiration equations for calculating daily PET against lysimeter data for a semi-arid Spanish experimental plot, López-Urrea et al. (2006) found that the Hargreaves-Samani equation was remarkably accurate and performed better than higher demanding input-data equations in, both, periods of high and low evaporative demand.

We used two Landsat 5-TM and Landsat 7-ETM+ images from August 1985 and 2009 (24 years apart) to assess changes in land use. The launch of the Landsat-5 in 1984 determined the availability of the earliest usable image for this study. The two images are used to identify differences in land cover processes as a function of seasonal differences in vegetation photosynthetic activity. We use the normalized differences vegetation index (NDVI) to analyse land cover change processes (Lasanta and Vicente-Serrano, 2012).

For the sake of attribution information, a non-parametric approach is used to estimate the climate elasticity of streamflow directly from observed data (Sankarasubramanian et al., 2001):

$$\varepsilon = \text{median}\left(\frac{\left(Q_i-\overline{Q}\right)/\overline{Q}}{\left(X_i-\overline{X}\right)/\overline{X}}\right) \tag{4}$$

Where Q_i and X_i are annual streamflow and the climatic variable (e.g., annual precipitation) and the overbar parameters are long-term averages of streamflow (Q) and the climate variable (X).

Table 2
Mann-Kendall's S values of the trend of PET for the period 1977–2009. Trends significant at the 5% level are in bold and at 10% level are in bold and italics.

ID	Surface temperature station	Altitude (m)	Annual	Winter	Spring	Summer	Autumn
B013	Escorca	490	***112***	84	***122***	***196***	−8
B228	Palma	3	104	**146**	**190**	98	6
B264	Bunyola	455	14	28	**186**	−14	**−140**
B273	Marratxí	152	***110***	***116***	***126***	54	66
B278	Aeroport	8	86	56	**160**	24	−100
B334	Llucmajor	140	−46	−84	16	20	**−186**
B614	Manacor	85	98	68	98	78	76
B682	Muro	50	**160**	−60	**156**	***136***	−106

The streamflow elasticity describes the sensitivity of the streamflow response to changes in the climatic variables at the annual time scale. This method was compared with an alternative non-parametric estimator where the elasticity can be regarded as the linear regression coefficient between the climatic variable and the discharge to overcome the problem associated with small sample size (Zheng et al., 2009).

A graphical assessment of streamflow elasticity was also performed (Wolock and McCabe, 1999). In our case, long-term hydrological data was splitted in subperiods of 11 years in a three-dimensional plot representing the co-variations of discharge with water losses and precipitation (Andréassian et al., 2016).

Time series data were examined for trends using the non-parametric Mann–Kendall (MK) test (Kendall, 1975; Mann, 1945). The MK test is widely used to examine randomness against trends in hydrology and climatology and is robust against outliers (i.e. Douglas et al., 2000; Hirsch et al., 1982; Kundzewicz and Robson, 2004). To perform the test, the Kendall's S statistic was computed from the Y, T data pairs, where Y and T represent the response variable and time, respectively. The null hypothesis is rejected when S (and therefore Kendall's τ of Y versus T) is significantly different from zero. We then conclude that there is a significant monotonic trend in Y over time.

When trends are estimated, the data are assumed to be serially uncorrelated, and the resulting confidence interval is sensitive to non-normality of the parent distribution (Sen, 1968). The MK test will produce misleading significance tests on the trend when autocorrelations exist in the data (von Storch, 1995). Positive (negative) autocorrelations in the time series tend to overestimate (underestimate) the probability of detecting a monotonic trend and thus render spurious confidence levels (Yue et al., 2002). To reduce the influence of serial correlation on the application of the MK test, a whitening of the series is highly suggested (von Storch, 1995). We thus applied the MK test over the whitened series W_t defined as:

$$W_t = x_t - \rho_1 x_{t-1} \tag{5}$$

Where ρ_1 is the autocorrelation coefficient of order unity.

The regional Kendall test (Helsel and Frans, 2006) allows for the extension of the MK test from the basin to the regional scale. A MK test is computed for individual locations, and those results are combined into one overall test for a consistent regional trend (Helsel and Frans, 2006). The regional Kendall test looks for consistency in the direction of the trend at each location and tests whether there is evidence for a general trend in a consistent direction throughout the region. The test is applicable to data where annual observations are available at numerous locations and one overall test is desired to determine whether the same trend is evident across those locations (Helsel et al., 2006).

3. Results

3.1. Water balance

In the long-term, temporary streams in Mallorca show a low discharge and high water losses (Table 1). Although precipitation is important in streams located in Tramuntana, the low runoff coefficients demonstrate that a large amount of water is exiting these karstic basins as losses. Due to the limitation of data availability and the impossibility of quantifying AET and deep infiltration independently, they are both considered jointly to represent total losses. The variant of the Budyko plot in Fig. 2 shows the annual and seasonal water balance for the main basins and the period 1977–2009. For purposes of clarity, the sub-basins and the two largest basins with a small number of days with flow (B1 and B58) are not represented. Fig. 2 points out the semi-arid climate of the Mediterranean region, with precipitation accumulations larger than potential evapotranspiration in winter and autumn and the contrary in spring. It also shows the importance and magnitude of water losses in these karstic basins. In fact, all catchments overpass the energy limit in winter, resulting in an effective replenishment of the groundwater levels. In general, the dynamics of these basins is groundwater dominated, as their aquifers are recharged in autumn and winter, and they mainly feed the streams as runoff in spring and, to a lesser extent, in summer. Fig. 2a shows a clear division between the basins with larger discharges or lower losses in the annual water balance, B04, B13 and B16, and the ones above the semiempirical curve of Budyko, which show lower discharges and higher losses. This characterizes the flow: ephemeral (high values of the loss index) and spring-fed (lower values), with a baseflow during 6–8 months on average. The dominance of groundwater contribution to streamflow on these basins is evident on the flow duration curve (FDC). Fig. 3 shows the FDC for 4 basins derived from daily streamflow data for two representative periods: 1977–1987 and 1999–2009. In the three basins with an influence of the groundwater on the streamflow (B04, B16 and B13) the FDC has a low slope. Instead, the high slope of the FDC is evident in the rain-fed and ephemeral stream of the basin B03, for which only in 20% of the time the flow equaled or exceed 0.1 m^3/s. The comparison of the FDC for the two periods shows a decrease in daily discharge between 5 and 20% of the time the flow is equaled or exceeded for the B03 and B16 basins. An increase is also evident for B04 and B13 basins. In terms of rainfall, the first period qualifies as normal (i.e., near the 1977–2009 average), and the second as humid (i.e., above average).

3.2. Annual and seasonal trends on streamflow volumes and frequency of days with water

Values of the MK test are shown in Fig. 4. None of the 14 studied stations show a statistically significant annual trend. Six stations show a decreasing streamflow trend, and 8 show an increase. For the annual frequency of days with water, 9 stations show a decreasing trend, and 4 show an increase. As the majority of stations with decreasing trends are located in the Tramuntana area, we decided to perform a regional Kendall test for the 12 stations located in the area. Significant changes ($p < 0.05$) are observed along the Tramuntana in the annual number of days with water, with an annual decrease of −0.44 days per year. Therefore, although no significant annual trends were detected for individual basins, there is a significant decreasing trend at the regional scale in Tramuntana.

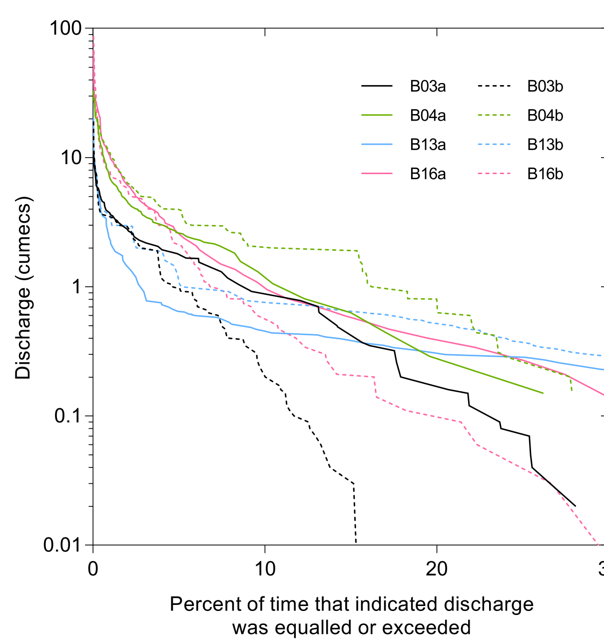

Fig. 3. The flow duration curve of 4 basins for 2 representative hydrological periods: a)1977–1987 and b)1999–2009.

