ORIGINAL PAPER

Hydrological modeling of three rivers under Mediterranean climate in Chile, Greece, and Morocco: study of high flow trends by indicator calculation

Abdelmounim Bouadila[1] · Ourania Tzoraki[2] · Lahcen Benaabidate[1]

Abstract
The study of the influence of climate change on the evolution of floods in areas under the influence of a Mediterranean climate is very important. This work aims to provide new analytical elements to decision-makers in flood management and forecasting in three Mediterranean catchments (Lonquen, Evrotas, and Azzaba), in order to better understand their hydrological behavior and to quantify the flow and its vulnerability to climate change. A semi-distributed conceptual model (HBV-A model) was used to simulate flows with a daily time step. The model results (simulated flows) were used to examine the evolution of high flows using two different approaches (linear regressions and statistical test). The Chilean and the Greece catchments show a decrease in flooding. However, the Moroccan catchment reacts differently, since a positive trend in high flows is observed. The overall results confirm the influence of climate change on the rainfall/runoff relationship.

Keywords Semi-arid Mediterranean regions · Climate change · HBV model-A · High flow indicators · Mann-Kendall test · Trend analysis

Introduction

Flooding phenomena are frequent in areas under Mediterranean climate according to the significant increase in flow coefficients. This increase being caused mainly by the torrential rainfall characterizes this climate. Intense precipitation in these contexts damages issues exposed to natural phenomena and sometimes causes economic and human losses (Poesen and Hooke 1997; Garry et al. 2002; Ballais

✉ Abdelmounim Bouadila
  abdelmounim.bouadila@usmba.ac.ma

  Ourania Tzoraki
  rania.tzoraki@aegean.gr

  Lahcen Benaabidate
  lahcen.benaabidate@usmba.ac.ma

[1] Laboratory of Functional Ecology and Environment Engineering, University of Sidi Mohammed Ben Abdellah, P.O. Box: 2202, 30000 Fez, Morocco

[2] Marine Sciences Department, School of Environment, University of the Aegean, Mytilene, Greece

et al. 2005; Delrieu et al. 2005; Rey et al. 2016). As such, it is legitimate to understand that this subject must receive the attention of public authorities and that it be the subject of studies and modeling.

The general evolution of the world's climate shows a remarkable change, especially in the 21st century, and these changes are accentuated according to season and geographical environment (Larrivée et al. 2010). The studied areas are not the exception of this change, and this is consistent with the study made by Boulet (2010), who mentioned that these areas are the scene of major changes such as climate change, water scarcity, etc. The interannual variability of precipitation and changes in the distribution of precipitation due to climate change in Mediterranean contexts could affect the natural environment by increasing the frequency of occurrence of certain phenomena, particularly floods (López-Moreno et al. 2006; Villa and Bélanger 2012). In this context, it is important to easily understand the need to develop management and decision-making tools. Among these tools, the hydrological models have emerged over the past 20 years, particularly in light of the rainfall-runoff relationship.

The rainfall-runoff model used in this study is the HBV model-A (hydrologiska byrans vattenavdelning) developed by the SMHI (Swedish Meteorological and Hydrological

Institute). It is used to better understand changes in flows on a spatial and temporal scale, and more precisely for estimating total contributions (base flows, surface flows, point flows, etc.), and used also to better reconstitute flows and simulate the behavior and response of the three Mediterranean catchments considered for this study. The use of the HBV model to simulate flows in regions under the influence of a semi-arid Mediterranean climate generally produces efficient results (e.g., Ouachani et al. 2007; Vrochidou et al. 2013). This model can also reproduce the observed flows of long historical series with a very high speed in terms of time consumed in the calculation of the outputs (simulated flows). It is also important to note the importance of integrating the HBV model for studying climate change in different regions of the world (e.g., Bergströms et al. 2001; Chen et al. 2012; Vrochidou et al. 2013). All these factors form the main basis for the choice of the HBV model for the development of this study.

The Evrotas (Greece), the Lonquen (Chile), and the Azzaba (Morocco) are intermittent rivers located in areas under the influence of a semi-arid Mediterranean climate. Tsakiris et al. (2007) noticed that 26% of the land area of the southern Mediterranean is covered by temporary rivers. Several studies highlighted the importance of comparing the use of rainfall-runoff models for the hydrological modeling of a large number of catchments in order to test their applicability (Perrin et al. 2001, 2003). It should also be noted that the comparison of the applicability of hydrological models in a limited number of catchments (three catchments) is also widely used (Weeks and Hebbert 1980; Beven et al. 1984; Refsgaard and Knudsen 1996; Gan et al. 1997; Ye et al. 1997; Nasr et al. 2007). The three catchments chosen for the realization of this work are located in three continents distributed in the Mediterranean context in order to understand in a general way the behavior of the HBV model in this context. To meet the different needs of hydrological studies, the HBV model is being applied for the first time in the three Mediterranean river basins considered.

Significant flooding is observed in these catchments (Qadem 2015; Querner et al. 2016; Tzoraki et al. 2016; Duque and Vázquez 2017). These floods sometimes cause catastrophic inundations and the analysis of the time series of flows observed in the three catchments studied shows a remarkable change in the frequency of occurrence of high flows and their intensities. All these factors encourage the study of high flow trends in these catchments to get an idea of how these flows evolve over the years.

The study of high flow trends is of crucial importance for better risk and water resource management. High flows are generally considered for several uses such as assessing the variability of hydrometeorological time series in different catchments around the world, designing structures for flood mitigation and also for the construction of water storage reservoirs, etc. (Cigizoglu et al. 2005; Hamed 2008). The detection

of trends in time series is usually done through the use of linear regression or statistical tests or both. The non-parametric Mann-Kendall test is widely used to detect trends in high flows in different parts of the world in order to better understand the effects of climate change on river functioning (Burn and Hag Elnur 2002; Cigizoglu et al. 2005; Hannaford and Marsh 2006a, 2008; Korhonen and Kuusisto 2010; Bormann et al. 2011; Yeh et al. 2015). The importance of this study in the semi-arid Mediterranean regions is reflected in the improvement of the knowledge of the hydrological behavior of these contexts, which are strongly affected by climate change.

High river flows are generally influenced by human-induced changes in floodplain conditions (e.g., Pinter et al. 2010), and changes in temperature and precipitation patterns caused mainly by climate change (e.g., McCarthy et al. 2001; Milly et al. 2002; Adger et al. 2003; Thodsen et al. 2008; Wenger et al. 2011; Stocker et al. 2013; Field et al. 2014; Molina-Navarro et al. 2018). Therefore, the best estimate of future flows is an important contribution to a good knowledge of the evolution of climate change in different parts of the world.

Over the last twenty years, the global scientific community has increasingly focused on studying trends in high flows, confirming the increasing incidence of climate change phenomena. For example, in Europe, the very interesting recent studies on trends are as follows : Hannaford and Marsh (2006b), López-Moreno et al. (2006), Stahl et al. (2010), Danneberg (2012), Murphy et al. (2013), Arheimer and Lindström (2015), Thober et al. (2018). These studies have shown significant trends in most of the areas chosen for the elaboration of these works, but the most important thing in all this is that no trend study has been carried out on the Greek catchment which is the subject of this work, and the same is true for the other two catchments (Lonquen:Chile; Azzaba:Morocco).

In this study, long time series of flows, precipitation, temperatures, evapotranspiration, and crop coefficients were used to simulate the flows of the three semi-arid Mediterranean catchments. The simulated flows resulting from the use of the semi-distributed conceptual model (HBV model-A) were then used to calculate high flow indicators, which are crucial for extracting some information on assessing the potential impacts of climate change and also for studying the variability of high flows over time in the three catchments considered for this study. Finally, the trends of these high flow indicators were detected using two approaches: the first approach is to detect high flow trends using visual observations (linear regressions: trend detection using slopes from the linear regressions of high flow indicator values plotted on a graph), and the second approach is more rigorous and consists of using a statistical test to accurately detect the presence of a trend (the Mann-Kendall trend test: trend detection using assumptions).

