



# Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping

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## Abstract

The karst environment presents a special challenge when it comes to identifying groundwater/surface-water interactions. Existing definitions of areas of regular flooding in karst regions are too general and lack a measurable approach for the determination of flood-liable land. This paper proposes a means of specific definition and quantitative determination of intermittently flooded karst areas, which takes into account the extent, duration and frequency of flooding, and includes the identification of data sources and processing methods. The procedure, involving spatial layers, was developed using a pilot area and tested in three additional areas in Slovenia. The derived definition determines that flood-liable land within karst poljes and intermittent lakes comprise areas where stagnant water or stream overflow is present for at least 10 days/year over a period of 30 years, and these waters have direct contact with groundwater. The results show that the proposed procedure is applicable to areas with different geomorphological settings and to areas where the quantity and quality of available data vary. The study is an example of the practical application of knowledge on karst, as the findings can be used for short-term purposes (mapping flood areas, determination of habitats) and long-term purposes (study of impacts of environmental changes). Attention should be drawn to the lack of available data and the fact that the national networks of hydrological observatories are often too sparse for this purpose. This study raises awareness of these shortcomings and improves the planning or expansion of such a network in collaboration with experts.

**Keywords** Karst · Groundwater/surface-water interaction · Intermittent lakes · Mapping procedure · Slovenia

## Introduction

Surface water flow is usually not present in karst areas because of the high porosity of the rock of which they are

composed. Water infiltrates rapidly and then flows through conduits and fissures underground (Hartmann et al. 2014). In special circumstances, such as areas of shallow karst and karst poljes, water overflows onto the surface and extensive groundwater/surface-water interaction occurs (Kovačič and Ravbar 2010; Naughton et al. 2012; Gutiérrez et al. 2014).

Flooding follows periods of intense or long-lasting precipitation and as a result of groundwater-level rise in a karst aquifer. Such aquifers are normally characterised by high spatial heterogeneity, highly diffusive flow and a low level of water storage. Water also floods the ground surface when the inflow of water exceeds the capacity of underground drainage channels. Along surface watercourses, this causes a backflooding effect and overflow along the length of stream channels. One particular characteristic of the described phenomena is the high variability of occurrence and duration, and for this reason such areas are known as ‘intermittent lakes’ (Kovačič and Habič 2005; Ford and Williams 2007; Bonacci 2013). Numerous karst poljes in the Dinaric Karst of Europe are known for causing the intermittent presence of surface water. The least hydrotechnically modified among them are

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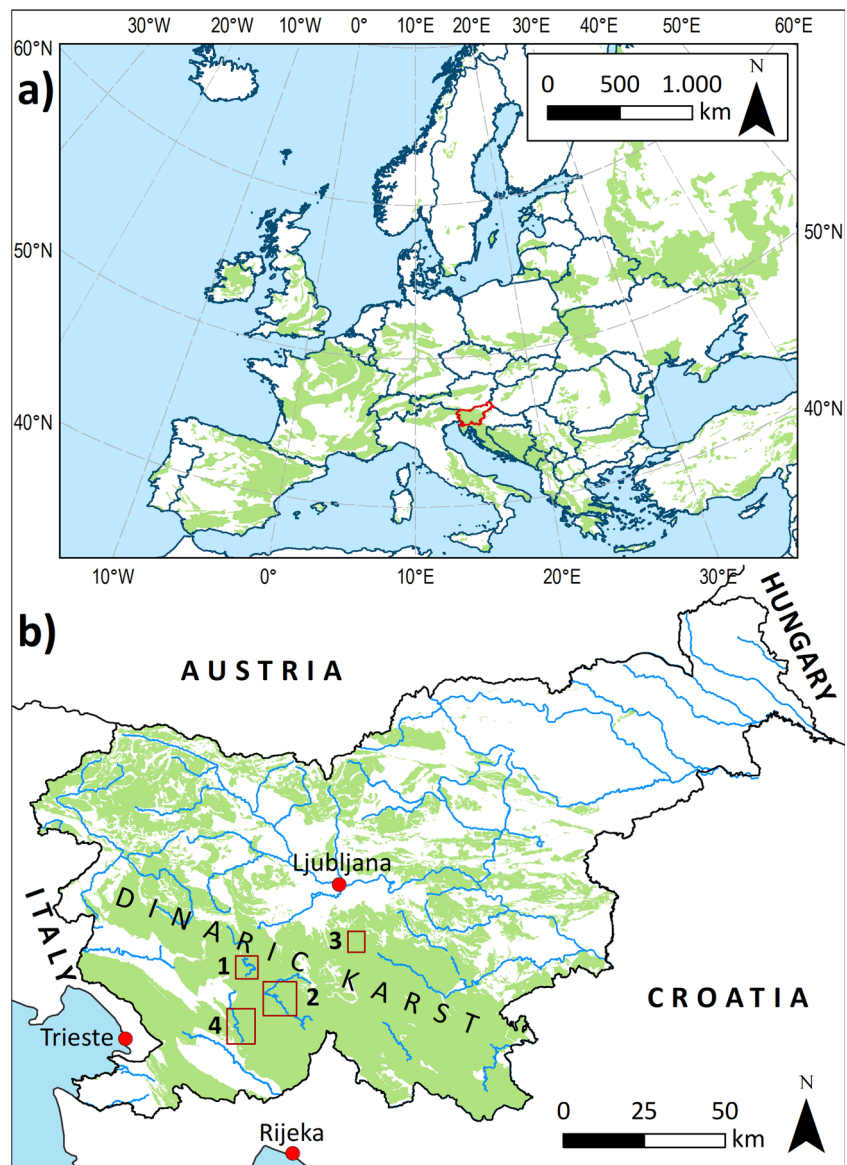
the poljes of the Classical Karst in Slovenia (area between Ljubljana and the port cities of Trieste and Rijeka; for location see Fig. 1). Intermittent lakes in karst areas are also characteristic of Ireland, where they are known as “turloughs”, and they also occur in Spain, Italy, Estonia, Canada, the states of Tennessee and Kentucky in the USA, the provinces of Guangxi, Guizhou and Yunnan in China, Minas Gerais state in Brazil, and elsewhere (Auler 1995; López-Chicano et al. 2002; Milanović 2004; Sheehy Skeffington et al. 2006; Zhou 2007; Simpson and Florea 2009; Naughton et al. 2012; Parise 2015).

As a result of periodic flooding and feeding by groundwater, wetland ecosystems have developed in these areas and represent unique habitats with a high level of biodiversity (Bonacci et al. 2009; Kløve et al. 2011; Pipan and Culver 2019; Côrtes Figueira et al. 2020). Furthermore, inundation

areas in karst poljes and intermittent lakes are an important natural resource that provide numerous other ecosystem services such as carbon storage, floodwater storage potential, etc. At the same time, after extensive material damage to buildings and infrastructure in recent decades caused by high water levels in karst poljes such as in Slovenia in 2010 and 2014, and in Ireland in 2009 and 2015/16 (Naughton et al. 2017; Jelovčan 2019; Mayaud et al. 2019), flooding in karst areas has attracted wider attention and is classified among the most frequent natural disasters in these areas (Gutiérrez et al. 2014; Parise 2015).

Since many inundation areas in karst poljes and intermittent lakes represent a unique and precious type of karst groundwater dependent ecosystem (GDE), some international treaties such as the Ramsar Convention on Wetlands and regional legislative framework such as the EU Water

**Fig. 1** Karst areas (shown in green) in **a** Europe and **b** Slovenia, and location of areas included in the study: 1 Planinsko Polje, 2 Cerkniško Polje, 3 Radensko Polje, 4 Upper Pivka and Pivka intermittent lakes (Data source: Gostinčar 2016; Chen et al. 2017)



Framework Directive (2000, 2000/60/EC) and Habitats Directive (1992, 92/43/EEC) require the maintenance of water quantity and quality. On the other hand, floods can represent a major risk to human health, the environment and economic activity. The increase in the level of damage caused is to a large extent connected to inadequate land-use planning. For this reason, the EU Floods Directive (2007, Directive 2007/60/EC), for example, envisages the reduction and management of risk through the preparation of maps of the probable spread of floods and the design of flood risk management plans. A precondition for the implementation of such measures is an exact demarcation of areas of regular flooding, the flood-labile land or so-called water land (a term meaning inland areas permanently or periodically covered by water), which in Slovenia has a basis in the Water Act (2002, UL RS 67/02). Determining and mapping these areas in this way also has practical consequences for the landowners, which is reflected in compensatory financial measures. An accurate definition of land that is regularly covered by water is therefore extremely important.

