Investigating hydrological regimes and processes in a set of catchments with temporary waters in Mediterranean Europe

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Abstract Seven catchments of diverse size in Mediterranean Europe were investigated in order to understand the main aspects of their hydrological functioning. The methods included the analysis of daily and monthly precipitation, monthly potential evapotranspiration rates, flow duration curves, rainfall–runoff relationships and catchment internal data for the smaller and more instrumented catchments. The results showed that the catchments were less "dry" than initially considered. Only one of them was really semi-arid throughout the year. All the remaining catchments showed wet seasons when precipitation exceeded potential evapotranspiration, allowing aquifer recharge, "wet" runoff generation mechanisms and relevant baseflow contribution. Nevertheless, local infiltration excess (Hortonian) overland flow was inferred during summer storms in some catchments and urban overland flow in some others. The roles of karstic groundwater, human disturbance and low winter temperatures were identified as having an important impact on the hydrological regime in some of the catchments.

Key words flow regimes; runoff generation; baseflow; Mediterranean

Étude des régimes et processus hydrologiques dans un ensemble de bassins versants aux eaux temporaires dans l'Europe Méditerranéenne

Résumé Sept bassins versants de tailles variables, situés en Europe Méditerranéenne, ont été étudies pour appréhender les principaux aspects de leur fonctionnement hydrologique. L'analyse est conduite sur la base de données de précipitations mensuelle et journalière, d'évapotranspiration potentielle mensuelle, de courbes de débits classés, de coefficients d'écoulement et, pour les bassins les plus petits et les plus instrumentés, de données internes aux bassins. Les résultats montrent que les bassins versants considérés sont moins "arides" que prévu. Seul l'un d'entre eux est vraiment semi-aride toute l'année. Les autres bassins présentent des saisons humides, avec des précipitations qui dépassent l'évapotranspiration potentielle, permettant la recharge des nappes, l'apparition de processus de génération de l'écoulement typiques de zones "humides" et une contribution significative du débit de base. Toutefois, des phénomènes de ruissellement liés, localement, au dépassement de la capacité d'infiltration (processus Hortonien) sont observés durant les événements orageux estivaux sur quelques uns des bassins et des phénomènes de ruissellement urbain sur quelques autres. Les rôles des aquifères karstiques, des perturbations anthropiques et des faibles températures hivernales ont été identifiés comme ayant un impact important sur le régime hydrologique de certains des bassins versants.

Mots clefs régimes hydrologiques; génération de l'écoulement; débit de base; Méditerranée

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INTRODUCTION

The traditional perception of runoff generation in Mediterranean areas is that the primary generation mechanism is overland flow as the result of rainfall falling at intensity greater than the local infiltration capacity of the soil (e.g. Beven, 2002). Nevertheless, field studies have shown that overland flow may also be produced in these environments as the result of saturation mechanisms, such as the saturation of thin soils during large events (Martinez-Mena *et al.*, 1998), the seasonal saturation of first order valley bottoms (Ceballos & Schnabel, 1998) or the seasonal formation of a water table and saturated areas throughout the catchment, with relevant contribution from subsurface flow (Gallart *et al.*, 2002; Latron & Gallart, 2007). Hydrological systems are complex, and different hydrologists might not necessarily agree on which are the most important processes in a catchment (Beven, 2002). Yet, many areas show a significant seasonality, so that the dominant processes may change throughout the year (Kirkby, 2005).

Within the framework of the EU-funded project TempQsim (EVK1-CT2002-00112), seven catchments were investigated in order to improve the understanding and modelling of water quality in temporary waters. With the exception of one (Vallcebre), which is a small research catchment, the catchments were selected to tackle real water quality issues rather than for fundamental research purposes. Therefore, there is variation not only in the sizes of the catchments, but also in the lengths of climate and flow series available for each catchment (Table 1).

The purpose of this paper is to describe the setting of perceptual models of the hydrological functioning of these catchments, i.e. the summary of perceptions of the processes controlling how the catchment responds to rainfall under different conditions (Beven, 2002). This is also an exercise in comparative hydrology in the sense of Kovacs (1989), complicated by the diverse catchment size and data availability. It further aims to determine if current precipitation, weather and discharge data at the catchment scale and daily time step provide sufficient information to build the perceptual models, or whether other additional information is required.

Table 1 Main characteristics of the studied catchments.

