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Streamflow timing of mountain rivers in Spain: Recent changes and future projections

Enrique Morán-Tejeda [a,c,*], Jorge Lorenzo-Lacruz [b], Juan Ignacio López-Moreno [c], Kazi Rahman [d], Martin Beniston [a]

[a] *Institute for Environmental Studies, University of Geneva, Switzerland*
[b] *Department of Geography, University of Zaragoza, Spain*
[c] *Pyrenean Institute of Ecology, CSIC, Spain*
[d] *School of Earth Sciences, Stanford University, USA*

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SUMMARY

Changes in streamflow timing are studied in 27 mountain rivers in Spain, in the context of climate warming. The studied rivers are characterized by a highflows period in spring due to snowmelt, although differences in the role of snow and consequently in the timing of flows are observed amongst cases. We calculated for every year of the studied period (1976–2008) various hydrological indices that enable locating the timing of spring flows within the annual hydrologic regime, including the day of 75% of mass, and the day of spring maximum. The evolution of these indices was compared with that of seasonal precipitation and temperature, and trends in time were calculated. Results show a general negative trend in the studied indices which indicates that spring peaks due to snowmelt are shifting earlier within the hydrological year. Spring temperatures, which show a significant increasing trend, are the main co-variable responsible for the observed changes in the streamflow timing. In a second set of analyses we performed hydrological simulations with the SWAT model, in order to estimate changes in streamflow timing under projected warming temperatures. Projections show further shifting of spring peak flows along with a more pronounced low water level period in the summer. The simulations also allowed quantifying the role of snowfall-snowmelt on the observed changes in streamflow.

1. Introduction

The streamflow pulses of mountain rivers are strongly dependent on the seasonal cycles of temperature, and normally experience a "dormant" stage during the cold season, and rapidly change to an active high-flow stage in spring when the period of snowmelt begins. The pace and magnitude of these stages will depend on the geographic characteristics of the mountains that control temperature regimes; these include elevation, latitude, distance to sea, or exposition to predominant winds. From a scientific point of view mountain rivers represent a valuable laboratory as they reflect the natural conditions of mountain environments before any disturbance by humans is taking place. River flows are sensitive to many changes occurring in the environment, including changes in climate variables (Arnell, 1999), changes in land use and land cover (Foley et al., 2005; López-Moreno et al., 2011), or changes in soil properties (Bormann et al., 2007). The magnitude and timing of flows, or even the physical–chemical properties of water, can directly reflect such changes in the environment. Mountains and the process of snow accumulation-melting are hotspots for climate change impacts (Beniston, 2003), due to the high sensitivity of the snow cover to seasonal temperatures, especially in low-to-middle elevation sites (Morán-Tejeda et al., 2013b). Increasing temperatures affect the consolidation of the snowpack in a double manner. Regardless of the precipitation regime, in warm winters the amount of snowfall is reduced as the zero degree isotherm is reached less often, thus there is less accumulation of snow. On the other hand, increasing temperatures in spring will anticipate the melting onset, thus reducing the duration of the snowpack. Reduced snow accumulation and the shortening of the snowpack season have been reported in the main mountain chains at mid latitudes during the last decades, coinciding with the recent global warming (Marty, 2008; McCabe and Wolock, 2009; Beniston, 2012). The consequences of reduced snow accumulation in mountains are broad, including alteration of mountain ecosystems, economic

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* Corresponding author at: Pyrenean Institute of Ecology-CSIC, Zaragoza, Spain. Tel.: +34 976369393x880033.

E-mail address: enriquemoran@gmail.com (E. Morán-Tejeda).

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losses in winter-tourism areas, or changes in the hydrological rhythm of mountainous rivers (Barnett et al., 2005; Mellander et al., 2007; Uhlmann et al., 2009).

The hydrological consequences of climate warming and reduced snowpack have been broadly studied in the mountains of North America (Hodgkins et al., 2003; Stewart et al., 2005; Hamlet and Lettenmaier, 2007; Kalra et al., 2008) thanks to the extensive monitoring systems on climate variables, snow, and river discharges existing since the beginning or middle of the 20th century. The observations conclude that during the last five decades spring flows resulting from snowmelt are occurring earlier in the season, runoff in the cold season is increasing and consequently runoff in the warm season is decreasing. In European mountains, research has been more scattered spatially, but different studies at smaller scales reached similar conclusions for the Alps (Birsan et al., 2005), and the Pyrenees (López-Moreno and García-Ruiz, 2004). Thanks to modeling, Adam et al. (2009) were able to identify the most vulnerable areas in the world in terms of changes on streamflow timing due to increasing temperature.

The headwaters of the main Spanish rivers are located in mountainous territories where late-autumn and winter precipitation falls in the form of snow leading to the formation of a sustained snowpack. In a country historically bound to water scarcity such as Spain, mountain rivers constitute a key element for water and risk management (García-Ruiz et al., 2011). Evidence of this is the large number of reservoirs located in the headwaters of rivers (Batalla et al., 2004; Lopez-Moreno et al., 2009; Morán-Tejeda et al., 2012b), or the water transfers between watersheds that exist or are planned in the Spanish territory. The management patterns of these hydraulic infrastructures are strongly dependent on the seasonal pulses of streamflow, as spring peakflows normally occur at the start of the irrigation season. They are, however, subject to be changed if any shift in the streamflow timing is to occur (López-Moreno et al., 2004).

