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DECIPHERING THE WATER BALANCE OF POLJES: EXAMPLE OF PLANINSKO POLJE (SLOVENIA)

O VODNI BILANCI KRAŠKIH POLJ: PRIMER PLANINSKEGA POLJA (SLOVENIJA)

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Abstract UDC 551.44:556.3(497.4 Planinsko polje)
Cyril Mayaud, Blaž Kogovšek, Franci Gabrovšek, Matej Blatnik, Metka Petrič & Nataša Ravbar: Deciphering the water balance of poljes: example of Planinsko Polje (Slovenia)
Poljes are flat closed karst depressions prone to regular flooding. The floods can be several meters high, last for months and damage significantly human infrastructures. To predict the maximum level reached, the polje water balance needs to be implemented. This technique encounters the difficulty that important part of the inflow and outflow flowing through many poljes is ungauged, as it is challenging to measure accurately the numerous springs and ponors activating temporarily with the rise of water level. This work aims to see whether this problem can be handled and the polje water balance reconstituted. To do so, a typical Dinaric polje is equipped with several water level stations installed over its surface and in the nearby water active caves. Combining a 1*1m digital elevation model of the polje surface with water levels and inflow records of the main two springs allowed assessing the variation of flooded volume and reconstructing the water balance. The highest total inflow values reached during the observed period were of about 140-150 m^3/s, with up to a third of it being ungauged. In addition, the effect of a large estavelles group on the polje inflow and outflow could be identified, and helped to characterize the outflow, with values comprised between 65 and 75 m^3/s. Finally, intense rainfall over the polje flooded surface showed to be a temporary important source of inflow. The values found by the water balance analysis have been used as input and calibration data in a numerical model reproducing the flood dynamics in the polje and its surrounding aquifer. Results validated both polje water balance and conceptual hydrogeological model. They justify the significance of combining water level measurements with

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Cyril Mayaud, Blaž Kogovšek, Franci Gabrovšek, Matej Blatnik, Metka Petrič & Nataša Ravbar: O vodni bilanci kraških polj: primer Planinskega polja (Slovenija)
Kraška polja so kotanje z ravnim dnom v poplavnem nivoju podzemne vode. Gladina vode ob poplavah na kraških poljih se redno zviša za več metrov, poplave pa lahko trajajo več mesecev in pri tem povzročajo škodo na infrastrukturi. Napovedovanje najvišje možne višine gladine vode ob poplavah temelji na dobri oceni vodne vsebnosti kraških polj, kar pa je v praksi težko izvedljivo, saj natančna meritev vseh dotokov in odtokov največkrat ni mogoča. V tem članku rešujemo problem vodne vsebnosti na primeru polja na Dinarskem krasu, kjer smo vzpostavili mrežo zveznih opazovanj vodnega nivoja na polju in v okoliških jamah. Z združevanjem visoko ločljivih lidarskih podatkov ter časovnih nizov vodnih nivojev in dotokov glavnih izvirov smo dobili časovne nize spreminjanja količine na polju uskladiščene vode in oceno vodne vsebnosti polja. Najvišje vrednosti skupnega dotoka v opazovanem obdobju so bile med 140 m^3/s in 150 m^3/s, od tega tretjino zajema dotok iz nemerjenih virov. Pomembno količino k dotoku in odtoku prispevajo estavele ob severozahodnem robu polja, kjer pretokov ne moremo meriti. Ocenili smo tudi pomen neposrednega dotoka ob intenzivnih padavinah. Skupni odtok s polja ocenjujemo med 65 m^3/s in 75 m^3/s. Izračunane časovne nize dotoka in odtoka smo uporabili kot vhodni podatek v numeričnem modelu, ki simulira poplavno dinamiko na polju in v jamah vodonosnika ob njem. Rezultati modela se dobro ujemajo z merjenimi nivoji v jamah in na polju ter potrjujejo ugotovljeno vodno vsebnost polja in konceptualni hidrogeološki model. V delu smo prikazali uporabnost združevanja meritev vodostajev z visoko ločljivimi

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a digital elevation model to monitor the floods. The method can be applied to other poljes flooding in a complex way of superposed input and output signals. Finally, the places to be equipped in priority if the polje has no measurement network or if available funding is limited are discussed.
Keywords: polje flooding, water balance, automatic monitoring, Dinaric karst, numerical modelling.

lidarskimi podatki pri poplavnih študijah na Krasu, še posebej na območjih, kjer so dotoki in odtoki slabo določljivi. Predstavili smo še smernice pri vzpostavitvi merilne mreže, kadar je število merilnih mest zaradi finančnih ali drugih ovir omejeno.
Ključne besede: poplavljanje kraških polj, vodna vsebnost, samodejne meritve, Dinarski kras, numerično modeliranje.