Catchment name	Area [(a)] (km^2)	Precipitation (mm $year^{-1}$)	Runoff coefficient	Temperature (ºC)	PET (mm $year^{-1}$)	Series length (years)
Albujón	556	384	<0.01	19.0	1475	1
Iskar	893	511	*0.48*	8.8	629	3
Pardiela	514	587	0.11	16.2	1182	9
Vène	67	659	*0.49* [(b)]	14.1	1338	10
Mulargia	66	740	0.38	14.3	1057	8
Vallcebre	0.52–4.17	824	0.32	8.3	700	10
Krathis	79–149	1512	0.58 [(c)]	9.1	849	2 [(c)]

PET: potential evapotranspiration; series length in years.
[(a)] Diverse values represent studied sub-basins.
[(b)] Runoff coefficient overestimated because of the contribution of karstic groundwater from elsewhere.
[(c)] Precipitation and discharge series are not fully synchronous.
Runoff coefficients in italics are not consistent with water balance.

STUDY CATCHMENTS

The locations of the catchments are shown in Fig. 1, their main characteristics are summarized in Table 1, and example annual hydrographs are shown in Fig. 2.

The Albujón catchment, located near Murcia in southeastern Spain, is the main tributary to the Mar Menor littoral lagoon. This is a low relief area on marls and lutites, and the area is used mainly for irrigated agriculture. This catchment was selected mainly to study the nutrient delivery to the Mar Menor, one of the largest coastal lagoons in the Mediterranean region and Europe, increasingly threatened by urban and agricultural pressures.

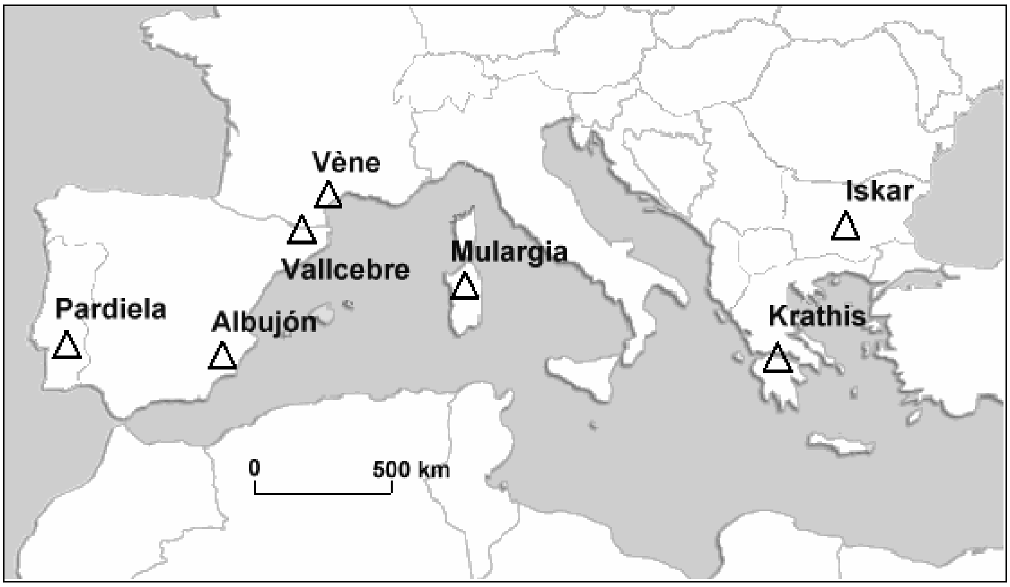

Fig. 1 Locations of the studied catchments.

The Upper Iskar catchment, located above the capital Sofia in southwestern Bulgaria is the main source of water for the nearby urbanized region. The relief consists of mountains and high fields, built up by schists and syenites, covered with brown forests and meadow mountain soils, or alluvial slightly sandy or stony soils along the rivers; land use is mainly agriculture (potatoes). Snow lies for two or three months in the mountains. This catchment was selected mainly to study the nutrient delivery to the drinking water Iskar Reservoir from municipal wastewater or diffuse agricultural polluters, as well as the runoff fluctuations and their extremes.

The Pardiela catchment, located near Évora in southeastern Portugal, is the main contributor to the Degebe catchment, a hilly area built up by siliceous and metamorphic rocks. The land use in the catchment area is mainly semi-natural woodland and rough pastures with sparse houses. Two different periods in the hydrological regime can be identified, one associated with lotic and the other with lentic conditions. During some flood events, organic material that has accumulated during the dry period is washed out and biological communities are dislodged. This catchment was selected mainly because of its unperturbed nature, representing the typical conditions of temporary streams in the south of Portugal.