The heterogeneity and anisotropy of hydrologically active conduits and fissures in the karst underground cause special scientific and practical challenges in relation to the determination of the mechanisms of groundwater level fluctuation, which can reach several hundred metres (Gabrovšek et al. 2018). The identification of ephemerally flooded areas in karst poljes and intermittent lakes requires, in the first place, good knowledge and understanding of hydrological connections and groundwater/surface-water interactions. Better understanding and monitoring of the dynamics, spatial dimension, duration and frequency of high water levels is therefore necessary.

Despite the fact that karst areas account for a significant percentage of the land surface worldwide (globally about 15% and more than a fifth in Europe alone; Chen et al. 2017; Goldscheider et al. 2020), basic research and the practical application of the results for the purpose of addressing these problems is inadequate even in developed countries. Current knowledge of groundwater/surface-water interactions is mainly based on qualitative descriptions (Naughton et al. 2012), while quantitative data or even continuous water level monitoring are spatially and temporally sporadic or limited to extreme events (e.g., Kovačič 2005; Kovačič and Habič 2005; Sheehy Skeffington and Gormally 2007). A review of the literature has shown that existing definitions of karst poljes and intermittent lakes are inadequate for the needs of flood-labile land identification. They focus, above all, on geomorphological descriptions, while the quantitative emphases of extent, frequency of occurrence and duration of water cover are somewhat loose (Gams 1978; Ford and Williams 2007; Sheehy Skeffington and Scott 2008; Bonacci 2013; Sackl et al. 2014).

The purpose of this study is to fill these gaps by (1) formulating a draft definition of karst areas that are frequently subject to flooding; and (2) specifying sources for data collection, as well as qualitative and quantitative methods for using such data, in order to define the water level reference values specific to each field area. The study focuses on Slovenia, a country that is home to some of the best-preserved karst poljes in the world that at the same time are considered as *locus typicus*.

## Pilot study area and proposal for flood areas determination

For the purposes of flood-labile land identification in karst areas, a proposal was drafted on the basis of a pilot study in Planinsko Polje, for the definition, collection and processing of the data obtained. An approach was established for the spatial definition and delineation of flood areas, taking into account the criteria set. The proposal was then tested in three additional areas with varying geomorphology and degrees of available data: Cerknjsko Polje, Radensko Polje, and the Upper Pivka and Pivka intermittent lakes (Fig. 1). Work consisted of a review of the literature, and analysis of topographic and hydrological data, and was also partly based on the authors' own database of field measurements and knowledge of the areas concerned. The key criterion for determining and recording areas that are frequently subject to flooding is the analysis of hydrological conditions.

### Planinsko Polje

Planinsko Polje was selected as a pilot area for this study because it is considered a typical example of the formation and development of karst poljes due to its geomorphological features. A polje is a larger closed depression developed on karst rocks, has noticeably flat bottom and steep slopes. Its origin is often polygenetic, including corrasional lowering and also neotectonic activity. The hydrology of a polje may be characterised by sinking rivers (Gams 1978; Ford and Williams 2007).

At the same time Planinsko Polje is very well preserved in its natural state and its wider surroundings are considered to be an area of pioneering speleological and karstological research (Gams 2004; Shaw and Čuk 2015). Therefore, the pilot area is well studied and provides a large amount of historical and current data.

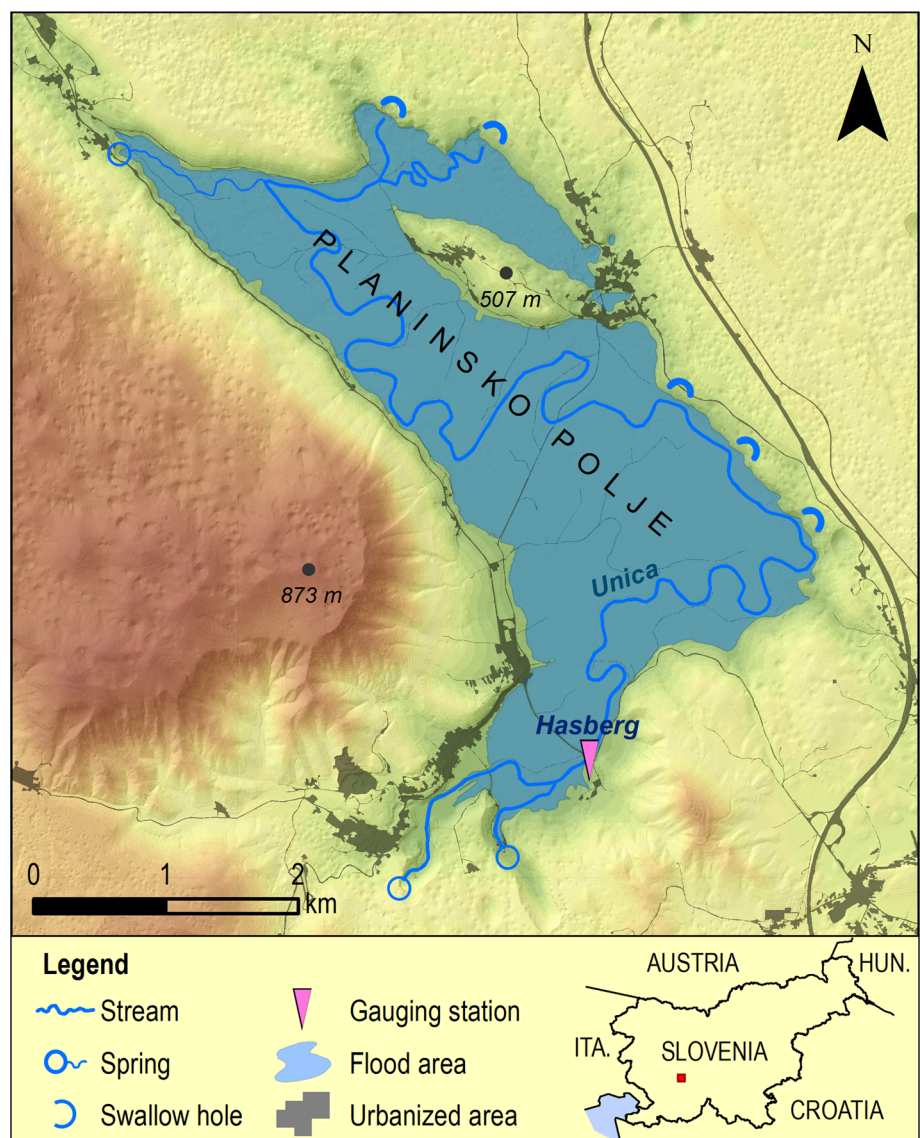
Planinsko Polje is a depression 5 km long and around 2.5 km wide, morphologically closed on all sides. The polje floor is flat with an area of more than 10 km<sup>2</sup> that mainly lies at an elevation of between 444 and 450 m above sea level (asl). A belt of less-permeable dolomite along the regionally strong active fault zone running along the polje forces water flowing from aquifers in the



south-west, west and north-west to rise to the surface. Its hydrology is completely linked to underground drainage, as there are no surface inflows or outflows. Two large karst springs and several smaller intermittent springs are located on the southern and western margins of the polje. The waters merge in a joint watercourse, the Unica, which crosses the polje and sinks underground on its eastern, northern and north-eastern edges (Fig. 2). For the purposes of flood prevention, detailed hydrogeological studies and hydrological monitoring have been established in this area since the late nineteenth century. A long series of detailed, high-quality hydrological data is therefore available for the area.