Materials and methods

Study sites

Three of the largest catchments in the Mediterranean area were chosen to simulate river flows and study trends in high flows (Fig. 1). The first catchment treated is the Evrotas River catchment, which is located on the southeastern peninsula of the Peloponnese in Greece, with an area about 2050 km^2. The catchment has a semi-arid climate, and a statistical analysis of a long time series (from 1970 to 2010) showed that this catchment has an average annual temperature of 15.9 °C, an average annual precipitation of 554.1 mm, and an average annual evapotranspiration of 1011.1 mm. Hydrologically, this catchment is characterized by a very dense hydrographic network and the main river with a length of 90 km. The Evrotas catchment contains temporary (Oinountas), episodic (Mariorema) tributaries, and also there are tributaries that feed the catchment by permanent flows (Magoulitsa, Gerakaris, kakaris, Rasina, Xerias). Geologically, this basin contains a mixture of highly permeable geological formations (karst limestones) and less permeable underlying formations (shales and quartzites), which gives rise to a significant number of karst springs especially in the lower part of the two Parnonas and Taygetos Mountains (Tzoraki et al. 2014).

The second study area is located between 36° 25′ latitude and 72°40 ′ longitude; it is the Secano Interior region in south-central Chile. The climate of this area is also semi-arid with an annual average temperature of 12.1 °C; and an annual average precipitation of 868.6 mm (1976–2014, Arithmetic Method for average precipitation), and also the annual average potential evapotranspiration is about 981.7 mm. The majority of rainfall occurs between May and August, and this area is characterized by soils developed from a granitic source, with a Variant Saprolite depth of about 0.6 to 0.8 m (Stewart et al. 2015). Generally, the soil in our catchment swells rapidly when it receives a quantity of water (precipitation or irrigation, etc.), and this strongly influences the generation of large run-offs from time to time and therefore the increased risk of occurrence of floods and inundations.

The Lonquen River is one of the largest tributaries of the great Itata River (140 km). The Lonquen River catchment has an important surface area of the order 2330 km^2, and whose natural regime is strongly affected by the four small hills that are successively: Treguaco, Quirihue, Portezuelo, and finally Ninhue, where concentrates a very important population.

The third area studied in this work is the Azzaba catchment, which is under the influence of Moroccan territories, more precisely between − 4° and − 6° of longitude and between 33° and 34° of latitude, in contact with the tabular Middle
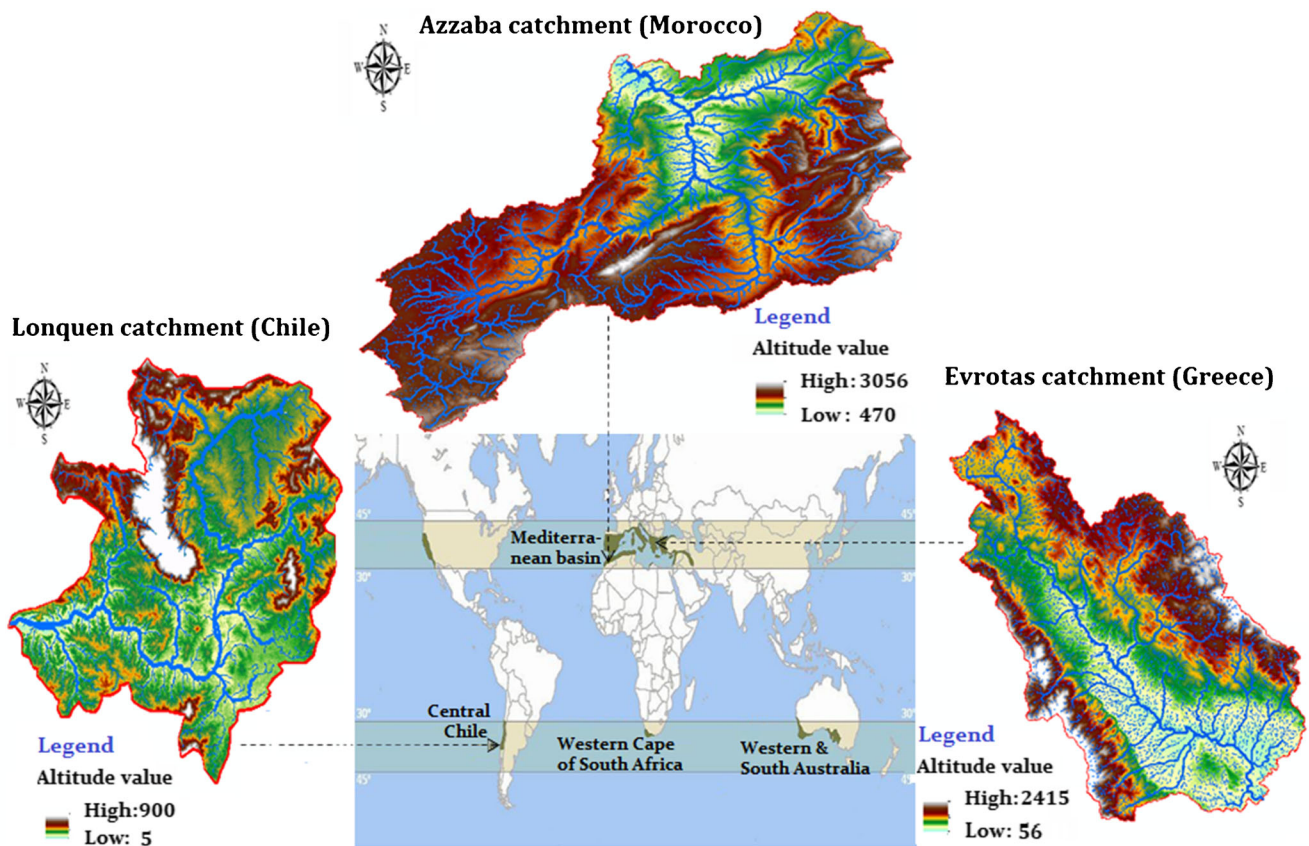

Fig. 1 The location of the three hydrographic catchments studied in the Mediterranean context

Atlas and the pleated Middle Atlas. The general climate in this basin is semi-arid with a Mediterranean influence like the other two catchments mentioned above. Statistical analysis of a long series of data (1970–2011), shows that the average annual precipitation in the Azzaba catchment is 369.9 mm, and the average annual values of temperature and potential evapotranspiration are successively 16.4 °C and 1050.3 mm.

The Azzaba catchment is the upstream part of the large Sebou basin and is characterized by its large surface area (4677 km^2) and the high availability of water resources which can be estimated at about 10% of the total Moroccan water resources (Bouadila et al. 2019). The main watercourse of this catchment area is the long Sebou River (174 km), which receives contributions from the main tributaries: Oued Guigou, Oued Maasser, Oued Zloul, and Oued Mdez. These tributaries play a very important role in the dry period since they strongly influence the flow regime (Akdim et al. 2012; Qadem 2015). During flood periods, other small streams feed the Sebou River.

Data

In this study, long series of daily rainfall, temperature, and discharge data were obtained for six meteorological stations and three gauging stations (Table 1). It is also important to note that the missing precipitation data in some stations are filled by data from other nearby stations using a linear regression between these stations. The data used in this study were provided by three services in the three countries considered, which are successively: the Hellenic National Meteorological Service in Greece; the General Water Directorate in Chile; and also the Moroccan flood warning service and measurement network. Also noted that meteorological data of more than 100 Chilean stations are available with different time scales for different uses in the following link (http://agromet.inia.cl/).