The Vène catchment, located near Montpellier in southeastern France, is the main contributor to the Thau littoral lagoon. The relief is hilly, built up by limestones and marls, and the area is mainly used for agriculture (vineyards), food industries and housing. There are two major karstic sources in the catchment, and urban effluents are worth taking into consideration in the catchment functioning. This catchment was selected mainly to study the nutrient and pollutant delivery to the Thau lagoon, used for shellfish breeding (oysters and mussels) and recreation.

The Mulargia catchment is located in the southeastern part of Sardinia. The outlet section of the studied watershed is just upstream of the Mulargia Reservoir, about 6 km before the confluence with the Flumendosa River. Shales, characterizing the entire low mountain zone, determine scarce bedrock permeability. Land use is mainly influenced by grazing; natural pastures of great extent satisfy large sheep-grazing requirements, and most of the cultivated land is dedicated to the production of animal fodder. Water quality within the basin area is also influenced by the discharge from the wastewater treatment plants of three different municipalities (Nurri, Orroli, Serri), with a total of 6300 inhabitants and 12 000 industrial-equivalent units.

Vallcebre is a set of small research catchments located in a middle-mountain area of the headwaters of the Llobregat River in the Pyrenees (Spain). The bedrock is formed by mudrocks and limestones. Most of the area was deforested and terraced for farming in the past, but most of