In this work we analyze the changes in the timing of mountain river flows in the Iberian Peninsula in the context of global warming impacts on snow and water resources. For an observational period (1976–2008) we calculated several hydrological indices that allow locating the timing of spring flows within the annual hydrologic regime, and analyzed their trends and changes in time on a set of rivers characterized by presenting spring high flows from snow melt. Trends in seasonal temperatures and precipitation were also calculated and considered as possible co-variables for explaining changes in river flows. Moreover we project future changes in flow regimes under climate change scenarios by modeling two catchments with SWAT hydrological model. This enabled quantifying the role of snowpack decline on the projected changes, and predicting spatial differences due to geographic factors.

2. Data and methods

2.1. Streamflow and temperature data

Daily streamflow data was collected from the national water agency of Spain, Centro de Estudios Hidrográficos (CEDEX, <http://hercules.cedex.es/anuarioaforos/default.asp>). To make sure that snowmelt pulses were present in all river regimes, we selected only rivers located in the foothills of mountain systems whose drainage watersheds had a mean elevation exceeding 800 m.a.s.l., and had no presence of reservoirs or impoundment systems upstream of the gauge station. A tradeoff between the maximum number of streamflow series, and the longest period possible was necessary,

Table 1
Studied rivers and geographic characteristics. PC: principal component; Change on time (days per decade according to Thiel–Sen's slope estimator) is shown for every studied index. D50 M, D75 M and D90 M indicate the day of the hydrological year when the 50th, 75th, and 90th percentiles of the annual streamflow are recorded; DSM indicates the day when the maximum flow in spring is recorded; and SPD indicates the day of onset of the spring pulse.

Station id	River name	PC	Elevation (m.a.s.l)	Thiel–Sen's slope estimator				
				D50 M	D75 M	D90 M	DSM	SPD[b]
1295	Sella	PC1	1004.9	−0.55	−0.55[a]	−0.63[a]	−0.91[a]	–
1335	Nalón		1076.8	−0.55	−0.86[a]	−0.97[a]	−0.79	–
1365	Aller		1088.3	0.03	−0.70[a]	−0.84[a]	−1.06[a]	–
2006	Tormes		1462.4	−0.13	−0.24	−0.20	0.11	–
2034	Besande		1567.1	−0.33	−0.64[a]	−0.99[a]	−0.14	–
2068	Curueño		1521.3	0.32	−0.42	0.21	−0.21	–
2101	Duero		1429.6	0.04	0.31	1.56[a]	−0.26	–
3226	G.St. María		1323.7	−0.78[a]	−0.45	0.27	0.02	–
3229	G. Cuartos		1270.1	−2.06[a]	−2.00[a]	−0.29	0.0	–
9063	Esca		1071.8	0.52	−0.52	−0.35	−0.41	–
9064	Salazar		958.3	0.6	−0.51	−0.35	−0.76[a]	–
9066	Irati		1081.2	−0.21	−0.36	0.42	−1.33[a]	–
9170	Aragón		1076.2	−0.11	−0.60[a]	−0.54[a]	−0.65	–
2009	Riaza	PC2	1628.1	−0.65	−0.63[a]	−0.79[a]	−0.21	–
2012	Duratón		1126.1	−0.22	0.29	1.30[a]	−0.21	–
2016	Cega		1280.8	0.50	0.0	3.03[a]	−0.66	–
2051	Moros		1592.3	0.23	−0.37	−0.58	−0.25	–
2057	Pirón		1179.5	0.15	0.20	0.09	0.39	–
9043	Linares		1305.3	−0.43	−0.78	−0.20	−0.51	–
9044	Cidacos		1334.6	−0.67	−1.14[a]	−1.00[a]	−0.56	–
9050	Tirón		830	−0.68	−0.4	−0.35	−0.81	–
9093	Oca		843.5	−0.11	−0.39	−0.18	−0.98	–
9158	Tirón		1246.8	−0.42	−0.21	−0.14	0.0	–
5086	Dilar	PC3	2011.4	−0.18	−0.14	−2.96[a]	−0.33	−0.31
9013	Esera		1525.2	−0.51	−0.60[a]	−0.21	−1.63[a]	−0.77[a]
9018	Aragón		1570.1	−0.16	−0.67[a]	−0.50	−1.14[a]	−0.27
9040	Ara		1497.9	0.16	−0.62[a]	−0.67	−1.00[a]	−0.54
Average				−0.23	−0.47	−0.22	−0.49	−0.47
Standard deviation				0.52	0.45	1.01	0.43	0.20

[a] Indicates two-sided p-value < 0.05.

[b] SPD was one only calculated for rivers of PC3