Potential evapotranspiration (PE) in the three catchments considered was calculated manually using the formulation proposed by Oudin et al (2005). The use of Evapotranspiration for hydrological modeling in semi-arid Mediterranean areas is of crucial importance (Oudin 2004; Amri 2013). Potential Evapotranspiration is generally one of the main inputs of the modified version of the HBV model, especially when applied in a context with a semi-arid climate where it strongly influences the availability of water resources.

Besides, values of crop coefficients (Kc) were calculated on a daily scale in order to determine the crop water requirements during the modeling periods in the three Mediterranean basins. The general concept of the Kc was first introduced by Jensen (1968) and subsequently improved by other researchers (Doorenbos and Pruitt 1975, 1977; Burman et al. 1980a, b; Allen et al. 1998) to increase the computational accuracy of this coefficient and also to simplify its use over a large spatial and temporal scale. Several studies highlighted the importance of determining crop water needs for better water resource planning and management in Mediterranean contexts (Hamdy 2001; Katerji and Rana 2008; Lazzara and Rana 2010). Generally, the variation in crop consumption is influenced by the succession of seasons, farming practices techniques, irrigation methods and also by crop physiology.

Description of HBV model-A

The semi-distributed conceptual model (HBV model-A) used in this study represents the modified version of the HBV-IWS hydrological model (Singh 2010). Since the development of the HBV model (Bergström 1976) by Swedish Meteorological and Hydrological Institute, several modifications have been made to this model to obtain more efficient and applicable versions in very different climatic contexts. The Institute for Water Resources Management in Hannover

Table 1 Periods for which records of precipitation, temperature, and daily flows are available at meteorological and gauging stations in the three Mediterranean catchments, and the values of potential evapotranspiration "PE" and crop coefficient "Kc" calculated for all the periods considered, and the average annual flows, and also the type of flow regime

River	Measuring station	Catchment size (km^2)	Rainfall (RF)	Temperature (T)	Potential evapotranspiration (PE)	Crop coefficient (Kc)	Discharge (Q)	Average annual flow (m^3/s)	Flow regime type
			Available data						
Evrotas	Evrotas	2050	1970–2010	1970–2010	1970–2010	1970–2010	1974–2010	6.6	Pluvial
	Vivari	498	1970–2010	1970–2010	1970–2010	1970–2010			Pluvial
Sebou	Azzaba	4677	1970–2011	1970–2011	1970–2011	1970–2011	1970–2011	16.2	Pluvial
	Pont M'dez	3460	1970–2011	1970–2011	1970–2011	1970–2011			Pluvial
Itata	Lonquen	2330	1976–2014	1976–2014	1976–2014	1976–2014	1986–2014	12.9	Pluvial
	Coelemu	300	1976–2014	1976–2014	1976–2014	1976–2014			Pluvial

(Germany) carried changes HBV-IWS model by considering land use through the introduction of crop coefficient values (Kc) into the model and through the use of Potential Evapotranspiration (PE) as model input (Wallner et al. 2013).

The choice of the conceptual model HBV is based on several reasons, among which: their low requirement with regard to the data used as input, and the model gives very efficient results in the Mediterranean areas (Ouachani et al. 2007; Perrin 2000). Furthermore, this model can simulate long data series and this is in good agreement with the problematic of the first part of this study which consists in modeling the three Mediterranean catchments over long periods.

The model uses the sub-catchment as a spatial discretization unit. However, the general HBV model scheme for a single sub-catchment (Fig. 2) shows that the model takes into account several routines respectively the snow routine, the ground routine, the response routine and finally a transformation routine. In the contexts studied, snow is not a dominant factor in the genesis of flows (Tzoraki et al. 2014; Qadem 2015; Duque and Vázquez 2017).

Based on the actual temperature (T) and threshold temperature (TT), the snow routine subdivides the actual precipitation (P) into snow (SF) and rainfall (RF). The sum of snowmelt and rainfall (ΔP) is also divided into water filling the ground box (SM) and recharging the underground reservoirs (UZ and LZ) according to the relationship between the maximum capacity of the ground box

(Fc) and its water content (SM). When SM/FC is above the potential evapotranspiration limit (LP), the actual evapotranspiration (AE) of the soil box is equal to the potential evapotranspiration (PE). And when SM/FC is less than LP, a quantity of water is added to the upper reservoir (UZ). The amount of melted snow per day from the stored snow depth (SD) is controlled by a day factor (dd), and this is described by Eq. 1 and Eq. 2. In the case of precipitation, the wet snow melting factor (wsmf) shows a very fast snowmelt.

$$\mathbf{MELT = DD.(T-CrT), If\ (T > CrT)} \tag{1}$$

$$\mathbf{DD = Dew + k.P} \tag{2}$$

where

Melt　Quantity of melted snow;
DD　　Degree-day factor;
P　　　Daily precipitation depth;
T　　　Average daily air temperature;
CrT　　Threshold temperature for triggering snowmelt;
Dew　Precipitation/degree-day relationship;
K　　　positive number.

The soil routine also contains a module that calculates contributing runoff (ΔQ). Equation 3 shows that the effective rainfall responsible for the occurrence of runoff (ΔQ) depends on the actual soil moisture content (SM), the maximum soil storage capacity (fc), The sum of snowmelt and rainfall (ΔP), and finally on a model parameter (shape coefficient) (β).
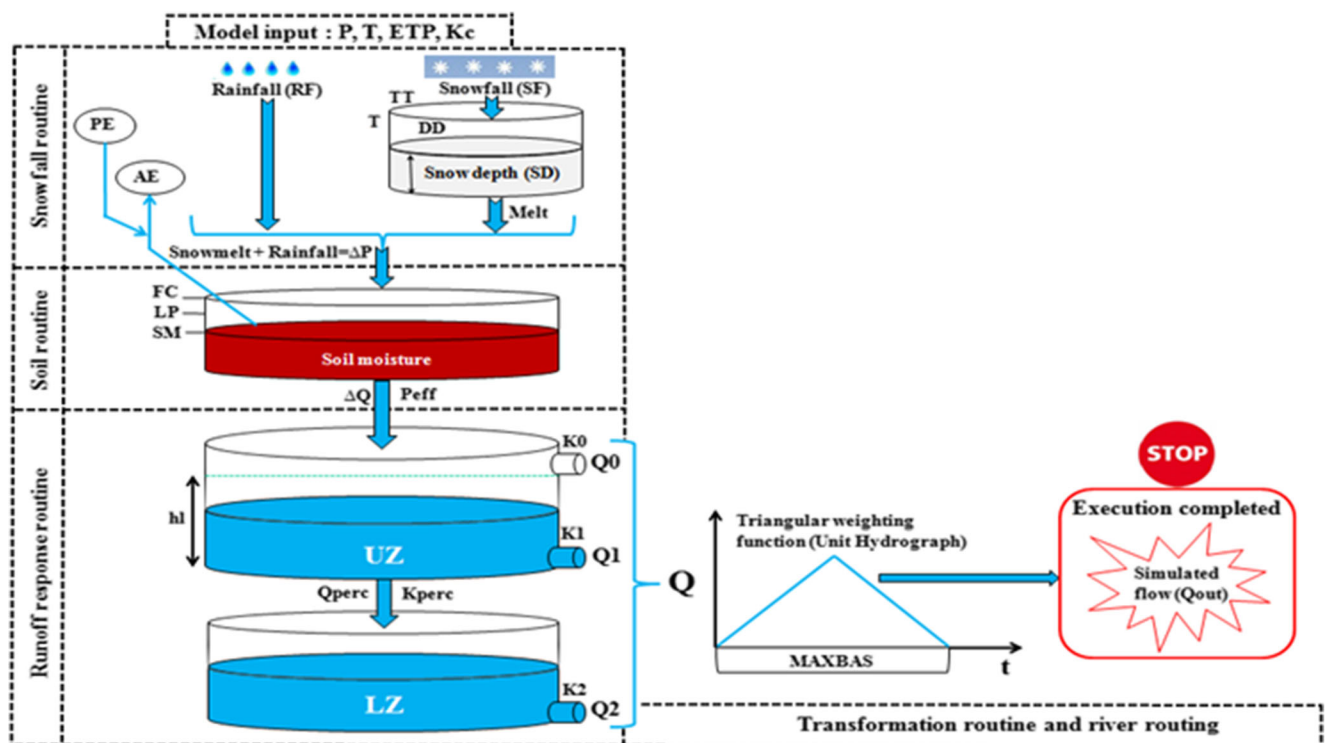

Fig. 2 Schematic structure of one sub-basin in the HBV model, with routines for snow (top), soil (middle), response (bottom), and transformation (right)

$$Peff = (SM/FC)\beta \cdot P + MELT \qquad (3)$$

In the response routine, several variables are determined and which are successively: the near-surface flow (Q0), the intermediate flow (Q1), the base flow (Q2), the actual water content of the upper reservoir (UZ), and the actual water content of the lower reservoir (LZ). Generally, a surface flow (Q0) is produced when the threshold value (hl) is lower than water content in the upper water box. The Qperc parameter determines the water contribution between the upper and lower groundwater box.