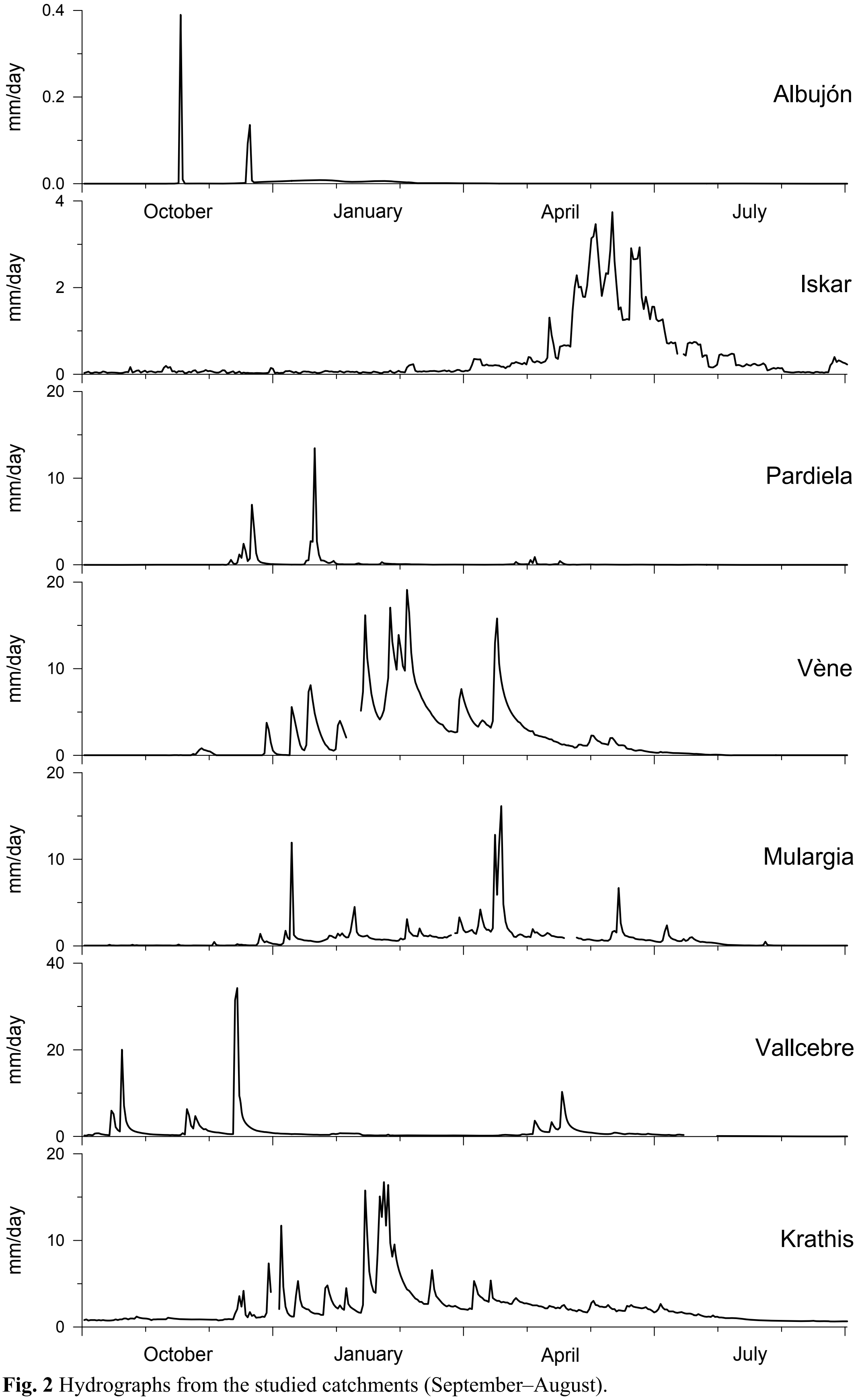

Fig. 2 Hydrographs from the studied catchments (September–August).

the old fields are nowadays used as pasture, or are undergoing an afforestation process. Small natural, intensely eroded areas (badlands) occur in the catchments and are responsible for large sediment loads in the streams. This part of the study was carried out in the Can Vila sub-basin, most of it on impervious mudrocks and with scarce badlands, although the analysis of the response time was also done for the main Cal Rodó basin.

Krathis is a nearly "pristine" mountainous river in a calcareous area in the Peloponnese (Greece) with steep slopes and high erosion capacity. There are many karstic springs in the catchment. During flood events, high sediment loads and associated nutrients enter the sea, creating blooms, even during summer following precipitation events. The coastal zone of the broader estuary has been developed for tourism, with numerous hotels and apartments. Sediment blooms create aesthetic problems and possibly enhance eutrophication. Local stakeholders are greatly concerned, as this situation adversely affects tourism and the economic growth of the area.

DATA AND METHODS

Daily precipitation data were obtained from the official networks for the Albujón, Iskar, Pardiela, Mulargia and Kratis catchments, and from denser research networks for the Vène and Vallcebre catchments. Potential evapotranspiration was estimated using the Penman-Monteith FAO method (Smith, 1992) from daily weather data. Daily flow data were obtained from the official networks for the Pardiela catchment, and from gauging stations managed by the Project teams in the other catchments. These stations are provided with flow control structures and electronic equipment for recording water stage data.

The observation equipment in most of the catchments could provide hourly or sub-hourly precipitation and discharge data, adequate for estimating the response times for floods occurring after the dry periods. Data were subsequently analysed at monthly (water balance), daily (regime) and hourly (response time) temporal scales.

The distributions of daily precipitation records for each catchment were analysed and fitted to lognormal distributions. Daily flow duration curves were plotted and fitted to lognormal and bimodal distributions, as convenient. When the records contained zero discharge values, only the non-zero values were used for fitting the distributions and then the frequencies obtained were multiplied by the frequency of the non-zero flows in order to take into account all the data, as recommended by Jennings & Benson (1969). Average monthly values for precipitation, temperature, potential evapotranspiration and runoff were plotted and inspected to investigate the seasonal trends.

Methods and hypotheses used for analysis and comparisons

First, a simple monthly soil water balance model was used to investigate to what extent the observed flow regime may be explained by the saturation of the soil profiles. The use of a monthly scale in the model means that the main role in flow generation is attributed to cumulated precipitation and low evapotranspiration demand, rather than to hourly or daily rainfall intensity.

Second, the relative baseflow contribution to daily streamflow (i.e. the impact of the discharge on the previous day to explain present discharge) was investigated using a baseflow filter. The relative importance of baseflow increases with soil depth, bedrock permeability and basin size, and with increasing role of saturation processes.

Third, the flow regimes observed in the catchments were classified using a customary classification method designed for ecological purposes. The objective of this exercise was mainly to assist in comparisons, although the results may be useful to identify some aspects such as the role of groundwater flow or snowpack melt in the stream regime.

Fourth, the response time for the first flood after a dry period was investigated for six of the catchments. Then, the relationships between response times and catchment sizes obtained were compared with the relationships published by other authors for catchments where runoff generating mechanisms have been investigated.

Finally, the results of the former analyses were used, along with the inspection of the flow duration curves and other available information, in order to assess the perceptual models of catchment hydrological responses.