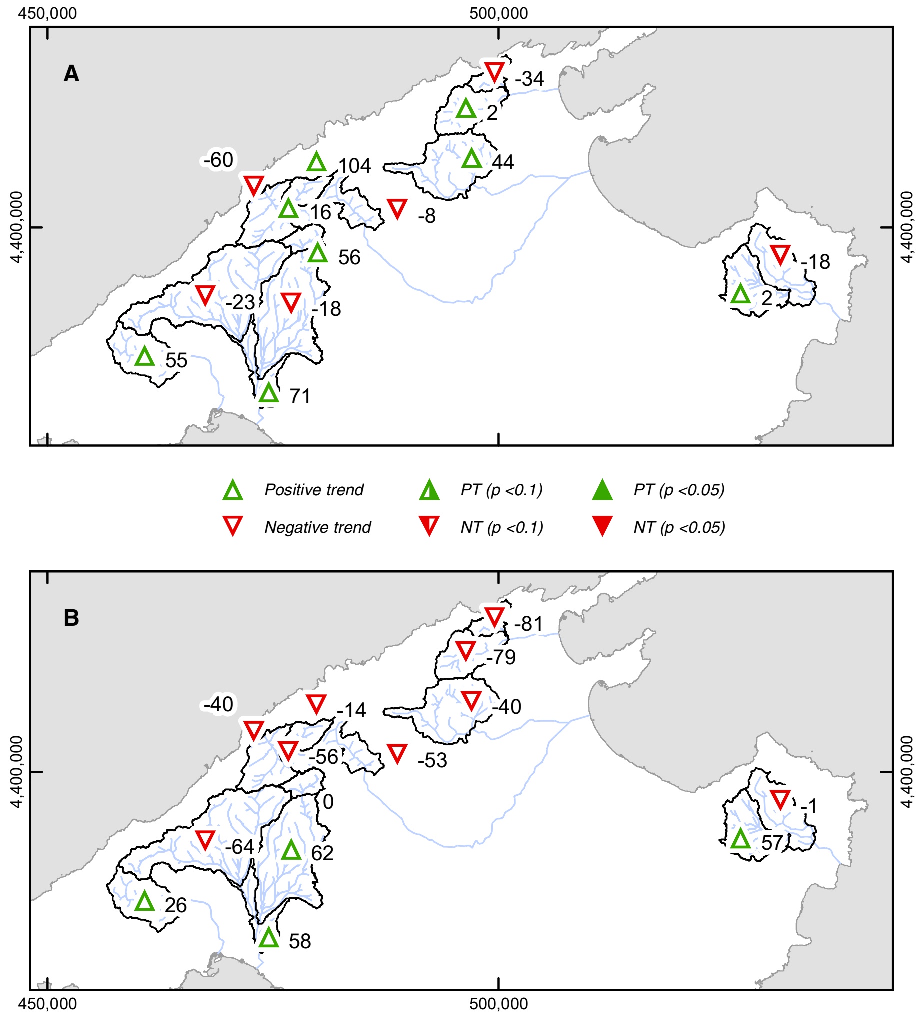

Fig. 4. MK test statistics of the mean annual streamflow (A) and of the number of days with water (B) in the studied catchments.

Regarding the seasonal analyses, seasons are defined as follows: winter (DJF), spring (MAM), summer (JJA), and autumn (SON). Significant negative trends in streamflow (Fig. 5) were found in spring (2 stations) and summer (6 stations), as well as two significant positive trends, one in autumn (B04) and one in winter (B54). The discharge during summer is very low, which is typical for these temporary streams. However, the impact on the spring streamflow for the B16 is important, as it represented the 36% of the annual discharge in the period 1977–88 and decreased to 18.8% for the period 1999–2009. For the same periods, the streamflow for the B52 diminished from 25% to 21%.

For the frequency of days with water, we found 2 significant negative trends in spring and 7 in summer (Fig. 6), while no statistically significant trends were detected in autumn and winter. Again, a reduction in the number of days with flow is recorded in more stations for the summer months and only for the B16 and B52 in spring. The regional Kendall test confirms the significant decrease in the frequency of days with water for the 12 stations located in the Tramuntana area in spring and summer.

3.3. Annual and seasonal trends in precipitation and potential evapotranspiration

We computed the annual and seasonal precipitation trends for each studied basin over the period 1977–2009 (Fig. 7). There are no significant trends for the annual series. However, 9 basins have a significant increasing trend for precipitation in autumn, and 3 have a significant decreasing trend in spring. Overall, there is a general increasing trend in precipitation over the basins during autumn and a negative decreasing trend in spring for the studied period.

Table 2 shows the results of the Mann-Kendall's trend analysis on PET for the same period. There are significant positive trends at the annual scale and for the spring and summer at all 8 thermometric stations. Annual PETs have clearly increased, and these increases are particularly important over the Tramuntana range (stations B013 and B264) in spring and summer, being a regionally significant trend.

3.4. Changes in the NDVI

Table 3 shows the changes of NDVI values in the period 1985–2006 for 8 basins located in Tramuntana where changes in the seasonal streamflow were significant. The NDVI class IV corresponds to an evergreen oak or ilex forest and is the category where the magnitude of change is highest, with increases between 5 and 18.6% in the last 24 years. The decrease in the NDVI class II corresponds to a reduction of the agricultural fields, and the one in class III corresponds to a decrease in areas with disperse and less vigorous vegetation. For the urban or artificial areas (class I), there was a slight increase of between 0.2 and 1.4% being the largest change of 6.1% in the B06. These data show the importance of forest colonization and growth in the Tramuntana during the last 24 years (some examples are showed in Fig. 8). The forest has occupied the land previously used for crops, most likely due to the abandonment of traditional activities in steeper slopes and the subsequent natural re-vegetation processes.

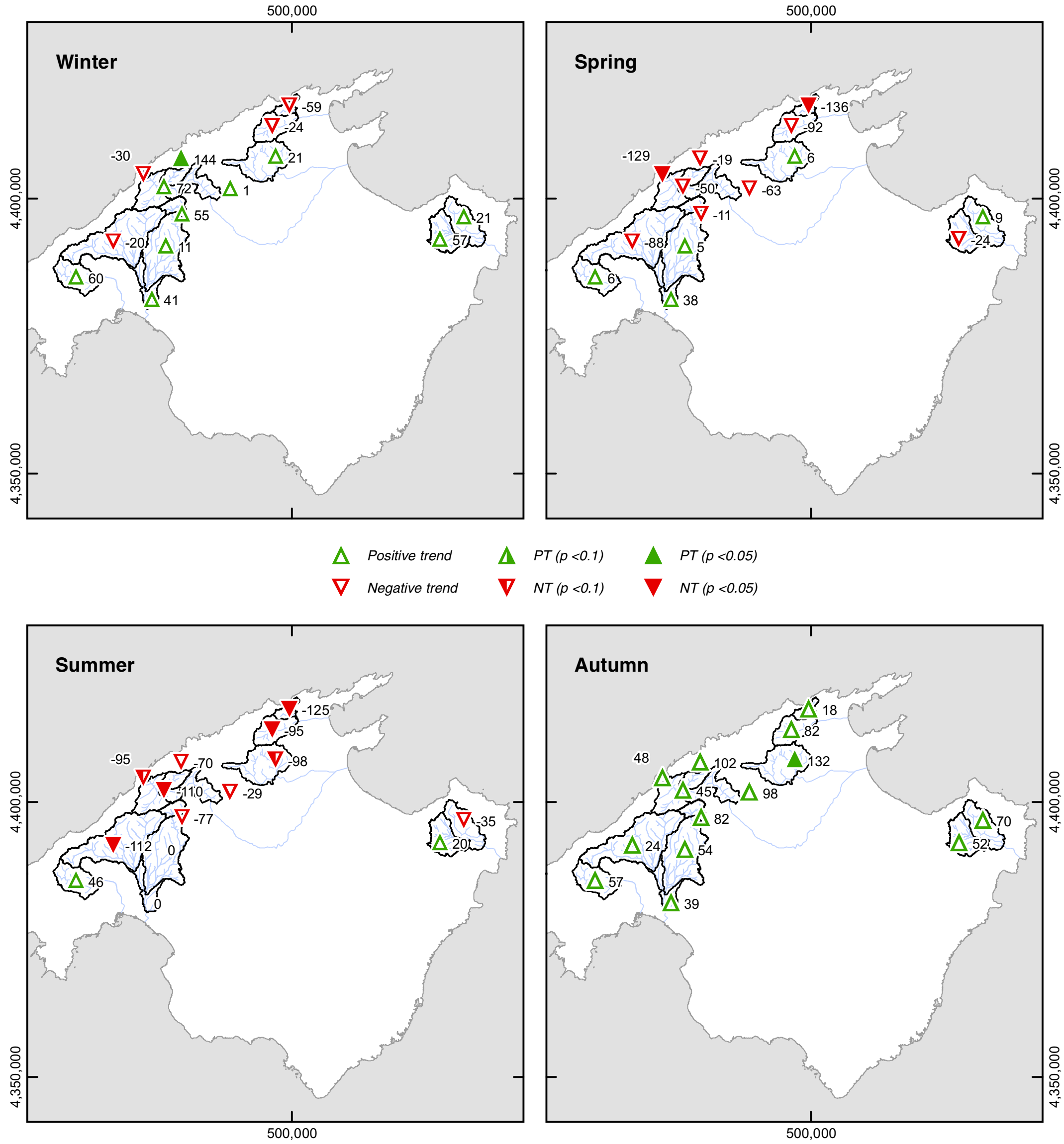

Fig. 5. Seasonal trends of streamflow.