In Planinsko Polje, reliable and continuous hydrological data are available for the Hasberg gauging station on the Unica River from 1954 onwards (ARSO 2019a). Analysis of water level dynamics shows that the bottom of the polje is flooded several times a year. On average, the polje is flooded for 38 days/year (Ravbar et al. 2018), while the high water level at the Hasberg gauging station can rise by up to 8 m. The volume of water at extreme stages (water level of 453.2 m asl), which reach an extent of 10.37 km<sup>2</sup>, can exceed 80 million m<sup>3</sup> (Frantar and Ulaga 2015). High water levels are usually seasonal and tied to the period of peak precipitation in late autumn, winter rainfall and snowmelt. The inhabitants of the area

**Fig. 2** Geomorphological and hydrological characteristics of Planinsko Polje, location of gauging station and spatial extent of flood areas





have adapted to floods and moved their settlements to the higher-lying margins.

According to figures from older literature (Gams 1980), the average level of floods in Planinsko Polje is defined at 448.2 m asl. More recent analyses, however, show that in the period 1954–2014, areas lying at between 447 and 447.9 m asl were on average flooded for 27.5–10.8 days/year (Ravbar et al. 2018). Lately, Jelovčan (2019) reconstructed the daily water-level time series recorded at the Hasberg gauging station for the period 1841–1954 using archive data and determined the level of flooding for the period 1884–2016 at 447.3 m asl.

The information collected was used to check the frequency and duration of daily water levels of the Unica River at the Hasberg station for the period 1954–2018 (ARSO 2019a), with the help of a cumulative frequency curve. The results are summarized in Fig. 3 and Table 1: water levels above 448 m asl are exceeded by 2.87% of all daily stage values, which is on average 10.5 days/year. According to the number of flood events, the frequency and duration of water levels above 448 m are referred to as more sporadic and extraordinary, while below this limit it is considered that the area can be defined as regularly flooded.

For this reason and for the purposes of rounding up, it is proposed to take an average of at least 10 days/year as a temporal definition of flooding and to use this as a reference in order to define the length of flooding. It is further proposed to process data for a longer period, which, following the model of standard referential climatological and other hydrological studies, amounts to a minimum of 30-year time series (Fadhel et al. 2017; WMO 2020). In Planinsko Polje this criterion is met by an elevation of 448 m asl. The area of Planinsko Polje that reaches this elevation measures 9.38 km<sup>2</sup>.

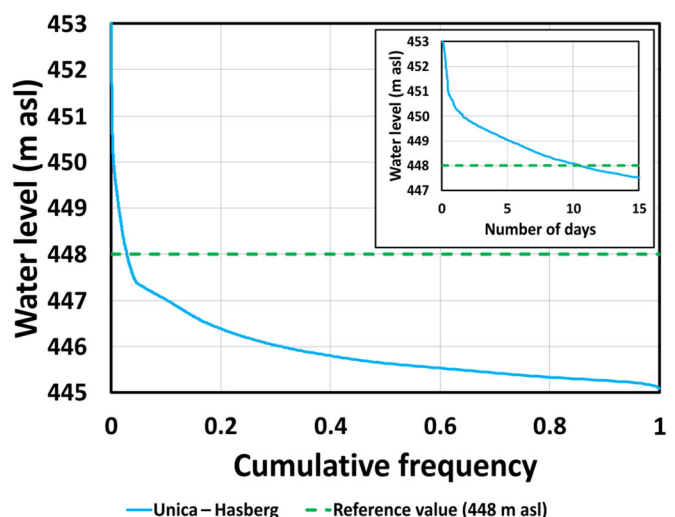
**Fig. 3** Cumulative frequency of daily water levels of the Unica River at the Hasberg gauging station for the period 1954–2018. The inset shows the initial part with frequencies converted in days (Data source: ARSO 2019a)

## Proposed definition, sources and criteria for data collection

As introduced earlier and discussed in the following, quite a large number of studies exist in the literature for intermittently flooded areas in karst regions. These occur in karst poljes, on the bottom of geomorphological depressions such as dolines, or on surfaces by sinking streams flowing from nonkarst areas. Owing to the excessive size of the topic, the last of these are not included in this study.

The literature is dominated by descriptions of the flooding of karst poljes or so-called intermittent lakes, although in most cases these are geomorphological descriptions (e.g., Gams 1978; Kranjc 1986; Auler 1995; Milanović 2004) and comparisons between different phenomena (Ravbar and Šebela 2004; Sheehy Skeffington and Scott 2008; Gill et al. 2013). It should also be emphasised that it is not necessarily the case that flooding occurs in all poljes or that it only occurs in dolines in areas of shallow karst. It thus turns out that there is no uniform term for hydrological phenomena of this type. Another reason for this is the prevailing geomorphological approach to karst research in the past. Some more recent studies place a greater emphasis on hydro-ecological interactions (e.g., Kovačič and Habič 2005; Naughton et al. 2012; McCormack et al. 2014; Côrtes Figueira et al. 2020; Pipan and Culver 2019). These are, however, too general for the needs of the identification of flood-liable land. A precise definition of frequently flooded land requires quantitative definitions of the extent, frequency and duration of flooding.

On the basis of an extensive review of literature from Slovenia and other countries, and the quantitative limit values described in the previous section, the following proposed definition of intermittently flooded areas was formulated:



**Table 1** Average number of days and its share on an annual basis and number of flood events that a certain water level is exceeded in the period 1954–2018

Statistic	Water level exceeded			
	447.9 (m asl)	448.0 (m asl)	448.1 (m asl)	448.2 (m asl)
Average No. of days/year	11.2	10.5	9.9	9.1
Share of all values (%)	3	2.87	2.69	2.5
No. of flood events	40	37	35	35

“Flood areas within karst poljes and intermittent lakes comprise areas of karst where, as a result of special hydrogeological conditions, stagnant water or stream overflow is present for on average at least 10 days/year in a 30-year period and has direct contact with groundwater. Ecosystems with vegetation and fauna adapted to hydrophilic conditions usually develop in these areas.”

For the purposes of identification of flood-labile land in karst areas, in addition to hydrological data from gauging stations, data on water levels from literature and field observations are used, along with basic topographic maps. Images from cyclical aerial photography, laser scanning and satellite images of flood areas can also be helpful, as can any data layers of the water register and flood areas and information on the extent of habitat types (Data sources in Slovenia: Environmental Atlas 2020; eVode 2020; ZRSVN 2020).

For areas where flowing water is at least occasionally present and in which water gauging stations existed in the past or still exist, it is proposed to use the longest possible series of hydrological data. Where such data do not exist, it is necessary to rely on the other existing sources of information.

### Processing collected data and mapping

For the purposes of identification of flood-labile land in karst areas, the following 4-step procedure for processing collected data and mapping was developed in this study (Fig. 4):

1. Hydrological data are collected for the longest possible time series, ideally for at least 30 years, and the frequency and duration of individual water levels is determined. In this study the cumulative frequency method was used for water levels, which shows the frequency of occurrence of each value. On the basis of this information, the reference elevation to which the surface is flooded for at least 10 days/year is determined.