Water balance model The Thornthwaite-Mather method (Thornthwaite & Mather, 1955; Steenhuis & Van der Molen, 1986) was used to estimate the monthly water balance and depth of water excess available for runoff generation and aquifer recharge, from the available precipitation and evapotranspiration records. The following parameters were derived from the model: WETMONTH (months) is the annual number of months with water excess, EXCFLOW [-] is the correlation coefficient between the monthly values of water balance excess and observed flow, and EXCREL [-] is the proportion of annual flow that was simulated through the water balance simulation. The available water capacity of the Thornthwaite-Mather model was calibrated between reasonable bounds to maximise EXCFLOW and to obtain EXCREL values close to unity.

Baseflow contribution An estimate of the relative contribution of baseflow to total stream-flow was obtained for every catchment by fitting the recession curves to hyperbolic curves, as currently used in the hydrological model TOPMODEL (Beven *et al.*, 1995).

$$\frac{1}{Q_b} = \frac{1}{Q_{n-1}} + \frac{t}{m} \tag{1}$$

where Q_b is baseflow estimated for day n, Q_{n-1} is the flow on the previous day, t is the time (days) and m is a recession coefficient, which was calibrated for every catchment. The parameter RELBAS [-] is the ratio between estimated annual baseflow and observed streamflow. The application of this analysis was not possible at the Albujón catchment, because the high flashiness of its response prevented the identification of the parameter m.

Flow regimes The regime of the selected streams was classified following the classification and indices proposed by Poff (1996), although the two last indices in the following list substituted the original ones that could not be applied because of the short length of the time series: DAYCV (%) is the average of the standard deviation of daily flows divided by the annual mean daily flow, multiplied by 100; ZERODAY (days) is the average annual number of days having no discharge; BFI (%) is the average annual percentage of the lowest daily flow to the mean daily flow; HIGHPRED (dimensionless, used instead of Poff's FLDPRED) is the proportion of days with flows in the upper 95th percentile that fall in any one of six 60-day windows starting in September, and can take values ranging from 0.167 (uniform seasonality) to 1 (perfect seasonality predictable); MINORPRED (dimensionless, used instead of Poff's LOWPRED) is the maximum proportion of days with flows in the lower 5th percentile falling in a seasonal 60-day window (as discussed above for HIGHPRED).

Response time The average response or peak lag times (delay between the gravity centre of the hyetograph and the peak of the hydrograph) for floods occurring in the catchments just after the dry period were analysed in relationship with the corresponding catchment size, and compared with the relationships summarised by Jones (1997) from preceding works.

RESULTS AND DISCUSSION

Overall and comparative results

Tables 2 and 3 show the variables obtained for the diverse catchments subsequent to the water balance, recession and regime analyses.

The simulated monthly water balance was very well correlated with observed flows (high EXCFLOW values) for the four rainiest catchments, suggesting that saturation processes are

Table 2 Variables obtained from the water balance and recession analyses.

Catchment	WETMONTH	EXCFLOW	EXCREL	m	RELBAS
Albujón	0	0	0	-	-
Iskar	5	0.23	0.29	0.08	0.62
Pardiela	2	0.44	1.00	0.40	0.49
Vène	5	0.81	0.29	0.02	0.84
Mulargia	5	0.86	0.97	0.18	0.65
Vallcebre	7	0.81	0.89	0.06	0.66
Krathis	7	0.78	1.08	0.02	0.89

Table 3 Results of the indices used for the flow regime analysis and the resulting classification after Poff (1996).

Catchment	DAYCV	BFI	ZERODAY	HIGHPRED	MINORPRED	Regime
Albujón	765.9	0.00	330 (41)	-	-	HI (IF)
Iskar	145.7	6.10	0	0.633	0.617	SR1
Pardiela	626.2	0.11	49	0.525	0.634	IF
Vène	252.5	0.00	22	0.461	0.617	IR
Mulargia	277.7	2.38	12	0.355	0.689	IR
Vallcebre	342.9	0.90	26	0.376	0.350	IR
Krathis	95.9	17.13	0 (171)	0.396	0.425	GW (HI)

HI: harsh intermittent; IF: intermittent flashy; SR1: snow + rain type 1; IR: intermittent runoff; GW: stable groundwater. Figures and regimes in parentheses correspond to the lower reaches of the streams

dominant. The proportion of flow simulated by the water balance (EXCREL) was zero for the Albujón catchment, where all the months had a water deficit, and were much smaller than unity for Iskar and Vène, demonstrating some problems with the catchment water balance that are discussed below.

The smallest values of the recession parameter m (meaning sustained recessions) along with largest values of RELBAS were obtained for the Krathis and Vène catchments; conversely, the shortest recessions and lowest values of RELBAS were found for Pardiela. The recession analysis could not be made for the Albujón catchment, as stated in the Methods section.