3.5. Effects of climate oscillation and land-cover changes in the evolution of streamflow

Herein, we assess whether the aforementioned climatic evolution and land-use changes have affected the temporal evolution of streamflow. To this end, we have computed annual and seasonal correlations and multiple linear regressions. Streamflow volumes, V_Q, and frequency of days with water, n_Q, have been considered as dependent variables, and precipitation, PET and NDVI are independent variables. In this way, we assess the interaction between the hydrological, climatic and physiographic variables at annual and seasonal scales. Land-use evolution was quantified using the NDVI classes I and IV. Thus, we can explore the possible impacts of the temporal evolution of the observed land-cover on changes in the hydrological variables.

Annually, cumulative precipitation exhibits strong positive correlations with V_Q and n_Q for all basins, although there is high inter-basin variability (Tables 4 and 5). Changes in precipitation explain most of the variance in the hydrological variables. Specifically, precipitation accounts for 39–76% and 38–78% of the inter-annual variance in V_Q and n_Q at the gauging stations, respectively, with mean values of 51% and 40%.

Correlations among the annual series of V_Q (n_Q) and PET are weaker, although negative values were obtained for most basins. PET explains a maximum of 49% (32%) of the variance, with a mean value of 6% (2%). In general, correlations are stronger for the streamflow volume than for the frequency of days with running water. Correlations with the observed land-use changes are uneven and rather uncertain for V_Q: the evolution of NDVI explains a maximum of only 24% of the variance, with a mean value of 3%. Slightly higher scores emerge with the number of days with flow: NDVI changes explain a maximum of 53% of the variance, with a mean value of 23%. Therefore, the evolution of annual precipitation arises as the main driver explaining the variance in V_Q and n_Q of the temporary streams in Mallorca. However, the land-cover changes also play a notable role in determining the number of days with water. At the annual scale, the PET does not seem a good variable to explain the changes in the water balance for this type of basins with higher losses.

Seasonally, the strongest positive correlations between V_Q (n_Q) and precipitation are found in winter, followed by autumn and spring (Tables 4 and 5). Winter precipitation explains 40–82% (46–80%) of the variance of the gauging stations, with mean values of 60% and 58%, respectively. Autumnal rainfall explains 34–82% (15–81%) of the

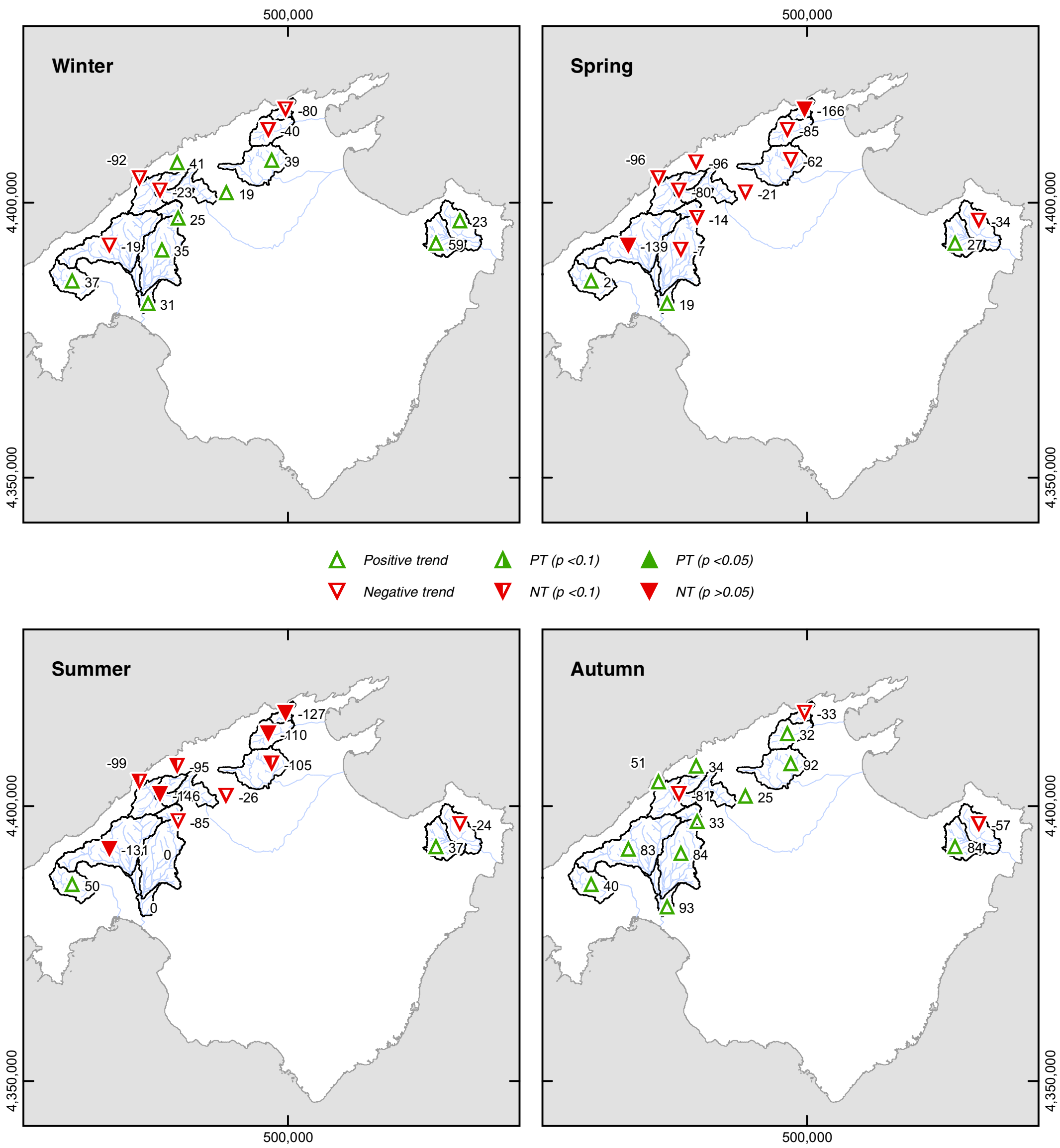

Fig. 6. Seasonal trends of the number of days with water.

variance, with a mean value of 52% (42%), and spring precipitation spans 0–83% (9–74%) of the variance, with a mean value of 51% (44%). Finally, the lowest scores are found in summer, where precipitation has a mean value of only 25% (5%).

The strongest negative correlations between V_Q (n_Q) and PET are found during the growing and warm seasons, when evapotranspiration far exceeds rainfall inputs (Tables 4 and 5). As the demand of water for evapotranspiration is reduced in the dormant seasons, negative correlation coefficients also decrease. Correlations between discharge and land cover changes are weak in winter and autumn. In contrast, moderately negative correlations are found between the evolution of the number of days with flow and land-cover in spring, with an explained variance up to 51%, and 44% for summer.

After applying multiple linear regressions to the annual series (Tables 4 and 5), we find large differences in the variance explained by the considered climatological and physiographic variables. The coefficients of determination (R^2) range from very weak to strong. Altogether, the considered variables explain 12–69% of the variance for the discharge at the 14 gauging stations, with a mean value of 28%. The variance for the inter-annual number of days with water ranges from 16 to 67% with a mean value of 17%.