1. INTRODUCTION

Poljes are flat closed depressions prone to regular flooding typically found in all karst areas around the world (Ford & Williams, 2007). The floods might occur several times per year and create temporary lakes lasting from a few days to several months (Kovačič & Ravbar, 2010). During the most extreme cases, the maximum water level can exceed a few tens of meters and covers several hundreds of square kilometres (Lučić, 2014). Such severe events greatly affect the life of people living around poljes, as houses, fields, roads and other important infrastructures might stay flooded for a relatively long period (López-Chicano et al., 2002; Ravbar, 2008; Frantar & Ulaga, 2015). Because climate projections tend to forecast a global increase of extreme rainfall events in a near future (Tramblay & Somot, 2018; Myrhe et al., 2019; Tabari, 2020), a resulting increase of the occurrence of severe floods in poljes can be expected. Therefore, it is crucial to continue improving our understanding on how poljes are functioning in order to provide long term adaptation and resilience to what might happen within the next decades. Such response should include an appropriate flood forecast that would be used to implement worst-case scenarios and a land-use management policy specific to these regions (Morrissey et al., 2021; Ravbar et al., 2021).

For these purposes, methods able to reproduce the polje flooding dynamics under different hydrological conditions are necessary. Distributed numerical modelling belongs to traditional characterization techniques of porous hydrogeology (Anderson et al., 2015), and has been used as well to understand the behaviour of many complex karst systems under various hydrological conditions (e.g., Worthington, 2009; Worthington et al., 2012; Gabrovšek et al., 2018; Gill et al., 2020; Pagnozzi et al., 2020; Schuler et al., 2020; Duran & Gill, 2021). Since the last ten years, distributed numerical models have been also employed to simulate floods in karst basins such as the Irish turloughs (e.g., Gill et al., 2013; McCormack et al., 2017; Morrissey et al., 2020) and the Dinaric poljes (Mayaud et al., 2019).

Before starting modelling, it's a prerequisite to perform the polje water balance. This method aims determining the polje inflow and outflow under different hydrological conditions, and is of particular importance to understand the flooding dynamics (Kovačič, 2010). Many authors such as Bonacci (1987), López-Chicano et al. (2002), Milanović (2004), Kovačič (2010) and Kovačič and Ravbar (2010) mentioned or applied it to several poljes. They were able to provide numbers regarding both inflow and outflow (e.g., López-Chicano et al., 2002; Milanović, 2004; Kovačič, 2010; Kovačič & Ravbar, 2010).

To characterize accurately the polje water balance upon time, the collection of a large dataset is essential (Kovačič & Ravbar, 2010). This requires recording hydrological data at points taken as representative to catch the flood dynamics in the polje and its surrounding aquifer (Kovačič, 2010). Such locations include the polje main inflows and outflows, namely springs, ponors, allogenic rivers as well as neighbouring water-active caves. In addition, manual measurements of discharge and outflow under various hydrological situations are necessary to obtain stage-discharge curves. They provide information on the polje behaviour during the day of measure, and allow extrapolating the flood dynamics under other hydrological conditions (Blatnik et al., 2017; Kogovšek, 2022).

Kovačič (2010) mentions that a rigorous quantification of both polje inflow and outflow upon time is highly challenging. One reason is that numerous springs and ponors might be unreported due to their temporary character. Some others might also activate while being submerged or have a distinct diffuse in- and outflow. Therefore, they are hard to monitor and frequently not considered in the water balance. In addition, a supplementary difficulty arise when identifying and separating each signal delivered and taken to the polje, as the effect of unmonitored inflows and outflows might be superposed. Moreover, estavelles represent another challenge because they act as springs or ponors depending on the hydrological situation in the polje and its surrounding aquifer (Bonacci, 2013; Mayaud et al., 2019). Thus, it is crucial to identify the moment when they switch from spring to ponor to assess properly their effect on the water balance (Mayaud et al., 2019). Finally, it is important to keep in mind that the successful collection of a complete hydrological dataset is a highly demanding work. Indeed, many springs and ponors might not activate from an event to the other depending on the hydrological conditions, which make their individual measurement practically impossible. In addition, many poljes are sparsely or not at all monitored due to technical and financial reasons. They frequently rely on water level and/or inflow data recorded at one or two stations; those locations are not necessary representative to catch properly the flood dynamics.