The analysis of flow regimes (Table 3) resulted in five different types, a more diverse range than that anticipated from inspection of the flow records. Two of the streams, the Albujón and Krathis, had different regimes in the lower reaches because of exchanges with groundwater (streamflow gain and loss, respectively).

The analysis of the response times of the first floods after the dry season (Fig. 3) suggested that quick responses attributable to precipitation excess (Hortonian) mechanisms were characteristic for the Albujón, Vène and Cal Rodó (Vallcebre) catchments. The responses at the Mulargia, Krathis and Iskar catchments were somewhat less rapid, although still more rapid than these typical from wet areas, attributable to a less important role of areas with low infiltration rates or the remote location of these areas in such, rather large, basins. The slow response of the Can Vila sub-basin (Vallcebre) has been attributed to the role of agricultural terraces (Gallart *et al*., 2005).

Perceptual models of catchment hydrological responses

The results shown in the above tables and graphs, as well as the information gathered in other studies for some of the catchments, allowed us to summarize the following modes of response for the catchments:

– The Albujón catchment remained dry for most of the time and only responded—quickly but with very small runoff coefficients—to very large rainstorms, that occur no more than once per year. Hortonian overland flow on low permeability soils and urban runoff are evoked as the main runoff generating mechanisms. In the lower reaches, baseflow occurred for most of

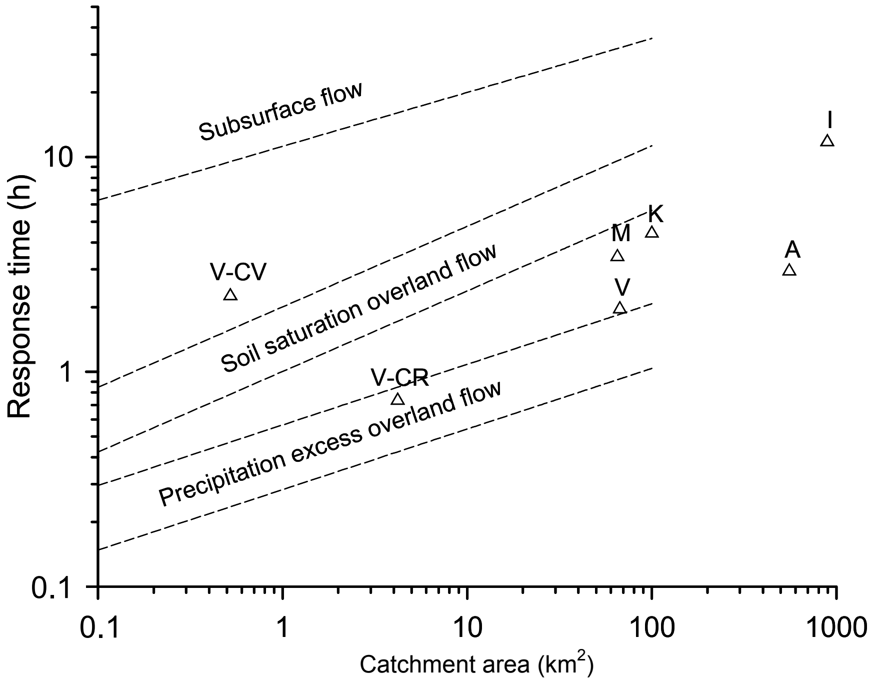

Fig. 3 Average response times for floods occurring after the dry periods. A: Albujón; I: Iskar; K: Krathis; M: Mulargia; V: Vène; V-CR: Vallcebre–Cal Rodó; V-CV: Vallcebre–Can Vila. The labelled divisions represent the main runoff generation mechanisms simplified from Jones (1997).

the year due to the water table being connected to the Mar Menor lagoon, which is recharged by the active irrigation (see also García-Pintado *et al*., 2007).

– Iskar had a permanent regime, but several months had a deficient water balance. The annual distribution of flows, as well as the high predictability of high flows in spring and low flows in winter, demonstrated the role of snowpack melt in the regime. These processes may explain the bi-modal shape of the flow duration curve (Fig. 4), although the low flows may also have been increased by urban effluents. An underestimation of snow precipitation in the heights may explain the excessive runoff coefficient (Table 1) and the low EXCREL value (Table 2).

– Pardiela showed a flashy response with rapid recessions, although the two months with positive water balance afforded limited baseflow for most of the year. Non-zero flows were observed 86% of the time, but the first non-zero value in the records (0.01 $m^3 s^{-1}$) was exceeded only 60% of the time. The non-zero values of the flow duration curve had an acceptable fit to a lognormal distribution (not shown).