Seasonally, there is a clear division between the groundwater-dominated streams and the ephemeral ones. In the first group (B16, B04, B06), the correlation coefficients are greater in spring, winter and autumn, whereas in the ephemeral streams (B01, B02, B58), the greatest coefficients of determination are found in winter and autumn. In winter, the independent variables explain 18–67% and 21–66% of the variance in the discharge volume and the number of days with flow, respectively, and the mean values are 36% and 34%, respectively. In spring, the variables explain greater maximum proportions of the variances (up to 76% and 63% for V_Q and n_Q, respectively), but mean values are lower (26% and 19%), indicating that the lower correlations of the ephemeral streams decrease the mean value. In summer, the maximum proportions of explained variance are even larger (up to 77 and 70% for the flow discharge and the number of days with water, respectively) but with lower mean values (6% and 10%, respectively). Finally, runoff variability is explained up to 68% and 77% for V_Q and n_Q in autumn with mean values of 27 and 18%, respectively. As aforementioned, this

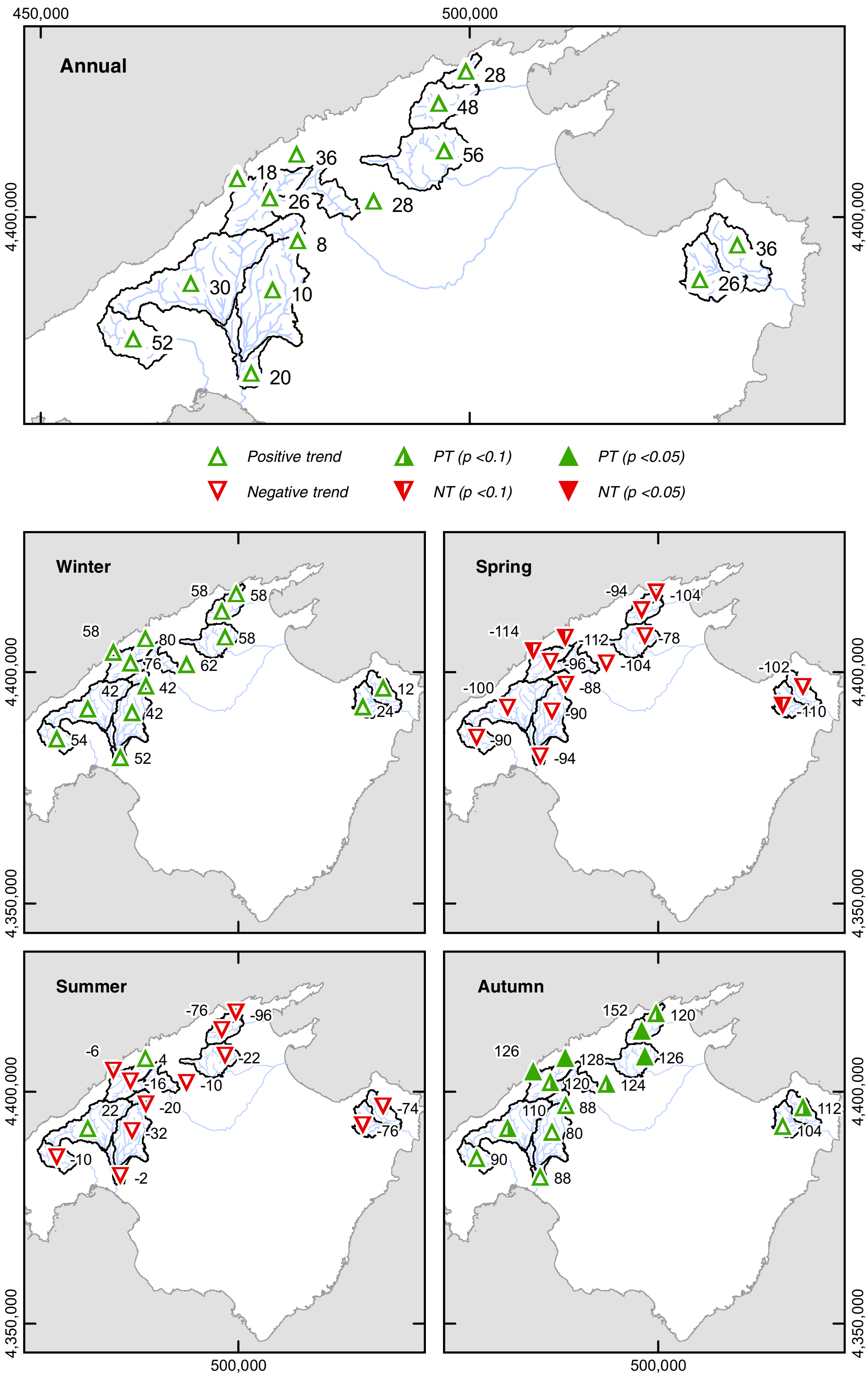

Fig. 7. MK test statistics of the annual and seasonal trends for precipitation over each studied basin.

Table 3
Changes in the NDVI land cover classes between the Landsat images of 1984 and 2009 for 8 selected basins in Tramuntana.

ID	B02		B03		B04		B06		B07		B16		B51		B52	
NDVI classes (value)	1985 (%)	2009 (%)	1985 (%)	2009 (%)	1985 (%)	2009 (%)	1985 (%)	2009 (%)	1985 (%)	2009 (%)	1985 (%)	2009 (%)	1985 (%)	2009 (%)	1985 (%)	2009 (%)
I (−1 to 0)	0.04	0.06	0.2	0.2	0.1	1.5	2.1	8.2	0	0.1	0.6	1.01	0.3	0.5	0.1	0.2
II (0 to 0.2)	30.2	14.5	34.8	26.9	44.6	38.5	58.2	54.2	33.5	36.2	29.9	23.2	45.7	36.6	48.9	44.9
III (0.2 to 0.4)	60	57.1	47.5	45.8	48.7	46	35.8	31.9	34.4	26.7	63.3	63.2	48.1	43.6	43.6	35.2
IV (0.4 to 0.6)	9.76	28.34	17.6	27.2	6.5	14	3.9	5.7	32.1	37	6.3	12.6	5.8	19.3	7.4	19.6

variability between basins and seasons can be explained by the natural variability of the Mediterranean climate and the idiosyncrasies of the physiography and hydrology of each individual basin. Particularly for the cases of streamflow dominated by groundwater (spring-fed stream) or flows ceased briefly after a period of rainfall (ephemeral).

We calculated the sensitivity of the basin's streamflow response to changes in precipitation at the annual time scale. The elasticity values obtained range from 1.7 to 3. This indicates that the basins are specially elastic (or sensitive) to changes in precipitation. This corroborates the results of the correlation analyses that highlight the precipitation as the most important variable. Interestingly, the highest elasticity values correspond to the ephemeral streams as they are rain-fed and depend more directly on rainfall.

Finally, we computed changes in the water balance and examined the empirical elasticity using a variant of the Budyko graph (Fig. 9a). These changes are calculated for each basin and 3 different 11-year periods (1977–1987, 1988–1998 and 1999–2009). Fig. 9a shows that water yield has decreased in basins B04, B06 and B16 as a consequence of natural reforestation. Essentially, these are becoming more evaporative. Basins B51, B07, B02 and B03 have similar water yields, appearing to be more elastic to climate oscillations and changes in land cover. However, these are undergoing an increase in dryness owing to the rise in temperatures. Basins B61 and B13 are the most sensitive to climate and land cover changes. Although their water yields have barely changed during the examined periods, they have experienced major impacts in terms of increases in aridity.

Another way of analysing historical co-varitions of runoff (R) with both P and L is using a pseudo three-dimensional graph (Fig. 9b). This graphical representation of empirical elasticity allows to visually check the variations in R for each basin and attributing them to the causing variables. The discharge decrease (0 to below −100 mm) or increase (0 to 100 mm) due to P and/or L for sub-periods of 11 years. The results show the largest reductions in R for the sub-period 1988–98, followed by the period 1977–87. Runoff increases are detected for the period 1999–2009, attributable to the humid nature of the period, with precipitations above the mean. Despite results show some scatter, a decrease in R can be mainly associated with a decrease in P, together with an increase in L, which includes the actual evapotranspiration and the percolation.

