Journal of Hydrology 529 (2015) 1890–1900

Contents lists available at ScienceDirect

Journal of Hydrology

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

Multidecadal changes in the river ice regime of the lower course of the River Drava since AD 1875

Katalin Takács [a,*], Zoltán Kern [b]

[a] Institute for Soil Sciences and Agricultural Chemistry, Centre of Agricultural Research, Hungarian Academy of Sciences, Herman Ottó út 15, H-1022 Budapest, Hungary
[b] Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budaörsi út 45, H-1112 Budapest, Hungary

ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form 30 October 2014
Accepted 17 January 2015
Available online 28 January 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of David M. Meko, Associate Editor

Keywords:
River ice
Freeze-up dates
Break-up dates
Winter temperature proxy
Anthropogenic effects

SUMMARY

River ice is principally controlled by atmospheric conditions, especially temperature, so these records provide useful information on the climate in general. A more than 130-year-time-series of ice-on and ice-off, and freeze-up and break-up dates was analysed from 4 selected hydrological stations along the lower course of the River Drava since the beginning of river ice observations the start- and end-dates of ice phenomena on Drava River have displayed a significant trend. Freeze-up dates have shifted to ~9 days later, and break-up dates to ~10 days earlier. A similar trend is present in the dates of ice-on and ice-off; these dates have shifted to ~23 days later and ~17 days earlier per 100 years on average. These changes have resulted in a pronounced reduction in the ice-covered and ice-affected seasons, too. The duration of ice-cover has decreased by ~14 days and the total number of ice-affected days has decreased by ~31 days over a century on average on the lower course of the Drava. Interannual variability was compared to local and regional instrumental temperature records. The strongest correlation was found between ice-off and January–February mean temperatures ($r = 0.81$, $p < 0.05$), and between the total number of icy days and the mean winter temperature ($r = 0.88$, $p < 0.05$). Statistical evidence indicated, however, that the subdued climate control from the 1970s is probably due to anthropogenic intervention in the upper course (e.g. reservoir construction, hydropower management). Spatial correlation analysis revealed that the temperature signal carried by the river ice records of the Drava prior to the anthropogenic disturbance seems to be a powerful proxy for the winter temperature of Central Europe.

1. Introduction

Freshwater ice is a major component of the terrestrial cryosphere (Brooks et al., 2013). Drift-ice or ice-cover can develop on rivers at higher latitudes in winter where temperatures fall below 0 °C (Weyhenmeyer et al., 2011). Seasonal ice cover can develop as far south as 33°N in North America and 26°N in Eurasia, producing effects on 7 of the world's 15 largest rivers (Prowse et al., 2007a). Although river ice is characterized by an excessive seasonal variability compared to the other components of the cryosphere, it has a broad ecological and economic significance (Prowse et al., 2006, 2007a). River ice dynamics, for instance, influence riparian and aquatic vegetation (Lind et al., 2014). The great potential of historical records of ice phenology from freshwater (e.g. break-up date), as useful indicators of past climatic variations, has been emphasized for more than 40 years (Williams, 1970).

Research has many times detected significant changes in the river ice regime in the Northern Hemisphere over the past decades/centuries. The historical records of freeze-up dates and break-up dates show significant trends. Freeze-up dates have shifted to 2–25 days later and break-up dates to 2–24 earlier per century (Magnuson et al., 2000; Smith, 2000; Punsalmaa et al., 2004; Hodgkins et al., 2005; Agafanova and Frolova, 2007; Prowse et al., 2007b; Jiang et al., 2008). As a result of changes in the dates of ice phenomena the ice-affected season has also decreased, on average by 2–38 days per century according to observations in the Northern Hemisphere (Rannie, 1983; Jiang et al., 2008; Klavins et al., 2009; Hodgkins et al., 2005; Punsalmaa et al., 2004).

The characteristic features of river ice regime are closely linked to temperature conditions; in parallel with a warming climate, ice phenomena become less frequent (Jiang et al., 2008). Moreover, there are geographical differences in the response of river ice regimes to temperature changes (Weyhenmeyer et al., 2011; Walsch et al., 1998). The catchment area of the Drava is located in a geographical region where the ice dynamics of freshwater

* Corresponding author.
E-mail addresses: takacs.katalin@rissac.hu (K. Takács), zoltan.kern@gmail.com (Z. Kern).

http://dx.doi.org/10.1016/j.jhydrol.2015.01.040
0022-1694/

systems are thought to be sensitive to temperature changes, based on global observations. Furthermore, the interannual variability of the ice phenomena on the Drava is high, which also increases the sensitivity of the river ice regime in response to temperature changes (Weyhenmeyer et al., 2011). A dozen studies have analysed the ice regime of rivers located at higher latitudes in the Northern Hemisphere; however, long ice phenology records at lower latitudes are rather scarce.

Nevertheless, many non-climatic factors are also capable of influencing the occurrence of different river ice phenomena, including bed morphology, or human activity (Starosolszky, 1990; Agafonova and Frolova, 2006; Beltaos and Prowse, 2009; Takács et al., 2013). These should be carefully studied before ice regime changes are linked to climate changes. Anthropogenic impacts could exaggerate or hide natural trends in the river ice regime if they operate either in the same or opposite direction as the natural forces.