The four equations listed below describe the relationship between each outflow (Q0, Q1, Q2, Qperc) and their storage coefficients (K0, k1, k2, Kperc), and also the actual water content in the upper and lower reservoirs.

$$Q0 = K0 \cdot (UZ - hl) \qquad (4)$$

$$Q1 = K1 \cdot UZ \qquad (5)$$

$$Q2 = K2 \cdot LZ \qquad (6)$$

$$Qperc = Kperc \cdot UZ \qquad (7)$$

The outflows from the upper and lower reservoirs (Q0, Q1, Q2) are summed to obtain the overall flow rate Q (Eq. 8). This flow rate is then transformed by a triangular weighting function (unit hydrograph) that depends on a free parameter (MAXBAS) to obtain finally the simulated flow rate as a model output.

$$Q = g(t; MAXBAS) \cdot (Q0 + Q1 + Q2) \qquad (8)$$

The HBV model subdivides the catchment into two sub-catchments connected to each other by the Muskingum method, and this method depends on two main parameters which are successively the weighting factor (mx :(min 0.1; max 0.4)) and the retention constant (mk: (min 0.25; max 10)).

The HBV model includes 12 parameters (Table 2), which are manually modified by the trial and error technique to reduce the difference between the observed and calculated values. The influence on the general appearance of the simulated hydrograph differs from one parameter to another, reflecting the importance of performing a sensitivity analysis to determine the most and least influential parameters on the model results and automatically on the values of the objective functions chosen to evaluate these results.

For this study, the model results are slightly sensitive to changes in parameters corresponding to the snow routine (wsmf, Crt, and dd), but the remaining nine parameters have a strong influence on the model outputs and also on the improvement or decrease in performance criteria.

Performance evaluation criteria

Each simulation requires an evaluation; in this context it is necessary to understand the need to use mathematical performance criteria to test the predictive capacity of models. The obtained results for the three catchments considered for this study were evaluated using the calculation of four performance criteria, which are successively (i) the Nash-Sutcliffe efficiency (NSE), (ii) the root mean square error (RMSE), (iii) the percent Bias (PBIAS), and (iiii) the coefficient of determination (R^2). These four criteria are characterized by different objectives (maximization of NSE and R^2, minimization of RMSE, and reaching a value of zero for the PBIAS).

Table 3 shows the ranges of four performance criteria used in this study, and the more detailed description of these criteria is presented as follows:

Table 2 The HBV model-A model parameters, and their description and units

Routine	Parameter	Description	Unit
Snowfall routine	Wsmf	Wet snow melt factor	mm^{-1}
	CrT	Threshold temperature for snow melt initiation	°C
	DD	Degree-day factor	$mm\ °C^{-1}\ d^{-1}$
Soil routine	FC	Maximum soil storage capacity	Mm
	Pwp	Threshold at which evapotranspiration is potential	Mm
	Beta	Shape coefficient	-
Runoff response routine	HL1	Threshold water level for near-surface flow	Mm
	K0	Near-surface flow storage constant	D
	K1	Interflow storage constant	D
	K2	Baseflow storage constant	D
	Per1	Percolation storage constant	D
Transformation routine	Maxbas	Duration of the unit hydrograph	H

Table 3 Intervals of mathematical performance criteria and their significance on the simulation

Performance evaluation	NSE interval	RMSE interval	PBIAS % interval	R^2 interval
Very good	0.75 < Nash < 1.00	0.00 < RMSE < 0.50	PBIAS < ± 10	0.70 < R^2 < 1.00
Good	0.65 < Nash < 0.75	0.50 < RMSE < 0.60	± 10 < PBIAS < ± 15	0.60 < R^2 < 0.70
Satisfactory	0.50 < Nash < 0.65	0.60 < RMSE < 0.70	± 15 < PBIAS < ± 25	0.50 < R^2 < 0.60
Unsatisfactory	Nash < 0.50	RMSE > 0.70	PBIAS > ± 25	0.00 < R^2 < 0.50

- Nash-Sutcliffe efficiency (NSE): the first proposition of this function is made by Nash in 1969 and subsequently taken up by Nash and Sutcliffe (1970) and is the most commonly used objective function in hydrology to evaluate the predictive power of hydrological models. The range of this criterion varies between $-\infty$ and 1, and a score of 1 is a perfect score. The general equation of the Nash-Sutcliffe criterion is as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Qobs,i - Qcalc,i)^2}{\sum_{i=1}^{n}(Qobs,i - Qobs,m)^2} \qquad (9)$$

Where **Qobs,i; Qcalc,i; Qobs,i; m** are respectively the observed and simulated flows over a time step and the average of the observed flows, and **n** is the number of data points.

- Root mean square error (RMSE): is a function generally used to measure the differences between the values predicted by hydrological models and the actual values measured in gauging stations. Since the proposal of this criterion (Janssen and Heuberger 1995), a multitude of studies have incorporated this function in evaluating the qualities of simulations, especially in the fields of climate and environment (Willmott and Matsuura 2005). The RMSE range varies between 0 (perfect value) and infinity. It is given as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Qcalc,i - Qobs,i)^2} \qquad (10)$$

- Percent Bias (PBIAS): the use of this criterion is essentially based on the knowledge of the tendency of the hydrological model to underestimate or overestimate flows. It varies between $-\infty$ and $+\infty$, and the zero value constitutes the optimal value for this criterion. Positive values indicate

an underestimation of flows by the model and negative values indicate an overestimation of flows (Gupta et al. 1999). The descriptive equation of PBIAS is written as follows:

$$PBIAS\% = \frac{\sum_{i=1}^{n}(Qobs,i - Qcalc,i)}{\sum_{i=1}^{n}Q,obs,i} *100 \qquad (11)$$

- Determination coefficient (R^2): it is a function that allows checking if the linearity between the observed and simulated flows is sufficient or not. The R^2 criterion varies between 0 and 1, the value of 1 indicates that the observation is identical to the simulation (ideal case). The mathematical equation describing this criterion is as follows:

$$R^2 = \frac{\sum_{i=1}^{n}(Qobs,i - Qobs,m).(Qcalc,i - Qcalc.m)}{\sqrt{\sum_{i=1}^{n}(Qobs,i - Qobs,m)^2}.\sqrt{\sum_{i=1}^{n}(Qcalc,i - Qcalc.m)^2}} \qquad (12)$$

Where **Qobs,i; Qcalc,i; Qobs, m; Qcalc, m** are respectively the observed and simulated flows over a time step and the means of the observed and simulated flows, and **n** is the number of data points.