4. Discussion

Flow trends in the temporary streams of 14 basins in Mallorca show a decrease throughout the period 1977–2009. The regional Kendall test for the mountainous area of Tramuntana reveals a significant decreasing trend in the annual number of days with running water. No significant trend was found for the annual streamflows. The trend of annual precipitation over the basins for the studied period is not clear. In contrast, an increasing trend in the annual PET series is significant for the 2 stations located in Tramuntana, and the NDVI values show an increase in ilex forest cover over the last 24 years (Fig. 8). The forest has increased within the basins >10% of their area due to rural abandonment, especially in

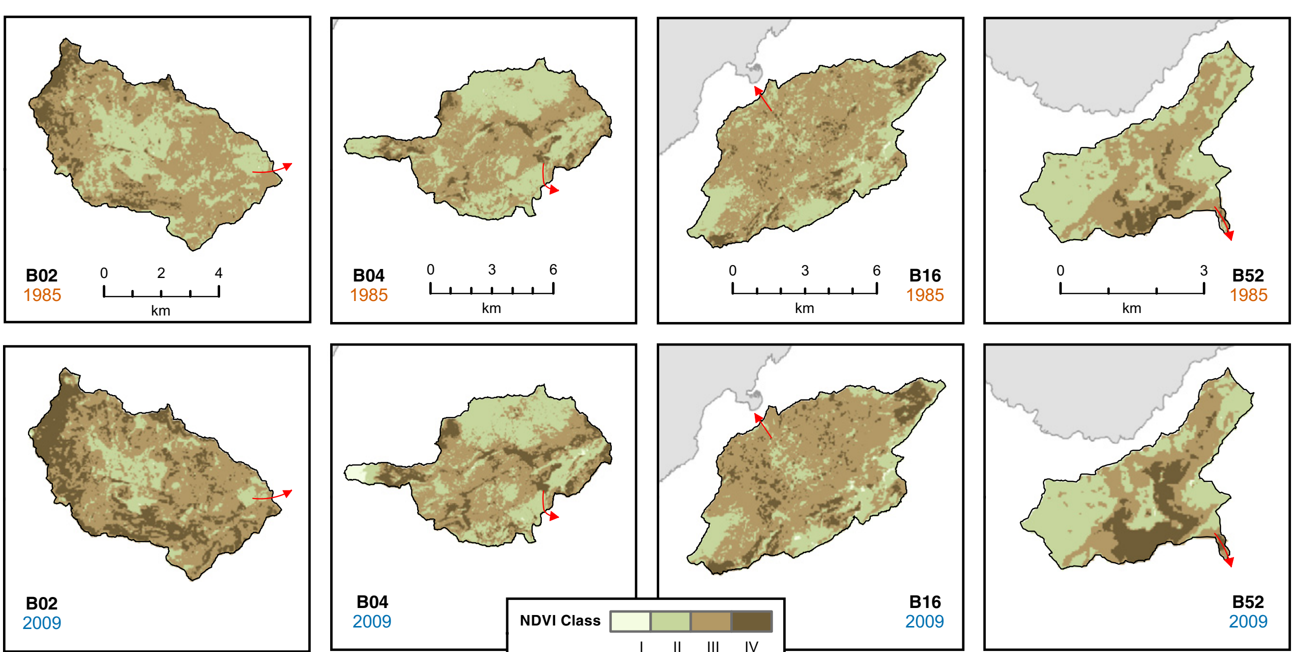

Fig. 8. Changes in land cover evaluated by comparing the NDVI values in LANDSAT images of 1985 and 2009 in 4 basins (B02, B04, B16, B52) where changes are most important.

Table 4
Correlation coefficients (r) between discharge (V_Q) and precipitation and PET and NDVI for the studied basins. The coefficients of determination (R^2) for the multiple regression are shown as well. R^2 and r are in italics when *p*-value < 0.05. R^2 and $|r| \geq 0.6$ are highlighted in bold.

ID	Annual				Winter				Spring				Summer				Autumn			
	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2
B01	*0.45*	−0.44	—	*0.26*	*0.4*	−0.37	—	*0.18*	0.32	−0.22	—	0.10	—	—	—	—	*0.43*	−0.43	—	*0.22*
B02	***0.61***	0.09	0.17	*0.44*	***0.74***	−0.09	0.19	*0.59*	*0.44*	−0.08	0.02	*0.22*	*0.36*	0.05	0.21	0.16	***0.68***	−0.30	0.05	*0.48*
B03	***0.61***	0.00	−0.09	*0.48*	***0.73***	−0.25	−0.09	*0.56*	***0.61***	−0.20	0.17	*0.39*	0.01	−0.17	*−0.44*	0.20	*0.55*	−0.20	0.02	*0.33*
B04	***0.7***	0.01	0.18	*0.55*	***0.66***	−0.16	0.13	*0.45*	***0.67***	−0.32	0.13	*0.53*	***0.72***	−0.47	−0.12	***0.77***	***0.68***	0.16	0.18	*0.57*
B06	***0.64***	−0.21	−0.14	*0.47*	***0.61***	−0.13	−0.15	*0.52*	***0.74***	−0.24	0.02	***0.67***	0.28	−0.06	−0.08	0.09	*0.55*	0.04	−0.02	*0.40*
B07	***0.72***	−0.10	0.26	***0.60***	***0.72***	−0.26	0.23	*0.56*	***0.78***	−0.35	0.07	***0.66***	0.19	−0.13	−0.04	0.08	*0.57*	−0.14	0.33	*0.41*
B13	0.39	0.05	—	*0.18*	***0.69***	−0.39	—	*0.48*	0	−0.01	—	0.00	−0.22	0.06	—	0.05	***0.71***	0.02	—	*0.54*
B16	***0.67***	−0.04	−0.13	*0.52*	***0.74***	−0.35	−0.11	***0.60***	***0.75***	−0.53	0.40	***0.63***	0.03	−0.19	0.05	0.04	***0.66***	−0.13	0.15	*0.50*
B51	***0.74***	−0.09	0.05	*0.57*	***0.71***	−0.16	−0.04	*0.56*	***0.72***	−0.35	0.11	*0.52*	*0.58*	−0.44	*−0.35*	*0.42*	***0.61***	0.05	0.28	*0.40*
B52	***0.7***	0.10	−0.24	***0.69***	*0.53*	−0.10	−0.23	*0.42*	***0.7***	−0.43	0.18	*0.50*	*0.58*	−0.37	*−0.36*	*0.40*	***0.61***	0.10	0.05	*0.45*
B54	**0.76**	−0.15	—	*0.58*	***0.82***	−0.40	—	***0.67***	***0.83***	−0.37	—	***0.76***	*0.48*	−0.29	—	*0.24*	***0.82***	−0.31	—	***0.68***
B55	*0.58*	−0.12	—	*0.33*	***0.7***	−0.41	—	*0.49*	***0.64***	−0.24	—	*0.47*	0.19	−0.31	—	0.10	***0.72***	−0.18	—	*0.54*
B58	*0.5*	−0.49	—	*0.32*	*0.53*	−0.56	—	*0.36*	0.24	−0.20	—	0.06	—	—	—	—	0.34	−0.35	—	0.14
B61	0.34	−0.14	—	0.12	***0.62***	−0.25	—	*0.40*	0.07	−0.26	—	0.07	−0.07	0.04	—	0.01	*0.51*	−0.08	—	*0.26*
All	*0.51*	**−0.06**	—	***0.28***	***0.6***	−0.30	—	*0.36*	*0.51*	−0.18	—	*0.26*	*0.25*	−0.05	—	*0.06*	*0.52*	−0.10	—	*0.27*

the highest parts of Tramuntana. This has been corroborated by the IV national forest inventory for the Balearic Islands (IFN, 2012) that gives data for the period 2006–2008, which can be compared with the other inventories for 1997–99, 1987 and 1971. The increase in surface occupied by dense forest is of 26% in the last 40 years, with >67% of Tramuntana covered by *Pinus halepensis*, *Quercus ilex* and mixed forest. The forest has increased in volume and number of trees. This necessarily results in an increase of evapotranspiration.

The abandonment of cultivated fields and pastures during the second half of the 20th century and their replacement by shrubs and forest has also been reported for the Pyrenees (Lasanta and Vicente-Serrano, 2012; Vicente-Serrano et al., 2004) and has affected runoff generation in the headwaters there, as a consequence of increased infiltration, interception and evapotranspiration rates. This fact shows that the interaction between forest expansion and temperature increase is detrimental to runoff (Buendia et al., 2015). This phenomenon has also been documented for perennial Mediterranean rivers, like the Turia, where the increase in mean temperatures is the main factor supporting an increase in evapotranspiration and a reduction in streamflow (Salmoral et al., 2015), and in the availability of water resources for the headwaters of the Llobregat and Ter rivers (Gallart et al., 2011).

Streamflows in the basins are found elastic to precipitation changes. Elasticity values are larger in basins with ephemeral streams, which correspond to the largest basins with the largest water losses. These streams are the most sensitive to precipitation changes as they are predominantly rain-fed and characterised by substantial water transmission losses from headwaters to outlet. The graphical analyses of historical co-variations of runoff reveal reductions ranging from 50 to 100 mm for the period 1977–1998, attributable to P and L, that accounts for the actual evapotranspiration and deep percolation.