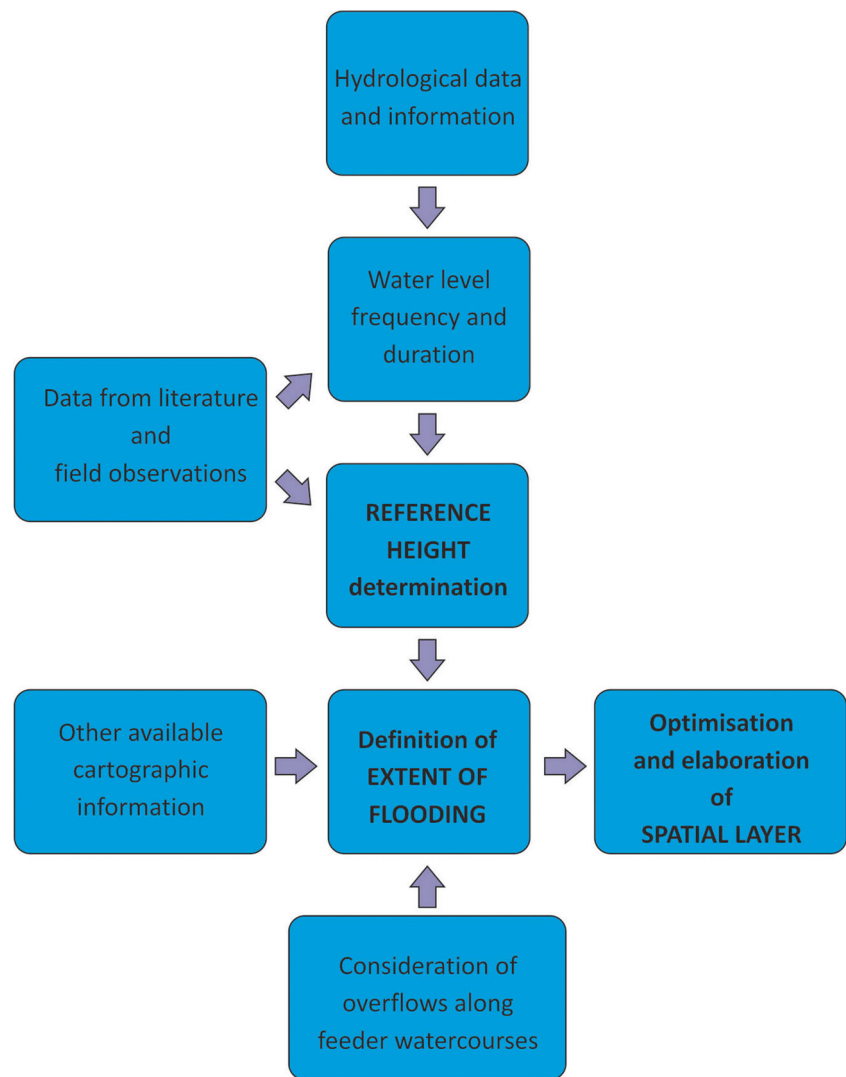
The data and software used and analysed in this study were as follows:

Water level data were collected from the hydrological database of the Slovenian Environment Agency ARSO (ARSO 2019a), as well as from the authors' own measurement network. This comprised four river gauging stations from ARSO (Unica River at Hasberg, Stržen River at Dolenje Jezero, Grosupeljščica River at Mlačevo, and

Pivka River at Prestranek) and two stations from the authors' own database (the lakes Palško Jezero at Matijeva Jama and Petelinjsko Jezero). The values were converted into elevation above sea level, with all reported changes of the starting measurement points taken into consideration. This included starting level correction for the stations Unica-Hasberg, Grosupeljščica-Mlačevo and Pivka-Prestranek (ARSO 2012, 2019c), while the stations of Stržen – Dolenje Jezero, Palško Jezero-Matijeva Jama and Petelinjsko Jezero had a constant starting measurement points over their respective monitoring periods. The data were analysed via cumulative frequency plots using the program MATLAB® (2018). Cumulative frequency plots show the frequency at which each individual level is under water on an annual basis. This helped assessment of the criterion for the definition of flood-labile land and allowed the selection of meaningful flood levels for each test site.

2. The results obtained are compared with water level data (mean stages, extreme stages) from literature and field observations and, in the case of deviation, the reference height is adapted to conditions identified in the field.
3. The extent of flooding is defined with regard to reference height and spatial layers are prepared. In this study, the latter were created on the basis of digital elevation models (DEMs) with resolutions of 1 and 12.5 m, created from raw LiDAR data (LAS format). The DEMs enabled the creation of layers of the contour lines corresponding to flood heights in an individual area. Where greater accuracy was necessary for the tracing of the area, a DEM with a resolution of 1 m was used. Elsewhere, DEMs with a resolution of 12.5 m were used.
4. The spatial layer obtained is optimised with regard to the data layers of other available cartographic information (e.g., aerial photographs, satellite and other images of the surface), where attention is paid in particular to overflows along principal watercourses and streams as a result of the backflooding effect (Fig. 5). In this study, the spatial data obtained were adapted in the light of the other available cartographic information on flood areas. Areas destined for other uses, e.g., roads that are built on a dyke and do not flood, were excluded. All cartographic work was carried out using ArcMap 10.3.1. software.

**Fig. 4** Flowchart presenting the processing of the collected data



Owing to the complexity of the occurrence, extent and duration of floodwaters in karst areas, which are extremely dependent on hydrometeorological and hydrogeological variables, each area must be dealt with individually, using a combination of various data sources. If quantitative hydrological data from any of the sources mentioned are not available, only qualitative sources of information are taken into account.

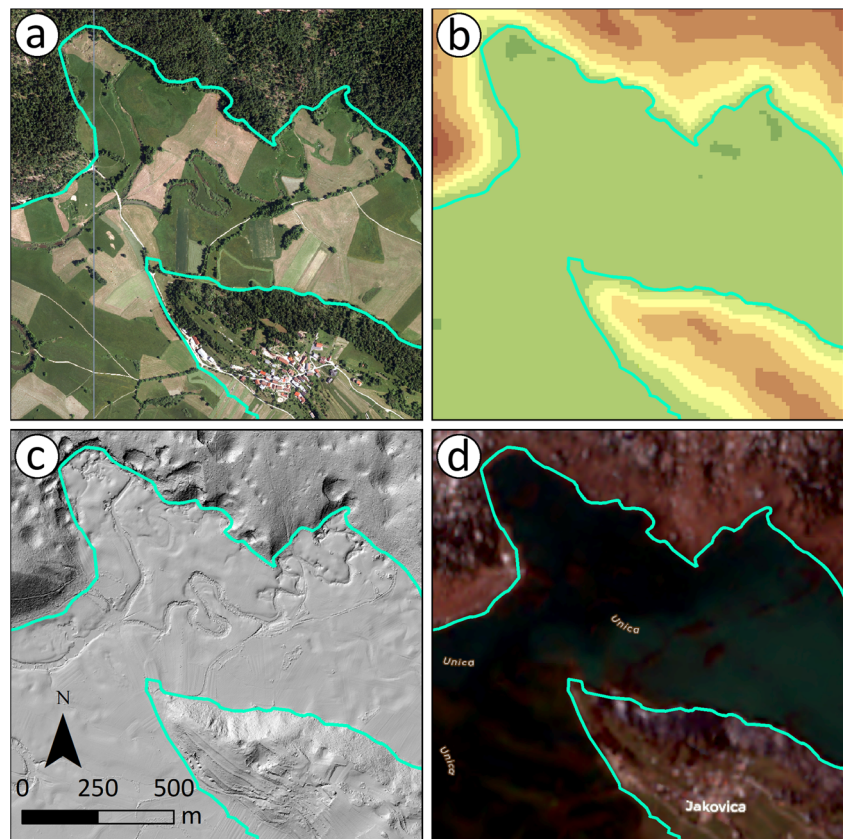
### Application in test areas: results and discussion

The process of work described in the preceding was tested in three areas with varying levels of available data and knowledge of floodwater occurrence: Cerknjsko Polje, Radensko Polje, and the Upper Pivka and Pivka intermittent lakes. The principal sources for the purposes of

identification of areas of this kind were basic studies of flood areas. These were carried out with greatest intensity in karst areas of Slovenia in the 1970s and 1980s (Jenko 1959; Lovrenčak 1971; Gams 1973; Habič 1974; Gospodarič and Habič 1976; Meze and Ilešič 1979; Gams 1980; Kranjc and Lovrenčak 1981; Kranjc 1981; Meze 1981; Meze 1983; Meze 1984; Kranjc 1986, and others), after which their number fell. These studies focused on the causes and frequency of floods, their extent and the damage they caused. More recent literature mostly deals with extreme floods in karst areas (Kovačič and Habič 2005; Kovačič and Ravbar 2010; Frantar and Ulaga 2015; Jelovčan 2019) or describes the causes of floods in karst poljes (Gabrovšek and Turk 2010; Kovačič 2010; Blatnik et al. 2019; Mayaud et al. 2019). Other important sources include the national network of hydrological observatories and accurate hydrological studies of the occurrence of floodwaters, aerial photographs, satellite images and other images of the surface.