High flow indicators

The high flow trend study recommends several indicators. For this investigation, seven indicators are used in calculating the maximum annual flows for a daily (MAM1), weekly (MAM7), biweekly (MAM14), triweekly (MAM21), monthly (MAM30), bi-monthly (MAM60), and three-monthly (MAM90) flow. The daily flows simulated by the HBV model over long periods in the three Mediterranean catchments are used to calculate the different high flow indicators. The MAM1 indicator and the subsets of 7, 14, 21, 30, 60 and 90 days were calculated using a moving average applied to the series considered. In the final phase, a linear regression is applied to all high

flow indicators to determine their evolution over time. The objective of using MAM1 indicator (1 day) is to determine the maximum annual flow values and to get an idea of how they are changing over time. Besides, the indicator that calculates the maximum annual flows for a weekly flow is very important for determining the weeks when the flows are very high. Thus, the indicators MAM14 (14 days) and MAM21 (21 days) were calculated in this study to highlight their evolution in comparison with MAM1 and the other indicators.

The MAM30 indicator (30 days) has a very important role in determining the months of the year when river flows reach very high values, this determination makes it possible to increase flood protection during these periods. Furthermore, the other indicators (MAM60, MAM90) are related to maximum seasonal flows. Knowing these flows can improve environmental monitoring against natural phenomena with regards to high flows such as floods, etc.

Mann-Kendall test

The Mann-Kendall test (Mann 1945; Kendall 1975) is a non-parametric test widely used for statistical studies in different disciplines. In hydrology domain, most uses of this test focus on detecting monotonic trends in hydrometeorological time series. This test takes on this importance since it allows the detection of trends in incomplete time series containing gaps and for series characterized by abnormal distribution.

The Mann-Kendall test application requires a time series of length n classified on a given rank $(x1, \dots xn)$, where x_i represents the data at time i. For the application of this test, it is first necessary to specify the null hypothesis H_0. If this hypothesis is accepted, the variables of the studied sample have a homogeneous distribution. However, when these variables have a significant Monotonic trend, the null hypothesis H_0 is rejected and the alternative hypothesis H_1 is accepted. Usually the Mann-Kendall test is performed in several steps where the first consists in determining the signs of all differences $(x_j - x_k)$ with $j \leq n$ and $j > k$ (Example: x2 - x1, x3 - x1, …, $x_n - x_{n-1}$), so for this reason, the statistics S can be calculated according to the following equation (Gilbert 1987):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{Sign}(x_j - x_k) \tag{13}$$

The calculation of the Sign (xj - xk) influences the sign of the statistic S according to the following explanation:

$$\text{Sign }(xj-xk) = \begin{cases} +1 & \text{if } (xj-xk) > 0 \\ 0 & \text{if } (xj-xk) = 0 \\ -1 & \text{if } (xj-xk) < 0 \end{cases} \tag{14}$$

The second step of the Mann-Kendall test consists in calculating the variance of the S statistic (VAR (S)), but this varies according to n value.

- In the case where $n \leq 40$ the VAR(S) formula is written as follows:

$$VAR(S) = \frac{n(n-1)(2n+5)}{18} \tag{15}$$

- In the case where $n > 40$ the VAR(S) formula is written as follows:

$$VAR(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)}{18} \tag{16}$$

where g = number of groups with equal values (tied groups). t_p = number of data in each group.

Example $\begin{array}{l} t1 = 2 \ t2 = 3 \\ : \textbf{g=2} \ 3 \rightarrow 8, 9, 8, 10, 12, 10, 10 \end{array}$

The last Mann-Kendall test phase consists in calculating the Z variable that can be positive (increasing trend) or negative (decreasing trend). Generally, the use of this bilateral test consists in comparing the value of Z with the value of $Z_{1-\alpha/2}$ (α: significance level). The value of $Z_{1-\alpha/2}$ is extracted from a table of the cumulative normal distribution (Pearson and Hartley 1966), which allows to accept ($|Z| < Z_{1-\alpha/2}$) or reject ($|Z| > Z_{1-\alpha/2}$) the null hypothesis H_0. When H_0 is rejected, the alternative hypothesis H1 is accepted and which affirms that there is an increasing or decreasing trend in the sample studied.

Analyses and results

HBV model application results in three Mediterranean catchments

The HBV model is used in this study to simulate the flows of the long historical series (continuous mode simulation) in three semi-arid Mediterranean catchments. Then the calibration in continuous mode is generally performed without subjective separation of base flow and runoff to allow the calculation of the total flow (Simulated Flow) in the final hydrological model execution phase, and from this flow several flood statistics can be extracted.

The rainfall-runoff model used in this study is highly parametric (12 parameters), which strongly influences the complication of the calibration phase. However, after dozens of iterations (trial and error groping), optimal parameters are obtained (Table 4). These represent the dynamics of the three

catchments studied, and this is confirmed by the very interesting results illustrated in Figs. 3, 4, and 5.

For the Greece catchment (Evrotas), the simulation is carried out over the period when rainfall, temperatures, evapotranspiration, and crop coefficients are available. In this catchment, flows are generally measured manually each month, i.e., only one flow value per month is available throughout the period 1974 to 2010. These flows are compared with simulated flow by HBV model. The general analysis of the resulting hydrograph (Fig. 3) highlights a satisfactory agreement between the observed and simulated daily flows. It is noticed also that the point flows are well reproduced by the model with some underestimation throughout the considered period. The importance of correctly estimating high flows is closely related to the result quality of trend investigation in high flows, lately treated in this study.

Simulation for Lonquen watershed is carried out for 1986–2014 period. Observed flows are recorded continuously since 1986 and, are then used to verify the simulation accuracy over the 1986 to 2014 period. The hydrograph calculated by the model is in daily time steps. This time step is particularly interesting for preserving the aquatic environment concerns. Indeed, a single day of unmet needs is enough to affect the hydrological cycle. In addition, after the computation of the simulated hydrograph with the daily time step, precipitation, observed flows and simulated flows data are converted into monthly time step in order to have a clear representation of results. Visual analysis illustrates that results are very relevant (Fig. 4), with a slight underestimation of point flows in almost

the entire hydrograph. Besides, low flows are well reproduced by the model. Most of high rainfall in this watershed generally occurs between May and September and this explains the high values of flows in these periods (maximum monthly flows = 248 m³/s). The variation comparison of simulated and observed shows a remarkable homogeneity.

The Moroccan catchment (Azzaba) was the subject of continuous modeling for the 1970–2011 period. The general analysis of results (Fig. 5) asserts that flows simulated by the model are close to those observed in the gauging station. The number of peaks in the simulated and observed hydrograph is very high, which shows that the probability of flood occurrence in this watershed is very high. Peaks with high flow values are always underestimated by the model. Nevertheless, the low peaks are overestimated. The most extreme flow values are observed in the last years of the considered period 1970–2011. Indeed, values of maximum monthly flows of 102 m³/s and 117 m³/s are recorded on February 2009 and March 2010 respectively.

Statistical evaluation of results

Generally, the human eye is not able to detect all the small differences that may exist between the simulated and observed hydrographs. Then a simple visual analysis of the compared hydrographs is not considered an objective evaluation of the model. Therefore, it is necessary to easily understand the need to use a statistical evaluation of the results through the calculation of a set of mathematical equations.