The streamflow in the studied temporary streams of Mallorca exhibits a generally decreasing trend, mainly due to the negative trends found in spring and summer, which represent around a quarter of the annual runoff. However, these trends are not always significant, as from a statistical point of view. The high inter-annual variability, typical of Mediterranean environments, may likely mask larger trends in the data series (Morán-Tejeda et al., 2010). Changes are significant in some basins of Tramuntana and in the spring-fed streams. These basins show reductions in both discharge and the frequency of days with water during spring. These decrement is particularly important in B16 and B52 stations, where spring flows reductions between 4 and 16%. An analysis of the changes in the water balance in these two stations by means of a variant of the Budyko graph show how the impact of natural reforestation, which needs more water during spring, through an increase in water losses. Similar results were observed in the spring and summer discharges of 74 perennial river headwaters in mainland Spain, when 81% and 70% of the rivers, respectively, exhibited significant negative

Table 5
Correlation coefficients (r) between number of days (n_Q) with flow and precipitation and PET and NDVI for the studied basins. The coefficients of determination (R^2) for the multiple regression are shown as well. R^2 and r are in italics when *p*-value <0.05. R^2 and $|r| \geq 0.6$ are highlighted in bold.

ID	Annual				Winter				Spring				Summer				Autumn			
	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2	r pcp	r PET	r NDVI	R^2
B01	***0.71***	−0.24	—	*0.52*	***0.8***	−0.46	—	***0.64***	*0.57*	−0.31	—	*0.38*	—	—	—	0.10	***0.63***	−0.43	—	*0.40*
B02	*0.59*	−0.02	0.03	*0.38*	*0.57*	−0.27	0.01	*0.33*	*0.37*	−0.12	−0.03	0.14	0.28	−0.07	0.15	0.21	***0.64***	−0.36	0.06	*0.42*
B03	***0.63***	−0.23	−0.29	*0.54*	***0.67***	−0.26	−0.22	*0.53*	*0.59*	−0.36	*−0.39*	*0.44*	0.05	−0.15	*−0.44*	**0.70**	***0.73***	−0.23	0.17	*0.55*
B04	*0.59*	−0.07	−0.12	*0.51*	***0.61***	−0.27	0.07	*0.42*	*0.52*	−0.38	−0.11	*0.35*	*0.37*	−0.49	*−0.33*	0.03	***0.75***	−0.10	0.16	*0.57*
B06	***0.62***	−0.11	−0.13	*0.45*	***0.74***	−0.20	−0.04	***0.66***	*0.52*	−0.59	−0.14	*0.40*	0.16	−0.06	−0.05	0.23	*0.52*	0.05	−0.05	*0.37*
B07	***0.78***	−0.20	−0.04	***0.67***	*0.59*	−0.31	0.13	*0.39*	*0.53*	−0.37	−0.02	*0.28*	0.25	−0.25	−0.13	0.08	***0.81***	−0.20	0.02	***0.77***
B13	*0.5*	−0.17		*0.25*	*0.46*	−0.21	—	*0.21*	0.26	0.04	—	0.11	−0.06	−0.25	—	0.19	0.23	−0.44	—	*0.22*
B16	*0.51*	−0.02	*−0.46*	*0.56*	*0.56*	−0.43	−0.25	*0.45*	***0.7***	−0.61	*−0.51*	***0.63***	0.11	−0.25	*−0.36*	*0.40*	*0.57*	−0.24	−0.04	*0.38*
B51	*0.54*	0.10	−0.3	*0.55*	***0.72***	−0.29	−0.15	***0.61***	*0.56*	−0.30	*−0.41*	*0.43*	*0.54*	−0.33	*−0.4*	*0.44*	*0.53*	0.26	0.07	*0.44*
B52	*0.47*	−0.10	*−0.53*	***0.61***	***0.6***	−0.28	−0.27	*0.50*	*0.59*	−0.54	*−0.55*	*0.59*	*0.59*	−0.44	*−0.41*	*0.20*	*0.44*	0.18	−0.11	*0.35*
B54	***0.61***	−0.32	—	*0.41*	***0.73***	−0.34	—	*0.53*	***0.74***	−0.59	—	*0.56*	*0.42*	−0.30	—	0.10	***0.61***	−0.32	—	*0.37*
B55	*0.38*	−0.22	—	0.16	***0.73***	−0.35	—	*0.53*	***0.69***	−0.57	—	*0.50*	0.14	−0.31	—	—	0.15	0.11	—	0.06
B58	***0.64***	−0.02	—	*0.55*	***0.72***	−0.38	—	*0.54*	*0.54*	−0.21	—	*0.42*	—	—	—	0.03	*0.55*	−0.24	—	*0.32*
B61	*0.45*	−0.04	—	*0.21*	***0.69***	−0.20	—	*0.50*	0.09	0.00	—	0.01	−0.15	0.10	—	**0.00**	***0.67***	−0.29	—	*0.47*
All	*0.4*	**−0.02**	—	**0.17**	*0.58*	**−0.30**	—	***0.34***	*0.44*	**−0.14**	—	***0.19***	0.05	**−0.01**	—	0.10	*0.42*	**−0.15**	—	***0.18***

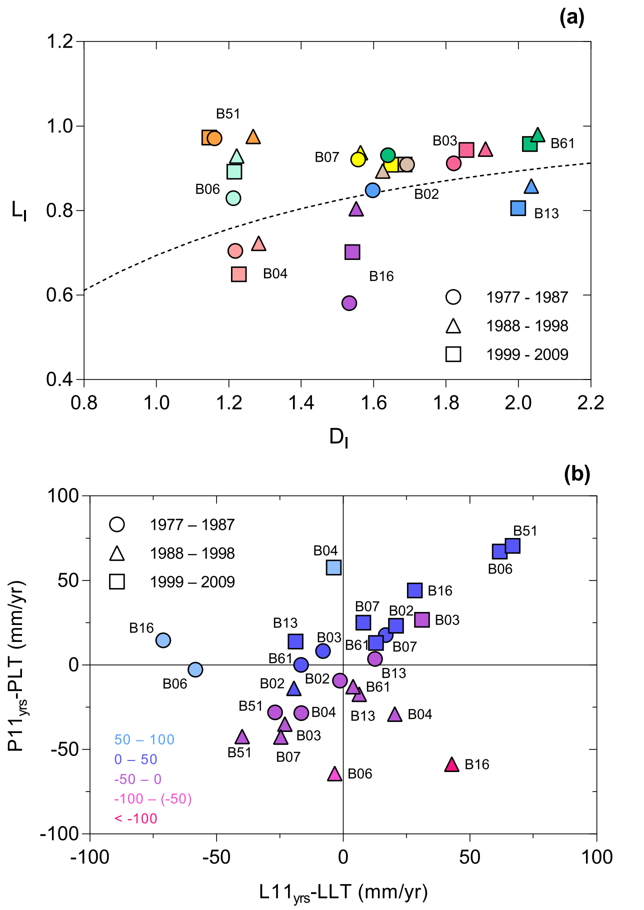

Fig. 9. a) Changes in the water balance using a variant of the Budyko graph for 3 different periods of 11 years (1977–1987, 1988–1998 and 1999–2009). b) Three-dimensional graph representing the historical co-variations of runoff (increase and decrease in classes of 50 mm) with water losses (L) and precipitation (P) for the same 3 subperiods of 11 years compared with the long-term mean (LLT and PLT).

trends (Martínez-Fernández et al., 2013), as well as in the spring discharges of 187 sub-basins in the Iberian Peninsula for the period 1945–2005 (Lorenzo-Lacruz et al., 2012).

The temporary streams in Mallorca are almost dry during summer, with a mean of 7 days with flow and a contribution to the mean annual discharge that is lower than 2%. The trend analyses show a general significant decrease in Tramuntana for the streamflow and the number of days with flow in summer. However, precipitation appears to follow a generally decreasing trend, albeit one that is not statistically significant. Again, the PET shows a significant increase and is a key factor explaining the reduction of the streamflow in summer.

5. Conclusions

This study has found negative streamflow trends in spring and summer for the majority of the 14 studied streams in Mallorca. Although seasonal variability is high between these two seasons, decreases in precipitation and increases in temperature and forest land cover explain the reduction in the number of days with flow observed in spring and summer and at the annual scale in the Tramuntana region. This pattern is especially noteworthy, as 12 of these streams are located in headwater basins where hydrological systems are very sensitive to any change. Also, the dominance of water losses on the water balance of these karstic basins implies that any significant increase in losses through the actual evapotranspiration has an important impact on their water balance and, consequently on their hydrological regime.

