Science of the Total Environment 503–504 (2015) 222–232

Contents lists available at ScienceDirect

Science of the Total Environment

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

Observed shift towards earlier spring discharge in the main Alpine rivers

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HIGHLIGHTS

- A comparison of long-term spring discharge timings over the Alps
- The largest rivers show similar trends and features of decadal variability.
- Analysis of precipitation, and snow-melting data derived from observations
- Snowmelt timing explains a portion of the discharge's decadal variability.
- Change of precipitation seasonality causes earlier spring discharge.

ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form 29 May 2014
Accepted 10 June 2014
Available online 5 July 2014

Editor: J.P. Bennett

Keywords:
Mountain hydrology
Spring
Snowmelt
River discharge
Precipitation seasonality
Water management

ABSTRACT

In this study, we analyse the observed long-term discharge time-series of the Rhine, the Danube, the Rhone and the Po rivers. These rivers are characterised by different seasonal cycles reflecting the diverse climates and morphologies of the Alpine basins. However, despite the intensive and varied water management adopted in the four basins, we found common features in the trend and low-frequency variability of the spring discharge timings. All the discharge time-series display a tendency towards earlier spring peaks of more than two weeks per century. These results can be explained in terms of snowmelt, total precipitation (i.e. the sum of snowfall and rainfall) and rainfall variability. The relative importance of these factors might be different in each basin. However, we show that the change of seasonality of total precipitation plays a major role in the earlier spring runoff over most of the Alps.

1. Introduction

The Alps are often called the "water towers of Europe" due to the large quantity of water that passes through e.g. the Danube, the Rhine, the Po and the Rhone. In this paper we focus on the timing of the spring discharge, which can affect water quality and management (Hänggi and Weingartner, 2011; Gunawardhana and Kazama, 2012; Vanham, 2012), flood risk (Eckhardt and Ulbrich, 2003; Wetter et al., 2011; Bard et al., 2012; Dobler et al., 2012), river navigation and water availability (Middelkoop et al., 2001), tourism (Elsasser et Burki, 2002; Beniston et al., 2011), energy production (Hänggi, 2012), insurance (Beniston, 2012) and natural ecosystems (Keller et al., 2005).

Changes in the timing of spring discharges in mountain regions were first investigated in the U.S. In the Western U.S., the shift towards an earlier spring discharge was attributed to an earlier snowmelt caused by the warming trend observed in that region (Aguado et al., 1992; Dettinger and Cayan, 1995; Cayan et al., 2001; Pederson et al., 2011). The earlier snowmelt was consistent with the observed trend in the reduced spring snowpack (Mote, 2003; Howat and Tulaczyk, 2005). The earlier spring discharge was also affected by the increased ratio of liquid to solid precipitation (Moore et al., 2007) and could be used as a proxy for snowmelt timing in many undisturbed basins (Kuntel and Pierce, 2010). However, human modifications of the river basins, such as damming, irrigation and urbanisation, can often play a part in determining the discharge timings (Arrigoni et al., 2010).

Abbreviations: RHI-BASL, Rhine River in Basel; DAN-BRAT, Danube River in Bratislava; RHO-BEAU, Rhone River in Beaucaire; PO-PLSC, Po River in Pontelagoscuro; GRDC, Global Runoff Data Center; HISTALP, historical instrumental climatological surface time series of the Greater Alpine Region; CRU, Climate Research Unit data; GRanD, Global Reservoir and Dam database; DJF, winter (December, January and February); MAM, spring (March, April and June); MAM-DJF, spring minus winter.

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http://dx.doi.org/10.1016/j.scitotenv.2014.06.036
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A trend in earlier spring discharge timing was observed in the North-Eastern U.S. as well (Hodgkins et al., 2003), in conjunction with a larger proportion of liquid to solid precipitation (Huntington et al., 2004; Knowles et al., 2006). This was also shown to be true for the U.S. as a whole (McCabe and Clark, 2005; Clow, 2010). Through modelling studies, the increase of rainfall over snowfall and the earlier snowmelt in the U.S. has been attributed to global warming (Hidalgo et al., 2009) and this trend is projected to continue in the future (Stewart et al., 2004; Rauscher et al., 2008).

Similar results are found for other mountainous and snowy regions in the world, such as Canada (Woo and Thorne, 2006) and the Nordic countries (Krasovskaia and Gottschalk, 2002; Kriauciuniene, 2012), the Spanish Pyrenees (Lopez-Moreno and Garcia-Ruiz, 2004), the Himalayas (Bookhagen and Burbank, 2010), the Japanese Alps (Yamanaka, 2012) and other key mountain regions (Stewart, 2009). This will have significant consequences for future water availability for a substantial portion of the global population (Arora and Boer, 2001; Barnett et al., 2005).

Regarding the Alpine rivers, severe winter droughts in the Upper Rhine basin and the associated low river waters were relatively rare in the 20th century compared to the last few hundred years (Pfister et al., 2006). This is consistent with the recent increase in the ratio of the winter over the summer discharge of the Rhine river (Hänggi and Weingartner, 2011). Many natural streams in the Alps, especially over the Northern flank, display a similar tendency towards a larger winter flow (Birsan et al., 2005; Stahl et al., 2010; Bard et al., 2012). This is compatible with the earlier spring snowmelt and the larger liquid to solid precipitation ratio observed from the 1980s, mainly at altitudes below 1500–2000 m (Beniston, 1997; Beniston et al., 2002; Laternser and Schneebeli, 2003; Vincent et al., 2007). Long-term analysis for the Po River discharge also suggests an increase of the winter over the summer discharge ratio (Zanchettin et al., 2008). However, none of these observation-based studies explicitly focused on the timing of the spring discharge, with the exception of Bard et al. (2012), who performed the analysis over the last 40 years.