To remedy this problem, an alternative method consists to postulate that the variation of lake stage upon time is linked to the surplus water creating the flood (Bonacci, 1987; López-Chicano et al., 2002; Kovačič, 2010). Therefore, combining the measured water level to an accurate digital elevation model (DEM) of the polje allows computing the change of volume during the flood (Kovačič, 2010). However, this implies that water level fluctuations occur homogenously over the polje surface. While base-level poljes and most of the Irish turloughs flood on this principle (Ford & Williams, 2007; Naughton et al., 2012), an important proportion of poljes are also recharged by large allogenic streams, or combine inflow from karst springs with a rise of the regional groundwater level (i.e., border and structural poljes; Ford & Williams, 2007). In this case, a uniform rise of the water level happens only after the total submersion of the terminal outflow zones. This implies to determinate the outflow before to reconstruct the total inflow entering the polje. In addition, the water entering and leaving such poljes is frequently delivered and taken by inputs and outputs functioning in an unphased dynamic (Mayaud et al., 2019) depending on the hydrogeological conditions in their respective recharge areas. Such behaviour adds a supplementary difficulty to identify and separate the impact of each signal on the flood rise and recession, especially if an important part of the in- and outflow is ungauged. Finally, it should be reminded that many poljes have notable altitude difference from their upper active springs to their terminal outflow zones. This might result in important water level differences between both inflow and outflow sides as long as the polje surface is not uniformly flooded. Therefore, it seems necessary to install monitoring stations widespread on the polje surface to catch entirely the flooding dynamics.

The goal of this work is to use the strengths of modern measurement techniques to compute the most possible accurate polje water balance. To do so, a typical Dinaric polje recharged by a complex combination of inflow from karst springs with a rise of the regional groundwater level is equipped with monitoring stations located all over its surface and in its surrounding aquifer. The dataset collected is analysed and the different flow components characterizing the water balance are assessed. The method allows identifying and separating the effects of the main in- and outflows signals, and propose an assessment of the ungauged inflow. Then, the inflow and outflow values arising from the analysis are tested in a numerical model aiming validating both polje water balance and regional conceptual hydrological model. Furthermore, a discussion on the most important places where to install data loggers if the polje is sparsely monitored or not equipped at all is implemented.

2. POLJE WATER BALANCE

The equation describing the polje flooding dynamics allows assessing its water balance (Bonacci, 1987; López-Chicano et al., 2002; Kovačič, 2010). The relationship is based on a simple inflow-outflow difference representing the variation of flooded volume upon time, and corresponds to the water level derivative multiplied by the polje surface:

$$\frac{dV}{dt} = \frac{dh}{dt} A_{Polje}(h) = (Q_{In} - Q_{Out}) \qquad (1)$$

where h is the stage in the polje [L],

$A_{Polje}(h)$ is the polje surface as a function of its depth [L^2] and

Q_{In} and Q_{Out} are the polje total inflow and outflow [L^3T^{-1}]

Therefore, flooding starts when the inflow is higher than the outflow at a given elevation (h):

$$Q_{In} > Q_{Out}(h)$$

Where Q_{In} is provided by:

(i) springs and allogenic rivers located at the polje margins and/or flowing into it.
(ii) estavelles turning into springs due to a rise of the regional groundwater level.
(iii) precipitations falling on the polje flooded surface. This is assumed to be an important source of inflow if the meteorological event is intense and the flooded surface is large (Kovačič, 2010).

And $Q_{Out}(h)$ is drained out from the polje via:

(i) individual ponors and large outflow zones.
(ii) estavelles turning back to ponors as soon as the regional groundwater level recedes below the polje bottom.
(iii) evaporation occurring over the flooded surface. This process is assumed to have a non-negligible impact during the warmest months of the year. However, it will not be considered hereafter.

Thus, the polje outflow corresponds to the maximum outflow the ponors can drain at a given elevation (h). Figure 1 shows the flooding dynamics and variation of flooded volume in a conceptual polje whenever the flood is exclusively caused by a uniform rise of the regional groundwater level (Figure 1a), or by a combination of the former process with inflow provided by rivers and karst springs (Figure 1b). A positive variation of flooded volume (surplus inflow) significates that the flood is rising. Conversely, a negative variation of flooded volume (deficit outflow) indicates that the flood recedes. Finally, a variation of flooded volume equal to 0 implies that the inflow entering the polje is equal to the outflow. The water level is stable at the given elevation.

In the case of Figure 1a, the water balance is immediately given by the values of surplus inflow and deficit outflow determined by the variation of flooded volume. Conversely, the situation shown in Figure 1b implies having a homogenous water level rise over the whole polje surface before computing these two quantities. This elevation is named uniformed level and corresponds to the point when all water level stations start to record the same water level. This significate that the polje outflow zones have to be submerged and that the outflow needs to be determined. Therefore, the variation of flooded volume occurring before reaching the uniformed level is removed from the analysis (Figure 1b). By adding the polje outflow to the variation of flooded volume, the total inflow entering the polje is determined and its water balance is characterized.