These streams show strong flow variability, which is a critical stressing factor for their ecosystems, as they have an average of <150 days per year of measurable flow. If the number of days with water that restore hydrological connections between river channels and parafluvial habitats (Jenkins and Boulton, 2003) is decreasing, as revealed by our results, the aquatic habitat ought to be adversely affected as well. While temporary streams occur in all biomes, they face particular threats in Mediterranean regions because of pressure on water resources from human populations and climate change. In Mallorca, current forest expansion and air warming cause higher water demand, increasing the actual evapotranspiration, and consequently leaving less available water for the temporary streams and their associated biodiversity. The duration of dry spells in these streams is increasing and can be longer during drought periods. These sensitive systems are losing water and we argue that a conservation plan is urgently required to protect these vulnerable freshwater ecosystems and assure their survival under the near-future changes and challenges already highlighted in this study. From the water resources perspective, the abandonment of cultivated fields and their replacement by the forest, together with a reduction in the precipitation accumulations, have modified the runoff response through increasing the water losses. This has an important impact on the water balance and, consequently, a direct effect on the water management of these basins.

Acknowledgements

Hydrological data was supplied by the Direcció General de Recursos Hídrics, Govern Illes Balears. Meteorological data was supplied by the AEMET and the gridded precipitation data was generated by Antoni López. Alfredo Baron, Jordi Gimenez and Esther Martínez-Miró helped during the hydrological data collection. This work has been partially sponsored by CGL2014-689 52199-R (EXTREMO) Spanish project, which is partially supported with FEDER funds. This project started 15 years ago with Albert Rovira and we acknowledge his time in an earlier research that did not come through. Ilja van Meerveld reviewed a first version of the manuscript. Comments made by reviewers and the editor Hedi Oberhänsli greatly improved the quality and contents of the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/10.1016/j.gloplacha.2016.11.010. These data include the Google map of the most important areas described in this article.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome.

Alpert, P., Ben-Gai, T., Baharad, A., Benjamini, Y., Yekutieli, D., Colacino, M., Diodato, L., Ramis, C., Homar, V., Romero, R., Michaelides, S., Manes, A., 2002. The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. Geophys. Res. Lett. 29:1536. http://dx.doi.org/10.1029/2001GL013554.

Álvarez, M., Pardo, I., 2007. Factors controlling epilithon biomass in a temporary, karstic stream: the interaction between substratum and grazing. J. North Am. Benthol. Soc. http://dx.doi.org/10.1899/0887-3593(2007)26[207:FCEBIA]2.0.CO;2.

Álvarez, M., Pardo, I., 2009. Dynamics in the trophic structure of the macroinvertebrate community in a Mediterranean, temporary stream. Aquat. Sci. 71, 202–213.

Amengual, A., Romero, R., Alonso, S., 2008. Hydrometeorological ensemble simulations of flood events over a small basin of Majorca Island, Spain. Q. J. R. Meteorol. Soc. 134: 1221–1242. http://dx.doi.org/10.1002/qj.

Andréassian, V., Coron, L., Lerat, J., Le Moine, N., 2016. Climate elasticity of streamflow revisited – an elasticity index based on long-term hydrometeorological records. Hydrol. Earth Syst. Sci. 20:4503–4524. http://dx.doi.org/10.5194/hess-20-4503-2016.

Beguería, S., López-Moreno, J.I., Lorente, A., Seeger, M., García-Ruiz, J.M., 2003. Assessing the effect of climate oscillations and land-use changes on streamflow in the central Spanish Pyrenees. Ambio 32, 283–286.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55, 3–23.

Budyko, M.I., 1974. Climate and Life. Academic Press, San Diego.

Buendia, C., Batalla, R.J., Sabater, S., Palau, A., Marcé, R., 2015. Runoff trends driven by climate and afforestation in a Pyrenean Basin. L. Degrad. Dev. 27:823–838. http://dx.doi.org/10.1002/ldr.2384.

Burn, D.H., Hag Elnur, M.A., 2002. Detection of hydrologic trends and variability. J. Hydrol. 255, 107–122.

Ceballos-Barbancho, A., Morán-Tejeda, E., Luengo-Ugidos, M.Á., Llorente-Pinto, J.M., 2008. Water resources and environmental change in a Mediterranean environment: the south-west sector of the Duero river basin (Spain). J. Hydrol. 351:126–138. http://dx.doi.org/10.1016/j.jhydrol.2007.12.004.

Cohuet, J.B., Romero, R., Homar, V., Ducrocq, V., Ramis, C., 2011. Initiation of a severe thunderstorm over the Mediterranean Sea. Atmos. Res. 100:603–620. http://dx.doi.org/10.1016/j.atmosres.2010.11.002.

Cosandey, C., Andréassian, V., Martin, C., Didon-Lescot, J.F., Lavabre, J., Folton, N., Mathys, N., Richard, D., 2005. The hydrological impact of the mediterranean forest: a review of French research. J. Hydrol. 301, 235–249.

Costa, M.H., Botta, A., Cardille, J.A., 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, southeastern Amazonia. J. Hydrol. 283:206–217. http://dx.doi.org/10.1016/S0022-1694(03)00267-1.

Cudennec, C., Leduc, C., Koutsoyiannis, D., 2007. Dryland hydrology in Mediterranean regions—a review. Hydrol. Sci. J. 52:1077–1087. http://dx.doi.org/10.1623/hysj.52.6.1077.

Döll, P., Fiedler, K., Zhang, J., 2009. Global-scale analysis of river flow alterations due to water withdrawals and reservoirs. Hydrol. Earth Syst. Sci. Discuss. 6:4773–4812. http://dx.doi.org/10.5194/hessd-6-4773-2009.

Douglas, E.M., Vogel, R.M., Kroll, C.N., 2000. Trends in floods and low flows in the United States: impact of spatial correlation. J. Hydrol. 240, 90–105.

Estrany, J., Garcia, C., Batalla, R.J., 2009. Groundwater control on the suspended sediment load in the Na Borges River, Mallorca, Spain. Geomorphology 106, 292–303.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Gallart, F., Llorens, P., 2003. Catchment management under environmental change: impact of land cover change on water resources. Water Int. 28, 334–340.

Gallart, F., Delgado, J., Beatson, S.J.V., Posner, H., Llorens, P., Marcé, R., 2011. Analysing the effect of global change on the historical trends of water resources in the headwaters of the Llobregat and Ter river basins (Catalonia, Spain). Phys. Chem. Earth 36, 655–661.

Garcia, C., Servera, J., 2003. Impacts of tourism development on water demand and beach degradation on the island of Mallorca (Spain). Geogr. Ann. Ser. A-Phys. Geogr. 85A, 287–300.

García, L., Delgado, C., Pardo, I., 2008. Seasonal changes of benthic communities in a temporary stream of Ibiza (Balearic Islands). Limnetica 27, 259–272.

García, L., Pardo, I., Delgado, C., 2014. Macroinvertebrate indicators of ecological status in Mediterranean temporary stream types of the Balearic Islands. Ecol. Indic. 45: 650–663. http://dx.doi.org/10.1016/j.ecolind.2014.05.030.

García-Ruiz, J.M., López-Moreno, J.I., Vicente-Serrano, S.M., Lasanta-Martínez, T., Beguería, S., 2011. Mediterranean water resources in a global change scenario. Earth Sci. Rev. 105:121–139. http://dx.doi.org/10.1016/j.earscirev.2011.01.006.

Gasith, A., Resh, V.H., 1999. Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. Annu. Rev. Ecol. Syst. 30, 51–81.

Grove, A., Rackham, O., 2001. The Nature of Mediterranean Europe: An Ecological History. Yale University Press, New Haven.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Appl. Eng. Agric. 1 (2), 96–99.

Hargreaves, G.H., Allen, R.G., 2003. History and evaluation of Hargreaves evapotranspiration equation. J. Irrig. Drain. Eng. 129 (1), 53–63.

Helsel, D.R., Frans, L.M., 2006. Regional Kendall test for trend. Environ. Sci. Technol. 40, 4066–4073.

Helsel, D.R., Mueller, D.K., Slack, J.R., 2006. Computer program for the Kendall family of trend tests. U.S. Geological Survey Scientific Investigations Report 2005–5275.

Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18, 107.

Homar, V., Ramis, C., Romero, R., Alonso, S., 2010. Recent trends in temperature and precipitation over the Balearic Islands (Spain). Clim. Chang. 98, 199–211.

Homar, V., Romero, R., Stensrud, D.J., Ramis, C., Alonso, S., 2003. Numerical diagnosis of a small, quasi-tropical cyclone over the western Mediterranean: dynamical vs. boundary factors. Q. J. R. Meteorol. Soc. 129:1469–1490. http://dx.doi.org/10.1256/qj.01.91.

IFN, 2012. Cuarto Inventario Forestal Nacional. (Illes Balears) http://www.caib.es/sacmicrofront/archivopub.do?ctrl=MCRST472ZI139398&id=139398.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310:1944–1947. http://dx.doi.org/10.1126/science.1119282.