Table 4 The optimal parameter values from the model calibration for the three catchments studied, with their calibration ranges

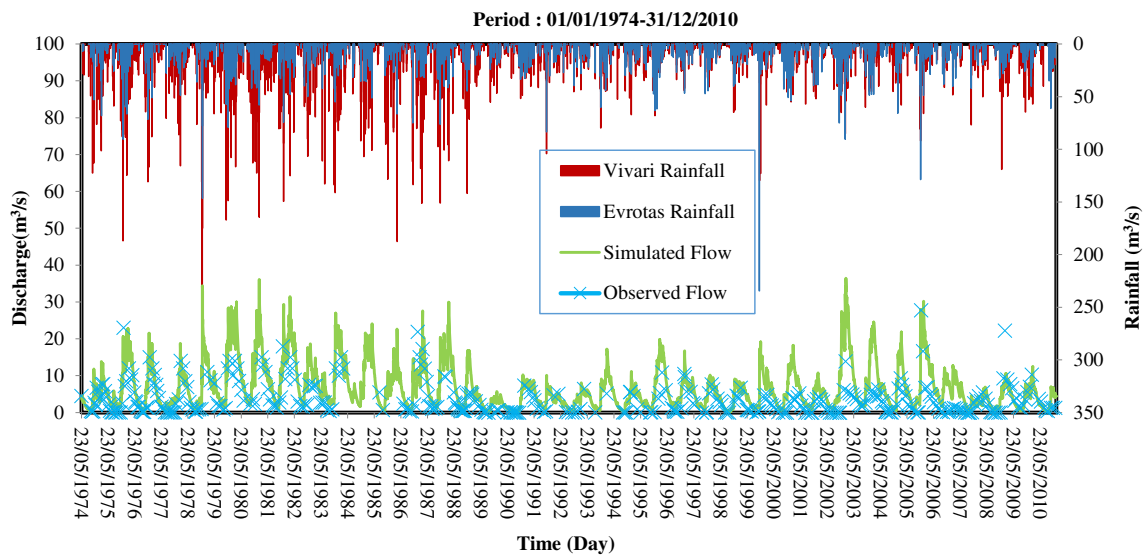| Model parameters	Parameter ranges (Wallner et al. 2013)		Greek catchment (Evrotas)		Chilean catchment (Lonquen)		Moroccan catchment (Azzaba)	
	Min	Max	Sub-catchment 1 (Evrotas)	Sub-catchment 2 (Vivari)	Sub-catchment 1 (Lonquen)	Sub-catchment 2 (Coelemu)	Sub-catchment 1 (Azzaba)	Sub-catchment 2 (Pont M'dez)
Wsmf	1	4	1	1	2	2	1	1
CrT	−1.5	1.5	1.5	1.5	1.5	1.5	1.2	1.2
DD	0.5	5	5	5	2	2	0.5	0.5
FC	50	300	100	300	300	300	50	300
Pwp	0.1	0.95	0.5	0.2	0.1	0.1	0.87	0.15
Beta	0.5	4	4	1	1.6	1.5	0.5	2.3
HL1	1	30	30	30	30	17	20	30
K0	0.25	5	5	5	5	4	3.2	5
K1	3	40	40	36	8	40	9	18
K2	50	500	50	50	500	500	50	500
Per1	3	40	3	3	3.4	3	3	4.5
Maxbas	3	10	10	10	10	10	10	10

Fig. 3 Illustration of the measured hydrograph, the modeled hydrograph, and the variation in precipitation at Evrotas and Vivari stations [(Greek catchment (Evrotas)]

The multi-criteria method is used to evaluate modeling results in the three watersheds by considering four mathematical performance criteria. Obtained results (Table 5) after the computation of these criteria are very interesting, especially for the PBIAS criterion which showed very good values (PBIAS = 1.32 for the Moroccan catchment, PBIAS = 4.80 for the Chilean catchment, and PBIAS = 8.70 for the Greek catchment). According to performance criteria intervals and their significance in simulation (see Table 3), the Nash-Sutcliffe value must not be less than 0.50 to have a satisfactory agreement between the simulations and the observations. In this context, the Nash-Sutcliffe values for the modeling of the Chilean, Moroccan, and Greek catchments are higher than the threshold value (NSE = 0.50), which indicates that the HBV model is relevant and accurate for simulating daily flows in the semi-arid Mediterranean catchments. The Root mean square error (RMSE) is also measured to evaluate the result performance. Generally to obtain a very good simulation, it is necessary to reduce the value of this error as much as possible. The RMSE measurement gives satisfactory values 0.68, 0.65 and 0.61 for the Chilean, Moroccan and Greek watersheds respectively, which is in agreement with the Nash-Sutcliffe values.

This confirms that the HBV model has well reproduced the flows in these watersheds and that the simulated values are very close to those observed.
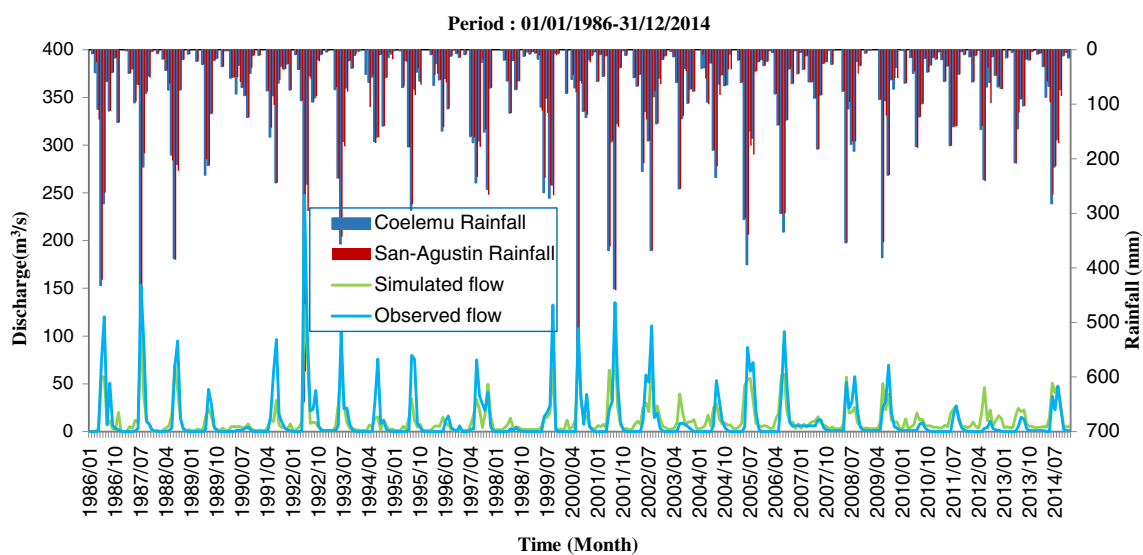

Fig. 4 Illustration of the measured hydrograph, the modeled hydrograph, and the variation in precipitation at San-Agustin and Coelemu stations [the Chilean catchment (Lonquen)]
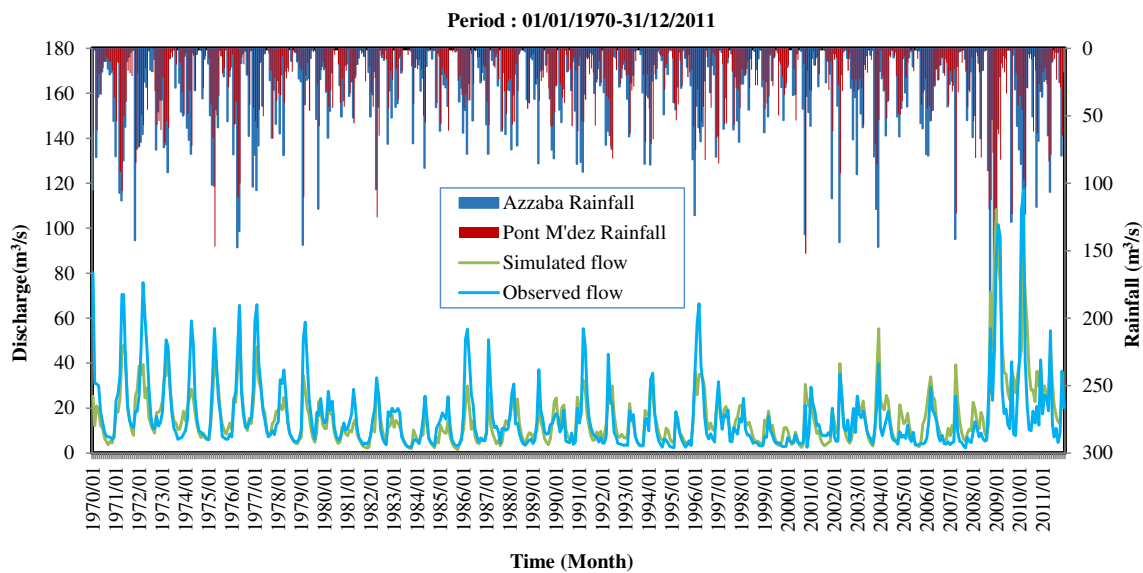
Period : 01/01/1970-31/12/2011

Fig. 5 Illustration of the measured hydrograph, the modeled hydrograph, and the variation in precipitation at Azzaba and Pont M'dez stations [Moroccan catchment (Azzaba)]

Trends in high flows

High flows are the maximum flows measured during the year at a given gauging station. In this study, trends in the maximum flows of three different study cases under Mediterranean climate are studied. Then seven high flow indicators (MAM1, MAM7, MAM14, MAM21, MAM30, MAM60, and MAM90) were calculated using the simulated flows and subsequently subjected to a linear regression in order to detect their evolution over the time.