– Vène showed a complex response (see also Tournoud *et al.*, 2005). The annual distribution of flows was well explained by the periods of water balance saturation, but both the excessive runoff coefficient and the high baseflow contribution revealed the role of the karstic aquifer, whose recharge area extends beyond the area of the catchment. Quick floods in response to rainstorms occurring after the dry period may be attributed to Hortonian overland flow on agricultural soils or paved areas. The flow duration curve (Fig. 5) had an intricate form coherent with the complexity of the response.

– Mulargia showed a regime driven by saturation, as was very well simulated by the monthly water balance (high EXCFLOW and EXCREL values in Tables 2 and 3, respectively), whereas runoff was limited during the months with the higher rainfall intensity. The first floods after the dry period seem to be related more to saturation than to precipitation excess processes (Fig. 3). In contrast, the recessions were relatively rapid and the baseflow contribution (RELBAS) was moderate, which is consistent with the poor permeability of the bedrock. The non-zero values of the flow duration curve showed a good fit to a lognormal distribution (not shown).

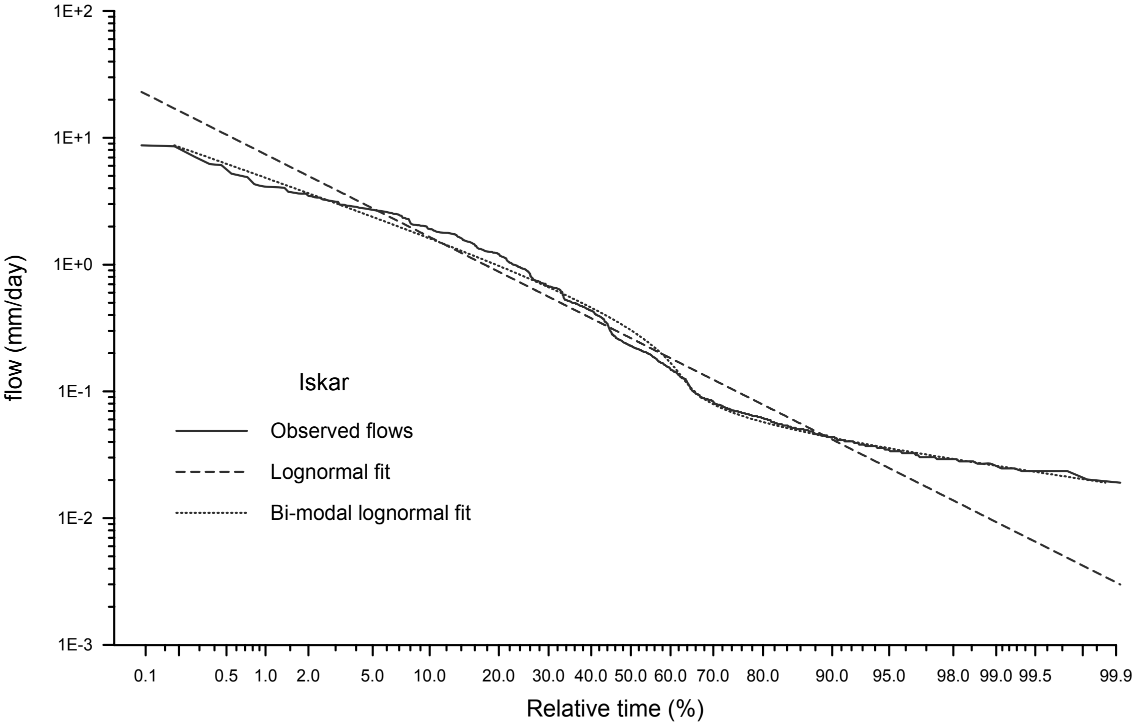

Fig. 4 Flow duration curve for the Iskar catchment.