Jenkins, K.M., Boulton, A.J., 2003. Connectivity in a dryland river: short-term aquatic microinvertebrate recruitment following floodplain inundation. Ecology 84: 2708–2723. http://dx.doi.org/10.1890/02-0326.

Jenkyns, H.C., Sellwood, B.W., Pomar, L., 1990. A Field Excursion Guide to the Island of Mallorca. The Geologists' Association.

Jiménez Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Döll, P., Jiang, T., Mwakalila, S.S., 2015. Freshwater resources. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 229–269.

Jourde, H., Roesch, A., Guinot, V., Bailly-Comte, V., 2007. Dynamics and contribution of karst groundwater to surface flow during Mediterranean flood. Environ. Geol. 51: 725–730. http://dx.doi.org/10.1007/s00254-006-0386-y.

Kendall, M.G., 1975. Rank Correlation Methods. Oxford Univ. Press, New York.

Kundzewicz, Z.W., Robson, A.J., 2004. Change detection in hydrological records - a review of the methodology. Hydrol. Sci. J. 49, 7–20.

Larned, S.T., Datry, T., Arscott, D.B., Tockner, K., 2010. Emerging concepts in temporary-river ecology. Freshw. Biol. 55:717–738. http://dx.doi.org/10.1111/j.1365-2427.2009.02322.x.

Lasanta, T., Vicente-Serrano, S.M., 2012. Complex land cover change processes in semiarid Mediterranean regions: an approach using Landsat images in northeast Spain. Remote Sens. Environ. 124:1–14. http://dx.doi.org/10.1016/j.rse.2012.04.023.

Lespinas, F., Ludwig, W., Heussner, S., 2010. Impact of recent climate change on the hydrology of coastal Mediterranean rivers in southern France. Clim. Chang. 99, 425–456.

Llorens, P., Poch, R., Rabada, D., Gallart, F., 1995. Study of the changes of hydrological processes induced by afforestation in Mediterranean mountainous abandoned fields. Phys. Chem. Earth 20:375–383. http://dx.doi.org/10.1016/0079-1946(95)00051-8.

Lorenzo-Lacruz, J., Vicente-Serrano, S.M., López-Moreno, J.I., Morán-Tejeda, E., Zabalza, J., 2012. Recent trends in Iberian streamflows (1945–2005). J. Hydrol. 414–415: 463–475. http://dx.doi.org/10.1016/j.jhydrol.2011.11.023.

López-Urrea, R., Santa Olalla, F., Fabeiro, C., Moratalla, A., 2006. Testing evapotranspiration equations using lysimeter observations in a semiarid climate. Agr. Water Manage. 85 (1–2), 15–26.

Ludwig, W., Serrat, P., Cesmat, L., Garcia-Esteves, J., 2004. Evaluating the impact of the recent temperature increase on the hydrology of the Tet River (southern France). J. Hydrol. 289:204–221. http://dx.doi.org/10.1016/j.jhydrol.2003.11.002.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13:245. http://dx.doi.org/10.2307/1907187.

Martínez-Fernández, J., Sánchez, N., Herrero-Jiménez, C.M., 2013. Recent trends in rivers with near-natural flow regime: the case of the river headwaters in Spain. Prog. Phys. Geogr. 37:685–700. http://dx.doi.org/10.1177/0309133313496834.

Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J.M., 2010. Hydrological response of Mediterranean headwaters to climate oscillations and land-cover changes: the mountains of Duero River basin (Central Spain). Glob. Planet. Chang. 72, 39–49.

Morán-Tejeda, E., López-Moreno, J.I., Ceballos-Barbancho, A., Vicente-Serrano, S.M., 2011. River regimes and recent hydrological changes in the Duero basin (Spain). J. Hydrol. 404, 241–258.

Munné, A., Prat, N., 2011. Effects of Mediterranean climate annual variability on stream biological quality assessment using macroinvertebrate communities. Ecol. Indic. 11, 651–662.

Porporato, A., Daly, E., Rodriguez-iturbe, I., 2004. Soil water balance and ecosystem response to climate change. Am. Nat. 164, 625–632.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. Glob. Biogeochem. Cycles 13:997–1027. http://dx.doi.org/10.1029/1999GB900046.

Robinson, M., Gannon, B., Schuch, M., 1991. A comparison of the hydrology of moorland under natural conditions, agricultural use and forestry. Hydrol. Sci. J. 36:565–577. http://dx.doi.org/10.1080/02626669109492544.

Romero, R., Ramis, C., Alonso, S., Doswell, C.A., Stensrud, D.J., 1998. Mesoscale model simulations of three heavy precipitation events in the western Mediterranean region. Mon. Weather Rev. 126, 1859–1881.

Romero, R., Ramis, C., Homar, V., 2014. On the severe convective storm of 29 October 2013 in the Balearic Islands: observational and numerical study. Q. J. R. Meteorol. Soc. http://dx.doi.org/10.1002/qj.2429 (n/a-n/a).

Rupp, D.E., Larned, S.T., Arscott, D.B., Schmidt, J., 2008. Reconstruction of a daily flow record along a hydrologically complex alluvial river. J. Hydrol. 359, 88–104.

Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. J. Hydrol. 178:293–309. http://dx.doi.org/10.1016/0022-1694(95)02825-0.

Sala, M., 2003. Floods triggered by natural conditions and by human activities in a Mediterranean coastal environment. Geogr. Ann. Ser. A Phys. Geogr. 85:301–312. http://dx.doi.org/10.1111/j.0435-3676.2003.00207.x.

Salmoral, G., Willaarts, B.A., Troch, P.A., Garrido, A., 2015. Drivers influencing streamflow changes in the Upper Turia basin, Spain. Sci. Total Environ. 503–504:258–268. http://dx.doi.org/10.1016/j.scitotenv.2014.07.041.

Sankarasubramanian, A., Vogel, R.M., Limbrunner, J.F., 2001. Climate elasticity of streamflow in the United States. Water Resour. Res. 37:1771–1781. http://dx.doi.org/10.1029/2000WR900330.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Colón-González, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., Kabat, P., 2014. Multimodel assessment of water scarcity under climate change. Proc. Natl. Acad. Sci. 111:3245–3250. http://dx.doi.org/10.1073/pnas.1222460110.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's Tau. J. Am. Stat. Assoc. 63, 1379–1389.

Serra, P., Pons, X., Saurí, D., 2008. Land-cover and land-use change in a Mediterranean landscape: a spatial analysis of driving forces integrating biophysical and human factors. Appl. Geogr. 28, 189–209.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L.M., Van Lanen, H.A.J., Sauquet, E., Demuth, S., Fendekova, M., Jódar, J., 2010. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. Hydrol. Earth Syst. Sci. 14, 2367–2382.

Stahl, K., Tallaksen, L.M., Hannaford, J., Van Lanen, H.A.J., 2012. Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. Hydrol. Earth Syst. Sci. 16, 2035–2047.

Sumner, G., Homar, V., Ramis, C., 2001. Precipitation seasonality in eastern and southern coastal Spain. Int. J. Climatol. 21, 219–247.
Trimble, S.W., Weirich, F.H., Hoag, B.L., 1987. Reforestation and the reduction of water yield on the Southern Piedmont since circa 1940. Water Resour. Res. 23:425–437. http://dx.doi.org/10.1029/WR023i003p00425.
Vicente-Serrano, S.M., Lasanta, T., Romo, A., 2004. Analysis of spatial and temporal evolution of vegetation cover in the Spanish central pyrenees: role of human management. Environ. Manag. 34, 802–818.
von Storch, H., 1995. Misuses of statistical analysis in climate research. In: von Storch, H., Navarra, A. (Eds.), Analysis of Climate Variability Applications of Statistical Techniques. Springer-Verlag, pp. 11–26.
Walling, D.E., 1999. Linking land use, erosion and sediment yields in river basins. Hydrobiologia 410, 223–240.
Wilkinson, B.H., McElroy, B.J., 2007. The impact of humans on continental erosion and sedimentation. Bull. Geol. Soc. Am. 119:140–156. http://dx.doi.org/10.1130/B25899.1.
Wolock, D.M., McCabe, G.J., 1999. Estimates of runoff using water-balance and atmospheric general circulation models. J. Am. Water Resour. Assoc. 35, 1341–1350.
Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. J. Hydrol. 259, 254–271.
Zhang, X., Tang, Q., Zhang, X., Lettenmaier, D.P., 2014. Runoff sensitivity to global mean temperature change in the CMIP5 models. Geophys. Res. Lett. 41:5492–5498. http://dx.doi.org/10.1002/2014GL060382.
Zheng, H., Zhang, L., Zhu, R., Liu, C., Sato, Y., Fukushima, Y., 2009. Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. Water Resour. Res. 45:1–9. http://dx.doi.org/10.1029/2007WR006665.