The trend results obtained by calculating high flow indicators in the three catchments are illustrated in Fig. 6. The visual analysis of the results obtained for the Greek catchment highlights a negative trend for the indicator that calculates the maximum annual flows for a daily flow (MAM1), and for the other indicators (MAM7, MAM14, MAM21, MAM30, MAM60, and MAM90) a slight decrease in the high flows is noticed. During the 41 years used to study trends in this catchment, the maximum value of flow observed is about 36 m^3/s, and this value is the maximum flow value also for the MAM1 indicator. The maximum flow values decrease from

the indicator with the lowest time scale (MAM1) to the three-monthly indicator (MAM90).

According to the in-depth analysis of high flow trends for the Chilean catchment, a slight decrease in these flows is observed for the MAM1, MAM7, MAM14, MAM21, MAM30 and MAM60 indicators. Nevertheless, for the 90-day moving average (MAM90) a slight increase is noticed. The maximum flow calculated by the moving average of 1 day is about 796 m^3/s. This important value influences the negative trend observed over time for the MAM1 indicator.

The study of high flow trends in the Moroccan catchment between 1970 and 2011 showed an increase in the contribution of high flows to total runoff and this is confirmed by the positive trend observed in all calculated indicators. Besides, the extreme values are observed in the last years of the considered period.

Statistical tests are more rigorous for detecting time series trends compared with linear regression. For this reason, the Main-Kendall test was used to verify and confirm the results extracted by the visual observation. This test was carried out on all the high flow indicators calculated for the three basins

Table 5 The optimal values of the most important objective functions and their meanings on simulations for the three catchments studied

Evaluation statistic								
Chilean catchment (Lonquen)			Moroccan catchment (Azzaba)			Greek catchment (Evrotas)		
Performance criteria	Values	Evaluation	Performance criteria	Values	Evaluation	Performance criteria	Values	Evaluation
NSE	0.54	Satisfactory	NSE	0.58	Satisfactory	NSE	0.64	Satisfactory
RMSE	0.68	Satisfactory	RMSE	0.65	Satisfactory	RMSE	0.61	Satisfactory
PBIAS %	4.80	Very Good	PBIAS %	1.32	Very Good	PBIAS %	8.70	Very Good
R^2	0.54	Satisfactory	R^2	0.58	Satisfactory	R^2	0.66	Good

Fig. 6 Trends in maximum annual flows for the three gauging stations in the Mediterranean context: high flow indicators for the Evrotas catchment (left); high flow indicators for the Lonquen catchment (middle); high flow indicators for the Azzaba catchment (right)

studied with a 10% threshold ($\alpha = 0.1$), which corresponds to a 90% confidence level. Also it is important to note that the lag-1 correlation showed a non-significant correlation for all the high flow indicators which implies the direct application of the Mann-Kendall test without the need for the pre-whitening procedure (Bayazit and Önöz 2007). The application of this test (Table 6) shows a decrease in high flows for the seven indicators calculated for the Greek catchment over the considered period. The Chilean catchment reacts in the same way with an exception for the MAM90 indicator, which has increased. However, The Moroccan catchment reacts

differently since a remarkable increase for all high flow indicators has been observed.

Discussion

The final results obtained through the use of the HBV conceptual model in the three catchments with a semi-arid Mediterranean climate are very interesting, which confirms that this model is relevant for the simulation of daily flows in these contexts. The application of conceptual models in
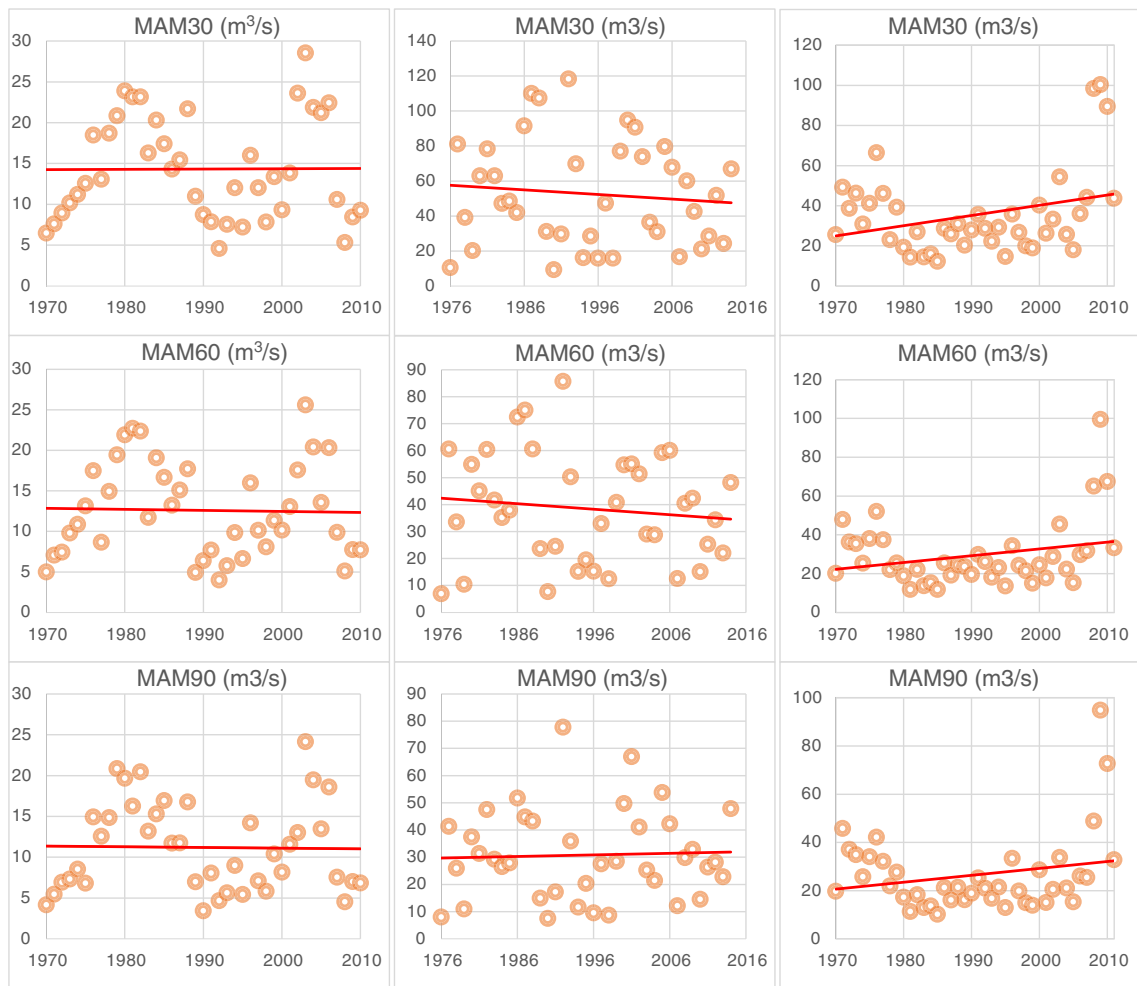
Fig. 6 continued.