Modelling studies predict a larger winter to summer Rhine discharge ratio related to the earlier snowmelt during the 21st Century in climate change scenarios of increasing greenhouse gases (Middelkoop et al., 2001; Beniston et al., 2003; Linde et al., 2010). Similar results are found for the Rhone (Beniston et al., 2011; Beniston, 2012), and in general for most Alpine rivers (Jasper et al., 2004; Zierl and Bugmann, 2005; Horton et al., 2006; Gunawardhana and Kazama, 2012).

In this study, we present an integrated long-term analysis of the discharge timings for the main Alpine rivers: the Rhine, the Danube, the Rhone and the Po. As in the previously cited studies, we investigate the influence of climate variability on the river discharge timings. In particular, we analyse the effects of precipitation seasonality, of its liquid portion (i.e. rainfall) and of snowmelt timing. We take advantage of a high-resolution gridded dataset of homogenised temperature and total precipitation time-series covering the Alps for the last 2 centuries, and we advance the understanding of the climatic factors that influence spring discharge timing, in terms of the earlier long-term trend and the low-frequency (decadal) variability.

2. Data and methods

2.1. River data

River discharge monthly time-series have been obtained by combining data from different sources, mainly from the Global Runoff Data Center (GRDC, http://www.bafg.de) and from local regional authorities. The measurement sites were selected for the length of the period covered by the observations and their proximity to the Alps.

Fig. 1 shows the geographical distribution of the four discharge measurement sites and the contributing river basins, covering most of the Alps. From north to south and from west to east, they consist of the Rhine River in Basel (RHI-BASL, from 1869 to 2010), the Danube River in Bratislava (DAN-BRAT, from 1901 to 2007), the Rhone River in Beaucaire (RHO-BEAU, from 1921 to 2008), and the Po River in Pontelagoscuro (PO-PLSC, from 1831 to 2012). These datasets allowed us to distinguish between the long-term trend potentially linked to climate change and the effects associated with natural climate oscillations, which can determine the features of decadal variability, especially on the regional scale (Zampieri et al., 2013).

2.2. Climate data

In order to analyse the sensitivity of spring river discharge on climate trend and variability, we used gridded datasets of monthly homogenised surface observations from the HISTALP project. The data were made available at 10′ resolution from 1801 to 2003 for precipitation, and from 1780 to 2008 for temperature (Efthymiadis et al., 2006; Auer et al., 2007; Brunetti et al., 2009) in the Alpine region (4–19E, 43–49N). These data include all basins in full, with the exception of the Danube, where a small area located in the north of the region is not covered. We also downloaded and analysed a reconstruction of solid precipitation (i.e. snowfall). This reconstruction was produced by applying a statistical technique on the HISTALP temperature and total precipitation using snowfall data taken from direct observations in Austria, on the north-eastern side of the Alps (Chimani et al., 2011). This snowfall data was validated by Zampieri et al. (2013) in other regions of the Alps as well. Finally, we computed the snowmelt, replicating the procedure of van der Schrier et al. (2007), which parameterised snowmelt using a minimalistic model based on the amount of accumulated snow and on the mean monthly temperature.

To strengthen our results on the precipitation timings, we integrated the analysis of total precipitation using the global gridded observations from the Climate Research Unit (CRU) TS 3.10.01 dataset for the period 1901–2009. This was available at a resolution of 0.5 by 0.5° (Mitchell and Jones, 2005). As an independent dataset, we adopted the corresponding product from the 20th Century Reanalysis Version 2, available from 1871 to present, at 2° spatial resolution (Compo et al., 2011). The results obtained with these datasets were compared to those of HISTALP during the overlapping period.

2.3. Determination of discharge, precipitation and snowmelt peak timings

In order to obtain a fine-scale estimate of the peak timings from the monthly discharge values, we fitted each annual cycle with analytical parametric functions as in Eq. (1).

$$D(y,m) = a(y)e\left(\frac{m-m_1(y)}{b_1(y)}\right)^2 + d(y). \tag{1}$$

Eq. (1) represents our model for the discharge seasonal cycle $D(m,y)$, where y represents the year and m the time of the year expressed in months. In Eq. (1) the a_1 parameter represents the amplitude of the peak, m_1 represents the timing of the peak (not necessarily an integer), b_y is the spread of the discharge over time and d the minimum flow value. We chose a Gaussian function because it resembles the seasonal cycles of the Rhine and Danube River discharges, characterised by one summer peak. For the Po River, where there are peaks in both spring and autumn, we used a bigaussian function (i.e. a linear superposition of two Gaussians), as represented by Eq. (2).

$$D(y,m) = a_1(y)e\left(\frac{m-m_1(y)}{b_1(y)}\right)^2 + a_2(y)e\left(\frac{m-m_2(y)}{b_2(y)}\right)^2 + d(y). \tag{2}$$

In Eq. (2), the second Gaussian is defined by a_2, m_2 and b_2, equivalent to the parameters in Eq (1). For the Rhone discharge, which does not have a winter minimum, we also used a bigaussian function, but with