**Fig. 5** Examples of the use of different data sources: **a** aerial photograph, **b** digital elevation model (DEM) with a resolution of 12.5 m, **c** shaded relief with a resolution of 1 m and **d** satellite image to capture flooded areas within Planinsko Polje



### Cerkniško Polje

With an area of 38 km<sup>2</sup>, Cerkniško Polje is the largest karst polje in the Classical Karst. It is 9 km long and between 4 and 5 km wide. Its bottom lies at an elevation of between 547 and 552 m asl (Fig. 6). Several streams flow onto the polje from the surrounding hills. Water drains underground through swallow holes on the bottom of the polje and through ponor caves on the western or north-western edge of the polje. When the polje's inflow is greater than the capacity of the swallow holes to drain the water, part of the polje floods and forms a lake (Kovačič 2010 and references therein).

Despite the fact that the basic topographic map 1:5000 (GURS 2020) gives a height of 549 m asl as the mean water level in Cerkniško Polje, Kranjc (1986) states that water reaches an elevation of 550 m almost every year. Below this elevation there are no cultivated fields and buildings on the ground surface. Flooding begins when water overflows the banks of the sinking streams that cross the polje and floods the lowest-lying parts of the polje bottom. Such a situation occurs when the water level at the Dolenje Jezero gauging station reaches 547.4 m asl (Kolbezen 1998; Kovačič and Ravbar 2010). Then the water level gradually increases to 550 m. Water levels above this height usually occur at least twice a year. The water level at 550 m floods approximately

20.3 km<sup>2</sup> or just under 53% of the area of Cerkniško Polje and is considered a normal flood (Smrekar 2000).

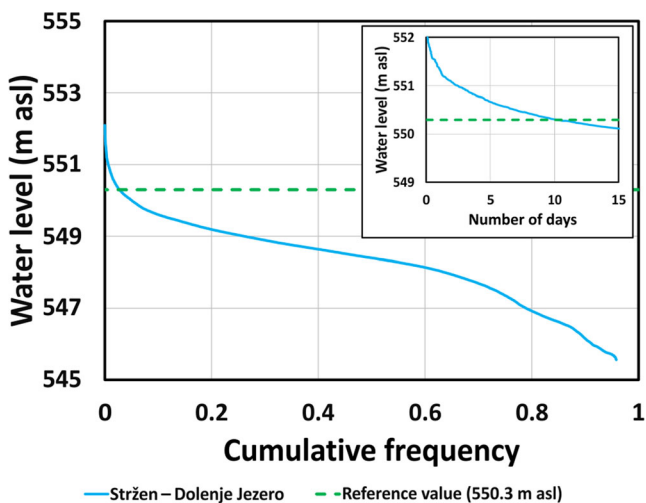
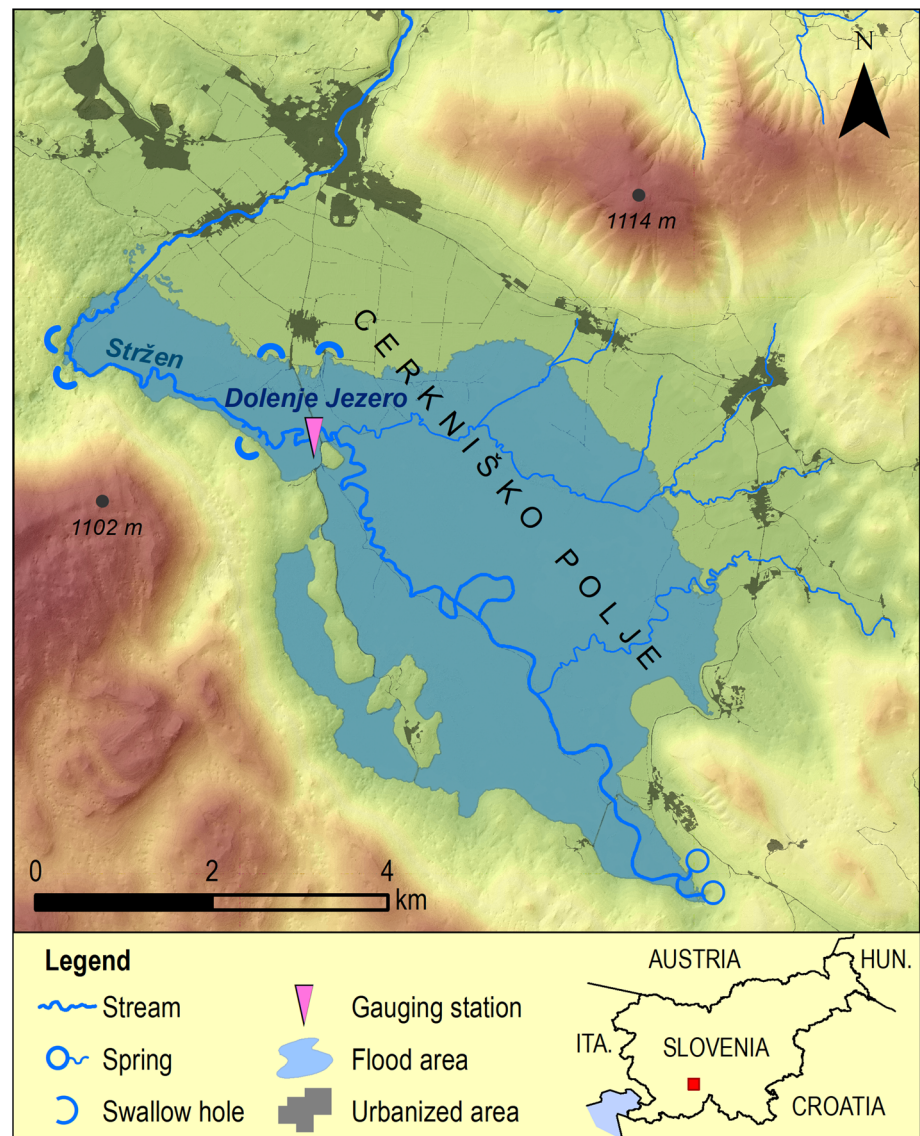
The cumulative frequency of water levels at the Dolenje Jezero station for the period 1954–2018 (ARSO 2019a) shows that the height of 550 m is exceeded by 5.1% of values (on average 18.6 days/year), while 2.79% (on average 10.2 days/year) corresponds to a height of 550.3 m (Fig. 7).

In order to elaborate the proposed data layers that meet the definition set, an elevation of 550.3 m asl was therefore taken into account. In addition, spatial information obtained on the basis of available cartographic information on flood areas was modified, primarily in overflow areas along feeder watercourses (eVode 2020). Areas defined as flood-labile land in Cerkniško Polje cover an area of 21.84 km<sup>2</sup>. The road that crosses the polje on a dyke was excluded.