Mediterranean contexts gives very good results and allows the best reproduction of flows, and this is confirmed by the studies carried out by Perrin 2000; Hreiche 2003; Ouachani et al. 2007; Aouissi et al. 2018; Aqnouy et al. 2019; Bouadila et al. 2019. The differences between the modeling results of three basins is due mainly to the fact that the conceptual models are sensitive to the spatial and temporal variability of precipitation, and this is consistent with Lobligeois et al. (2014). The areas of the three catchments chosen for this study are very important, and the HBV model is generally efficient for simulating flows of catchments with large areas. This support the good results obtained after the application of this model in the three large catchments (area > 2000 km^2).

Krysanova et al. (1999) tested the application of the HBV model in large catchments in the German part of the Elbe, and concluded that this model correctly simulates flows of catchments with large areas and gives very interesting performances.

The semi-distributed version of the HBV model has an important role in better reproducing flows observed in the catchments studied, and this is explained by the fact that the semi-distributed approach takes into account the spatial variability of precipitation which is considerable for a semi-arid Mediterranean climate. Several studies have shown the benefits of using the semi-distributed approach of a hydrological model to improve the quality of simulations (see e.g. Kite and

Table 6 Trend in high flow indicators found using the Mann-Kendall test (negative trend: ↓; positive trend: ↑)

High flow indicators		MAM1	MAM7	MAM14	MAM21	MAM30	MAM60	MAM90
Greek catchment (Evrotas)	Mann-Kendall test	↓	↓	↓	↓	↓	↓	↓
Chilean catchment (Lonquen)		↓	↓	↓	↓	↓	↓	↑
Moroccan catchment (Azzaba)		↑	↑	↑	↑	↑	↑	↑

Kouwen 1992; Michaud and Sorooshian 1994; Corral et al. 2000; Boyle et al. 2001; Ajami et al. 2004; Garavaglia et al. 2017). The values of 12 parameters resulting from the calibration of the model are realistic and represent well the hydrological functioning of the semi-arid Mediterranean catchments treated in this study. It is also important to note that these values belong to the intervals proposed by several previous studies (Singh 2010; Wallner et al. 2013), which confirms the relevance of the HBV model for the reproduction of observed flows in the Mediterranean context.

The simulation results obtained for Evrotas catchment are of a good quality, and this is due to the fact that the modeling of this catchment using semi-distributed models gives very important results. The study done by Tzoraki et al. (2013) highlighted the importance of using a semi-distributed model for the reproduction of flows in the Evrotas catchment characterized by karstic terrains which influence the underestimation of peak flows. Flow modeling in karst catchments can cause significant underestimations of flood peaks (Jourde et al. 2007; De Waele et al. 2010). The HBV model takes into consideration the water exchanges between the surface and underground formations, which reduces the degrees of error produced by hydrological models in most cases, especially the significant underestimation of flood peaks for catchments with a karstic nature. In this context, it should be taken into consideration that the majority of the low underestimations of the flow peaks in resulting Hydrograph are mainly due to the karst nature of the terrain. The significant values of the performance criteria confirm the interpretations extracted above, and that the use of HBV models has well reproduced the flows in the Evrotas catchment.

Modeling of the Chilean catchment is different from that of the Greek and Moroccan catchments. The flows in this river are very high and can reach extreme values (sometimes higher than 900 m^3/s), and also the geological nature of the terrain is completely different. Surface soils in the Lonquen catchment swell rapidly when receiving a quantity of water either by precipitation or irrigation (Stewart et al. 2015). This strongly influences the occurrence of very high flood peaks in the resulting hydrograph. Generally, the underestimation of the simulation's flood peaks in this catchment may be due to poor rainfall recording during extreme events (floods and low water levels), which sometimes causes weaknesses in the rainfall database. Furthermore, the value of PBIAS 4.80 is positive, which mathematically confirms the tendency of the rainfall-runoff model to underestimate flows in the Lonquen catchment.

The underestimation of the major flow peaks for the Moroccan catchment (Azzaba) is mainly due to its karstic nature, which strongly influences the increase of the infiltrated water rate. The very high value of the maximum soil storage capacity (FC 300: maximum value) for the Pont M'dez sub-catchment shows that infiltration is very high, especially in the upper part of Azzaba where the majority of the land is dominated by the rural aspect and large fissured karst areas. Generally, the combination of the rural aspect and the Karstic nature of the land favors a very high infiltration of rainwater. The Karstic nature of the studied area allows to the hydrogeological reservoirs to be supplied by rainwater and subsequently gives rise to numerous artesian springs in the downstream part of this area (El Khalki 1990; Nejjari 2002; Akdim et al. 2012). Meanwhile, a large part of rainfall in the Azzaba catchment is lost by infiltration due to the karstic nature of the terrain, and this leads to flow underestimation. This underestimation is also statistically confirmed by the positive value of the mathematical performance criterion PBIAS 1.32.

The trend study in high flows for the three Mediterranean catchments present special results moving from one catchment to another. Indeed, the Mediterranean context is highly sensitive to climate change (Giorgi 2006; Giorgi and Lionello 2008; Colin 2011), this sensitivity also influences the change in the hydrological functioning of the catchments under the influence of the Mediterranean climate. Several researchers have shown that global warming in the Mediterranean context tends to increase (Gibelin and Déqué 2003; Somot et al. 2007, 2008). These studies are in good agreement and confirm the results found for the Greek and Chilean catchments, specifically the warming in the Mediterranean context influences on the spatial variability of the rainfall and their decrease in terms of quantity in some regions of this context, then automatically a decrease in the frequency of occurrence of floods. It is also important to say that the change in the spatial variability of rainfall can cause rainfall increase in some areas of the Mediterranean context. It is the case for the Moroccan catchment where an increase in the high flows is observed for all the indicators calculated for this catchment. The results obtained through the use of two trend detection approaches are in good agreement and confirm the influence of climate change on the Mediterranean context.

Conclusion

This study focused on hydrological modeling and the study of trends in high flows in three semi-arid Mediterranean catchments. The flow simulation is performed using a semi-distributed conceptual model (HBV model-A), and using the continuous approach to simulate the flows of the long historical series in the three catchments considered. Model calibration requires continuous series of rainfall, temperature, evapotranspiration, and crop coefficient, all these climatic factors are taken into account by the HBV model for the best flow reproduction.

The performance studies used to control the quality of the results obtained confirm that the HBV model performs well for

catchment flow simulation with a semi-arid Mediterranean climate. In this context, it is necessary to understand the importance of this hydrological model for improving flood estimation, water resource management and also for understanding the hydrological behavior of semi-arid Mediterranean catchments.

Trends in high flows have been examined by calculating several indicators in the three Mediterranean climate watersheds. Trends of high flow indicators were detected using two approaches. The first approach was based on detecting high flow trends using visual observations (linear regressions: trend detection using slopes from the linear regressions of high flow indicator values plotted on a graph). The second approach is more rigorous and consisted on using a statistical test to accurately detect the presence of a trend (the Mann-Kendall trend test: trend detection using assumptions).

Generally, these indicators change in the same way for each watershed, except for some exceptions. For the Greek and Chilean watersheds, a negative trend has been noted for most of the calculated indicators, which shows a decrease in the frequency of occurrence of high flows and automatically suggests a decrease in the risk of floods and inundations. The Moroccan watershed reacts differently with high flow trends, and the calculated indicators show a positive trend in high flows, these interesting results show the importance of improving flood forecasting and developing water resource management in this watershed for better protection against floods. Generally these results confirm the influence of climate change on the hydrological functioning of catchments and the availability of water resources, especially in regions influenced by a Mediterranean climate.

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