The aims of this study are to:

1. Analyse changes and trends in river ice regime on the lower course of the River Drava.
2. Discover the relationship between the river ice regime and winter air temperature in order to analyse the response of freshwater ice to climatic variability.
3. Test the impacts of anthropogenic intervention on the river ice regime.
4. Compare the results on a global scale.

2. Materials and methods

2.1. The study area

The source of the River Drava is in South Tyrol (Italy), and it joins the Danube in Croatia. On its lower course it serves as the border between Hungary and Croatia for about 160 km (Fig. 1). Its length (730 km) and catchment area (41,238 km^2) (Bonacci and Oskoruš, 2011) make it the fourth largest and longest tributary of the Danube.

The catchment of the Drava is subject to Atlantic, continental and Mediterranean climatic influences. On the lower course of the river, the continental effect is dominant, so the winters are cold; the mean temperature in January is below 0 °C. The river is located in the climatic area where river ice phenomena can occur in winter (Mantuano, 1974).

Originally the Drava was meandering and anabranching in the studied section. In the present day, the river bed has been partially altered by river regulation and damming. The flood protection system was established in the 18–19th centuries. As a result, the length of the river was shortened by 182 km; between 1784 and 1848 the river bed of the Drava was cut off in 62 places (Remenyik, 2005). By the beginning of the 20th century the main parts of the flood-protection system downstream of Barcs had been completed, and since then just minor local interventions have been carried out: revetments, groins, and the cutting off of 3 meanders. So, downstream of Barcs the Drava is regulated, but upstream, due to the low number of regulation objects, it has remained unregulated, thus staying close to its natural state (Kiss and Andrási, 2014).

Upstream as far as Őrtilos the stream gradient is more than 71 cm/km and then it decreases to 25.3 cm/km. In contrast, upstream of Barcs, the stream gradient is 35.4 cm/km, while downstream it is just 15.9 cm/km. From Drávaszabolcs to the Danube River the stream gradient is only 1 cm/km (Lovász, 1961). The characteristic shape of the river bed also varies along the river, resulting in different hydromorphological conditions for river ice occurrence (Fig. 2).

In the course of the 20th century a few hydroelectric stations were built on the Drava River and in its catchment area. These interventions had a great influence on its water regime and morphology (Bonacci et al., 1992; Kiss et al., 2011; Kiss and Andrási, 2014). Three Croatian hydro power plants (HPP) (built in 1975, 1982, 1989) are those located closest to the study area, therefore

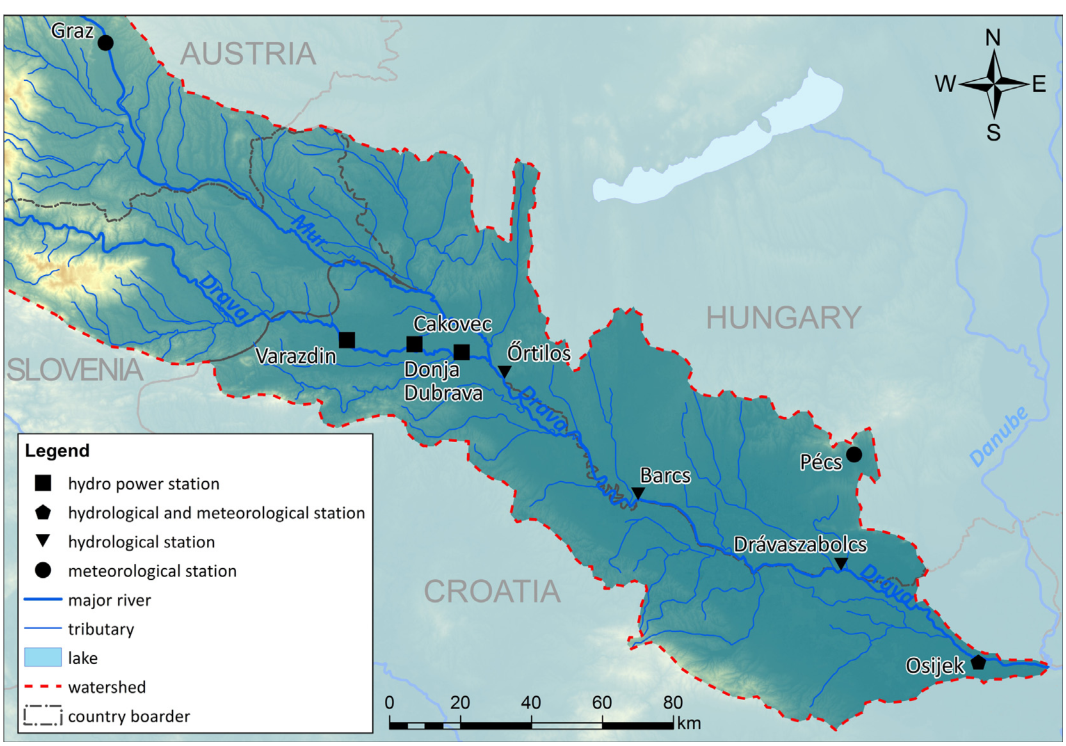

Fig. 1. The drainage basin and the location of the hydrological and meteorological stations studied on the lower course of the River Drava.