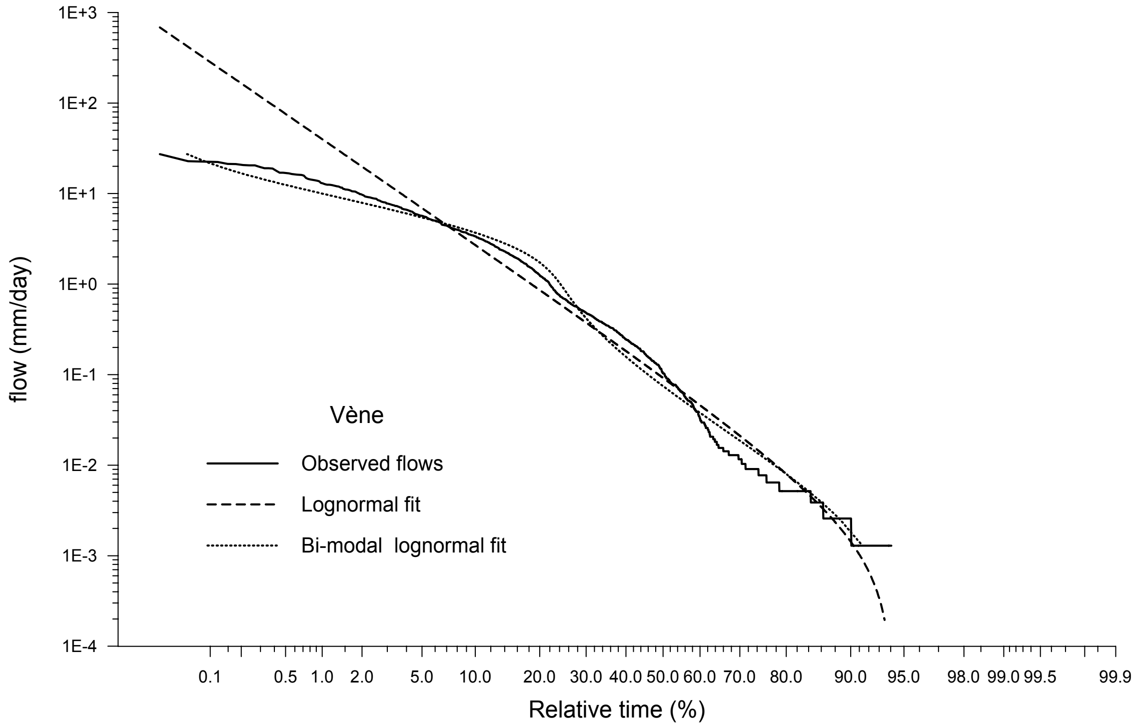

Fig. 5 Flow duration curve for the Vène catchment.

– Vallcebre also showed a response dominated by saturation processes, well simulated by the monthly water balance, and the flow duration curve had a good adjustment to a lognormal distribution (not shown). The recessions were relatively sustained for such a small catchment over impervious rocks, presumably due to the role of thick soils in the old agricultural terraces. Nevertheless, the analysis of first flood response times demonstrated clear differences between the rapid response of the Cal Rodó basin (with a relatively large extent of eroded areas) and the slow response of the Can Vila sub-basin (mainly terraced). Previous studies performed in this area using diverse kinds of information (Gallart *et al*., 2002, 2005; Latron *et al*., 2008) demonstrated that the main response is driven by saturation mechanisms, although small floods during the dry periods are linked to Hortonian processes, and the first relevant floods after these periods are related to the saturation of upper soil horizons when copious rainfall events do occur.

– Krathis, in the intermediate reaches, showed the most regulated response of the catchments, which was unexpected because of the torrential appearance of the stream channel. The large proportion of baseflow should be attributed to the role of the karstic aquifers, whereas the possible role of snowpack melt was not demonstrated, given the high value of the correlation coefficient EXCFLOW. The intermittent regime of the lower reaches may be attributed to the transmission losses through the thick alluvial sediments.

CONCLUSION

The exercise shown herein was helpful to improve the understanding of the hydrological functioning of the investigated catchments. In some cases, the results emphasized the role of the characteristics of the catchments that were presumed relevant, such as the role of karstic underground flow or the impervious character of bedrock. In other cases, the results denied the preliminary assumption of the chief role of Hortonian mechanisms in the catchment response.

The main aspects of the hydrological response could be determined by analyses made using daily data, which may be obtained from operational networks, but in some cases, as in Vène and Iskar, these data only demonstrated that the response was complex and that other kinds of information were needed. The analysis of the response times, which needed more detailed data, was helpful to complete the information for most of the catchments, and in Vallcebre it demonstrated that the use of daily data would give a false impression of a simple hydrological functioning of the catchments.

Therefore, the methods used may be recommended for the establishment of perceptual models of catchment hydrological response, as these happened to be more objective than the more intuitive or routine preconceptions. Nevertheless, these methods do not warrant the detection of complex responses and, therefore, should be complemented with other kinds of information, particularly in complex environments.

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