### Radensko Polje

Radensko Polje lies on the northern edge of the Dinaric Karst. It extends over an area of just over 4 km<sup>2</sup> at an elevation of around 325 m asl. It is the smallest of the well-defined karst poljes in Slovenia. The polje is surrounded by steep slopes except on its north-western edge, where it opens towards a slightly higher lying basin. A surface watercourse flows onto the polje from this side and at lower water levels already

**Fig. 6** Geomorphological and hydrological characteristics of Cerkljiško Polje, location of gauging station and spatial extent of flood areas



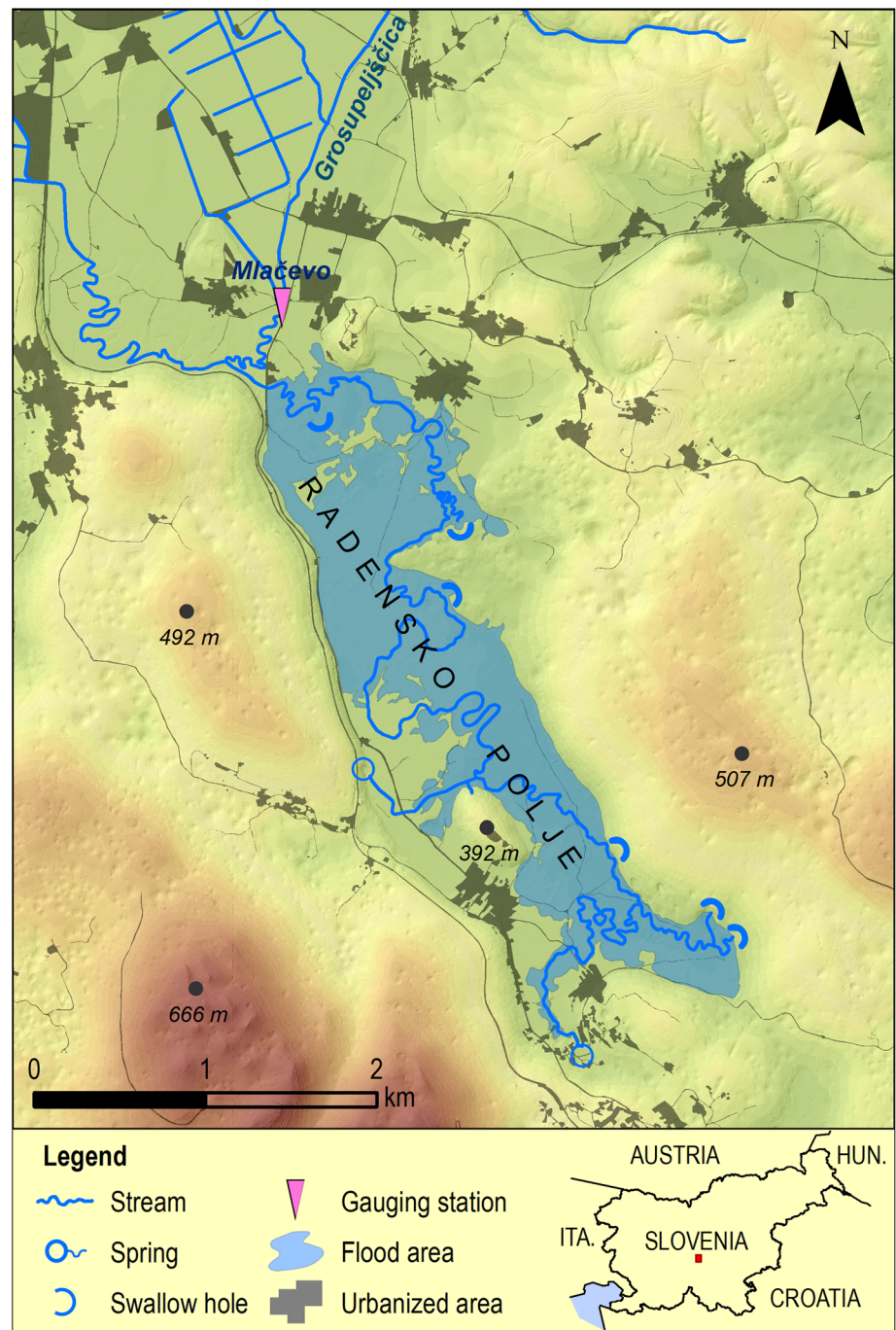
**Fig. 7** Cumulative frequency of daily water levels of the Stržen River at the Dolenje Jezero gauging station for the period 1954–2018. The inset shows the initial part with frequencies converted in days (Data source: ARSO 2019a)

disappears underground in the northern part of the polje. At higher water levels, the water overflows across the surface for just under 1 km towards the south and sinks into ponors located on the polje eastern side. In the southern part of the polje, two additional karst springs recharge streams that cross the polje from west to east (Fig. 8). When water levels are high, these three watercourses join and drain towards ponors on the polje south-eastern edge. Occasionally, when drainage is not rapid enough, a karst lake forms and extends as far as the settlements located on the polje margins.

It is evident from the data in the available literature that Radensko Polje floods regularly, with the majority of its surface being flooded for up to several months a year (Meze 1981). The cumulative frequency curve is based on water levels measured at the Mlačevo gauging station. Due to the relocation of the gauging station, data from the period 1954–1975 had a different base level than data from



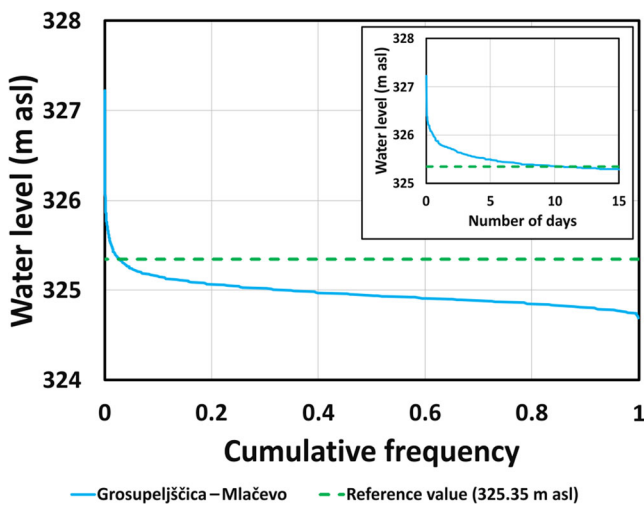
**Fig. 8** Geomorphological and hydrological characteristics of Radensko Polje, location of gauging station and spatial extent of flood areas



the period 1976–2018. Information on the early base level of the gauging station is not available. Therefore, only the latter period data were considered within the analysis, although gaps in the dataset were present between 1 June and 31 December 1993, between 1 January and 31 December 2008 and between 1 January 2012 and 12 April 2016 (ARSO 2019a). The results show that 2.89% of all daily water level values exceed 325.35 m asl (Fig. 9). This

corresponds on average to 10.6 days/year. This value also coincides with field observations and was therefore taken as a reference value for the elaboration of the proposed data layers. These were then additionally optimised in the light of other available cartographic information on flood areas (eVode 2020). The identified areas cover a total of 2.85 km<sup>2</sup>.





**Fig. 9** Cumulative frequency of daily water levels of the Grosupeljščica River at the Mlačevo gauging station for the period 1976–2018. The inset shows the initial part with frequencies converted in days (Data source: ARSO 2019a)

### Upper Pivka and Pivka intermittent lakes

The region of the Upper Pivka is an area covering the southern part of the Pivka Basin (Fig. 10). It is a flat landscape around 15 km long and up to 5 km wide that is divided into an erosion surface along the Pivka River and its tributaries, and a karst plain broken up by various types of karst depressions and conical peaks. It is in these closed karst depressions, which do not usually have a surface connection to the surface flow of the Pivka, that the Pivka intermittent lakes appear when water levels are high. The size of the individual lakes depends on the shape of the karst depression, while the frequency of occurrence and duration depends above all on the position and elevation of the bottom of the depression.

There are no stations of the national water gauging network in any of the lakes. However, quite a number of field observations were made in the past with regard to the appearance of the lakes, although these observations were only of short duration (e.g., Ravbar and Šebela 2004; Kovačič and Habič 2005; Petrič and Kogovšek 2005; Šajn 2009; Kirn 2016). Lately, two monitoring stations were installed by the authors in the siphon of the cave Matijeva Jama (considered as one of the main infeeders of Palško Jezero) and at the bottom of Petelinjsko Jezero. These stations have delivered continuous data at a half hour interval since August 2016 and June 2019, respectively.

The water levels associated with the usual appearance of the Pivka intermittent lakes and their duration were determined on the basis of the data collected from several sources (GURS 2020; Ravbar and Šebela 2004; Kovačič

and Habič 2005; Petrič and Kogovšek 2005; Šajn 2009; Kirn 2016). For two locations these have been compared to the information from the authors' own database (Palško Jezero-Matijeva Jama and Petelinjsko Jezero). The harmonised data that were the principal source of the proposed data layers are shown in Table 2 and Fig. 10.

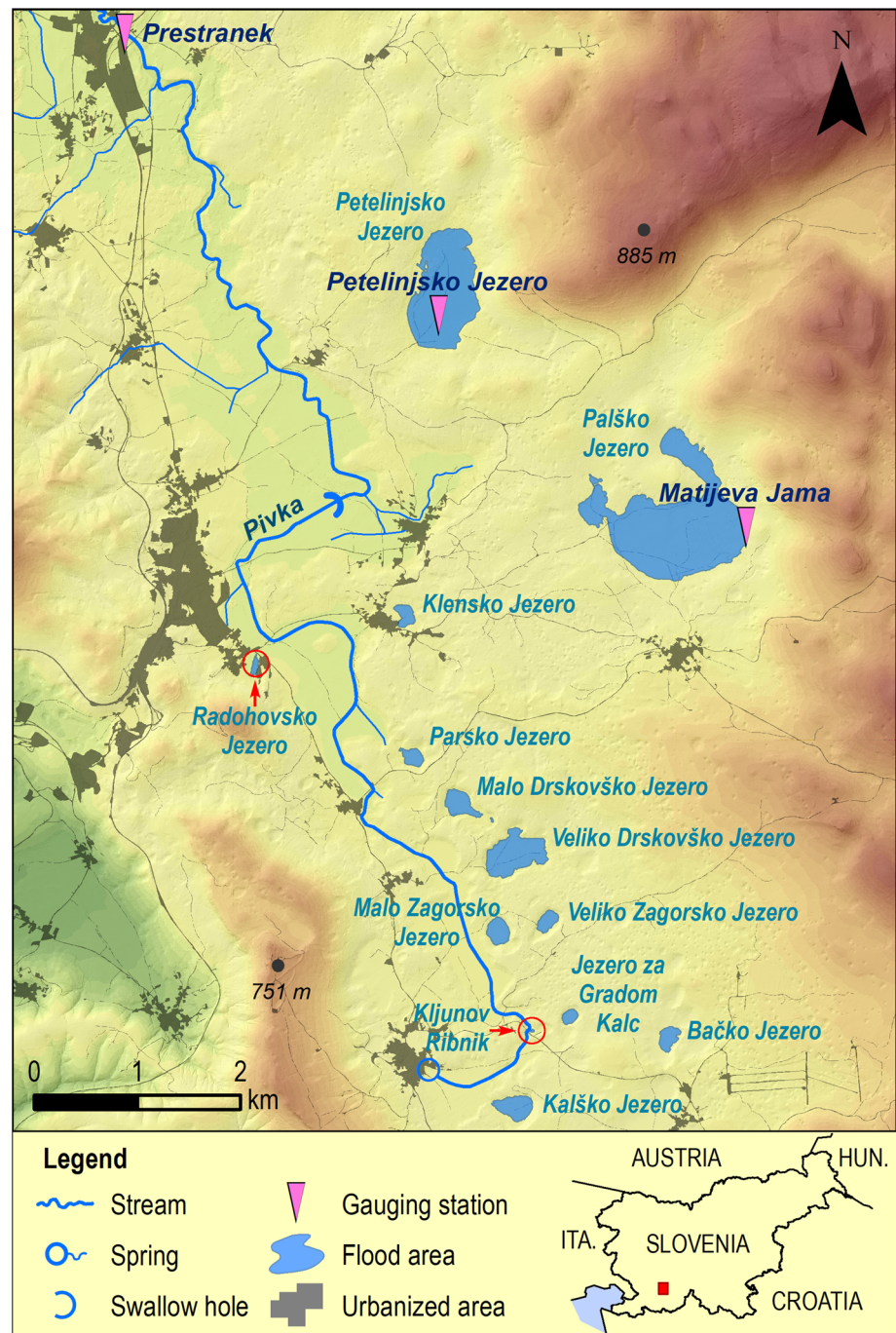
A cumulative frequency curve of water levels recorded inside Matijeva Jama, which is hydrologically connected to Palško Jezero, was created for the period between 25 August 2016 and 31 July 2019 (Fig. 11). The monitoring device is installed approximately 35 m below the bottom of the lake and permanently records fluctuations of the groundwater level also when the lake is dry. Nine hydrological events occurred during the monitored period and flooded Palško Jezero for different durations. A period of 10 days/year corresponds to a cumulative frequency of 2.74% and to an elevation of 555.4 m asl, which coincide quite well with the data collected in the literature (Kovačič and Habič 2005).

In the case of Petelinjsko Jezero, the monitoring device was installed on the bottom of the depression. Continuous measurements took place between 13 June 2019 and 11 August 2020. During this period the lake was dry for 69% of time (below the elevation of 531 m asl; Fig. 12). Three complete hydrological events were recorded and caused the occurrence of the intermittent lake. The results show that the water level rose above an elevation of 539 m asl for a period of more than 30.24 days (cumulative frequency: 9.25%; Fig. 12). This elevation corresponds well to the border between grassland and forest with escarpments, and agrees with the data from the literature. According to the step 2 of the proposed processing of the collected data (for description see section 'Processing collected data and mapping'), the level 539 m asl has therefore been used to define the extent of the flood-labile land.

Since the short-term continuous measurements from Matijeva Jama and Petelinjsko Jezero coincide very well with the figures from the literature, these were considered to be sufficiently reliable for those areas for which long-term continuous measurements are not available and were taken into account in the preparation of the spatial layers. The areas of the two intermittent lakes identified in the region (Laneno and Šembijsko Jezero) do not meet the established criteria and were therefore not considered as flood-labile land (Table 2; Fig. 10).

Flooding also occurs along the Pivka River in Upper Pivka, but owing to a lack of information these areas are not included in the existing layers of flood-labile land. It is evident from field observations that at the Prestranek gauging station (Fig. 10) the Pivka overflows its banks at a level of 523.03 m asl (ARSO 2019b). Calculations of the cumulative frequency of water levels for the period 1954–2018 (Fig. 13; ARSO 2019a) show that the Pivka

**Fig. 10** Geomorphological and hydrological characteristics in Upper Pivka, location of gauging and monitoring stations, and spatial extent of flood areas



only exceeds this level in 0.27% of all daily water level values (which is on average 1 day/year). However, since the location of the gauging station, which lies at the extreme northern end of the area, is not representative for the entire area (because of differences of level, different geomorphological conditions, etc.), it will be necessary to devote more attention and research to this area in the future.

### Evaluation of the proposed procedure

The procedure developed for the Planinsko Polje case study provided good and verifiable results also for other presented areas with different characteristics and quality of the input data. The procedure is straightforward, and the application of the proposed data processing method and mapping instructions ensured the comparability of the results obtained. This is

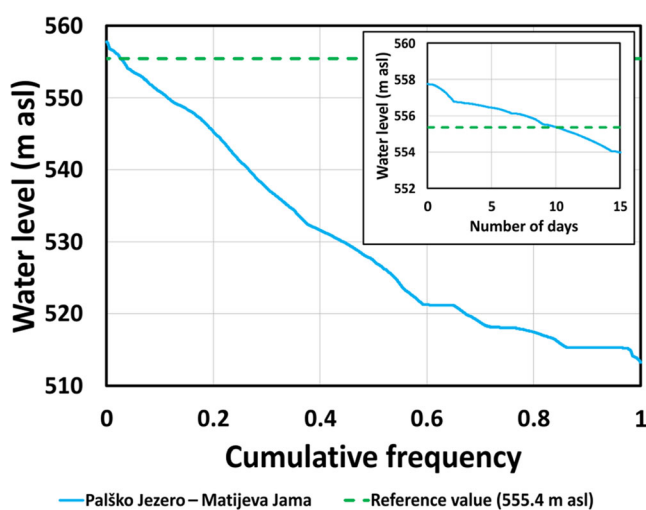
**Table 2** Frequency of occurrence, duration and reference water levels of the Pivka intermittent lakes and the superficial extent of the identified flood-labile land: data taken and harmonised from basic topographic maps (GURS 2020); Ravbar and Šebela 2004; Kovačič and Habič

Name of intermittent lake	Average No. of days per year (and No. of lake-formation events per year) in the period Dec 2006 to Dec 2011 <sup>a</sup>	Reference water level (m asl)	Area (ha)
Petelinjsko Jezero	136–151 (4× per year)	539	58.03
Palško Jezero	68–78 (5× per year)	555.4	106.96
Klensko Jezero (Jezero v Klenskem Dolu)	28–33 (2× per year)	546	2.89
Radohovsko Jezero	69–80 (4–5× per year)	535.5	0.80
Parsko Jezero	102–115 (5× per year)	539	2.71
Malo Drskovško Jezero	76–88 (4× per year)	541	5.60
Veliko Drskovško Jezero	78–90 (3× per year)	545	17.43
Malo Zagorsko Jezero	95–109 (5× per year)	546	4.32
Veliko Zagorsko Jezero	16–21 (2× per year)	550	2.81
Jezero za Gradom Kalc (Veliki Dol)	20–25 (1–2× per year)	555	1.61
Kljunov Ribnik	84–96 (5× per year)	550.2	0.09
Bačko Jezero	17–21 (1–2× per year)	562.5	3.35
Kalško Jezero	77–88 (5× per year)	554.7	6.34
Laneno Jezero	No information, but at least one event lasting 10 days in the 5-year period	NI	NI
Šembijško Jezero	7–9 (1× per year)	NI	NI

<sup>a</sup> The values in this column show the entire period in which the lake is present and not the period above the reference level

NI not included

especially important, as the quality and quantity of data available for each area strongly differed. Where available, the use of additional data sources (such as visual observation from historic chronicles and/or satellite data) enabled further verification of the result and site-specific corrections.



**Fig. 11** Cumulative frequency of half hourly water levels in Matijeva Jama and Palško Jezero monitoring station for the period between 25 August 2016 and 31 July 2019. The inset shows the initial part with frequencies converted in days

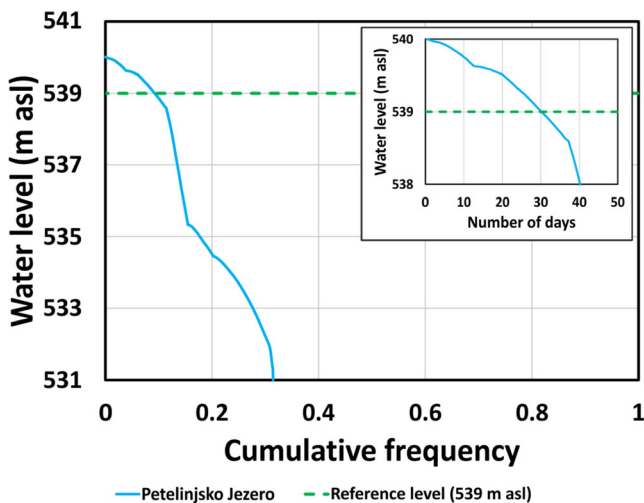
2005; Petrič and Kogovšek 2005; Šajn 2009; Kim 2016. The reference water levels for Palško Jezero and Petelinjsko Jezero are based on continuous measurement and a calculation of cumulative frequencies, and are consistent with information from the literature

## Conclusions

Karst areas, in which underground water flow predominates, are considered natural reservoirs for discharge surpluses and good flood regulators in the lower parts of river basins. Particularly in karst poljes and areas of shallow karst, however, distinct groundwater/surface-water interactions occur. Owing to the complexity of hydrodynamics, defining areas that are frequently subject to flooding represents a unique challenge for the designers of various water policies and management mechanisms for the protection of special habitats, in part because of a lack of temporal and spatial information on flooding and limited understanding of local hydrogeological conditions. In order to correctly record the likelihood of a given area to flooding, knowledge of the recharge and retention capacities of karst aquifers is of key importance, while specific determination criteria are also necessary.

In the present study, a definition has been formulated, using the example of Planinsko Polje, of karst areas that are subject to intermittent flooding. An approach has been developed for the collection of data and analysis of frequency and duration, along with a procedure for flood reference value determination and mapping the spatial extents that must be taken into account. The study is based above all on calculations of the

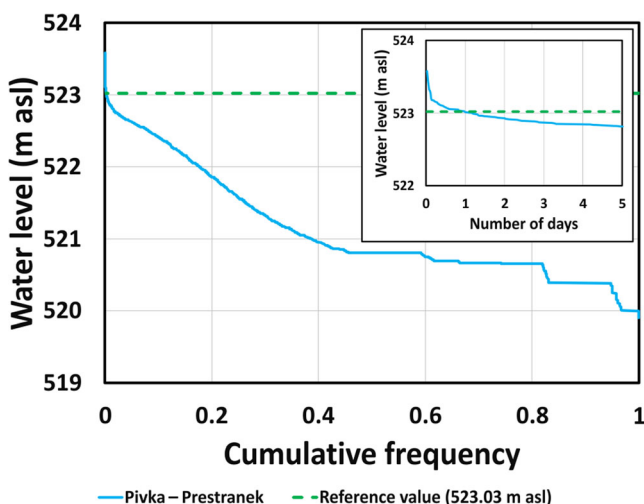




**Fig. 12** Cumulative frequency of half hourly water levels in Petelinjsko Jezero monitoring station for the period between 13 June 2019 and 11 August 2020. The inset shows the initial part with frequencies converted in days

cumulative frequency of daily water level values and DEMs created from LiDAR data with a resolution of 1 or 12.5 m.

The results can provide important spatial information on (ground)water levels, which is of key importance in, for example, drawing up national plans for protecting sources of drinking water, protection of groundwater dependent ecosystems, identifying the effects of environmental changes on groundwater, and so on. The proposed approach is suitable for application in countries where karst systems are known for intermittent flooding. It can be used in the design of management plans dictated at the international level by instruments



**Fig. 13** Cumulative frequency of daily water levels of the Pivka River at the Prestranek gauging station for the period 1954–2018. The inset shows the initial part with frequencies converted in days (Data source: ARSO 2019a)

such as the EU Water Framework Directive, the Floods Directive and the Habitats Directive.

At the national level, the findings will be directly applicable to implementation of the provisions of the Slovenian Waters Act, since the method of identification used is transferable to the level of the country as a whole. It is, however, envisaged that in this case it will not be possible to carry out accurate hydrological analyses in full, since many karst areas of Slovenia still lack adequate measurements from gauging stations. Many of the gauging stations established by the Slovenian Environment Agency in the past, which were located on smaller karst watercourses, have not been operational for some decades. Therefore, they will need to be renovated in the future. On the other hand, modern technological solutions also enable the establishment of systematic long-term monitoring in water-active karst caves. However, because of difficult access to underground areas and a lack of suitable technical equipment and expertise, the cooperation of karstologists with specific knowledge and caving skills would be necessary.

The establishment of water quantity monitoring by monitoring water levels at selected locations in karst poljes and intermittent lakes or accessible points underground would contribute to the more complete knowledge of the dynamics of surface-water/groundwater interactions and to the study of the impacts of environmental changes on such dynamics.

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