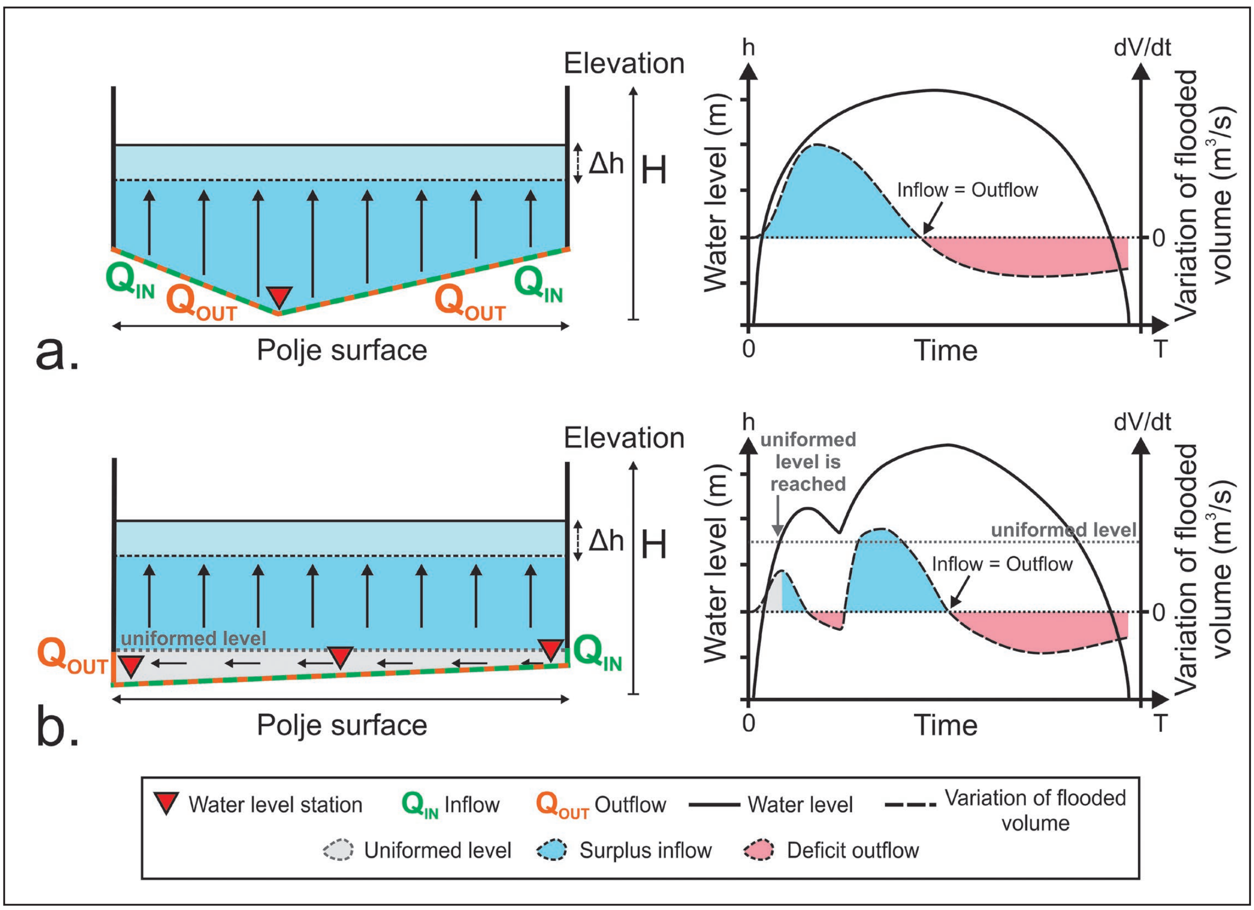

Figure 1: Flooding dynamics in a conceptual polje with measured water level and variation of flooded volume. (a) Situation when flooding is solely caused by a rise of the regional groundwater level. (b) Situation when flooding is caused by a combination of inflow provided by rivers and karst springs and rise of the regional groundwater level.

3. PLANINSKO POLJE

Planinsko Polje (Slovenia) is selected as a test site. This polje can be considered as a locus-typicus of border and structural poljes, as it floods due to the effect of inflow provided by karst springs with a rise of the regional groundwater level. Thus, its choice allows a representative overview of all possible issues expected to be encountered when computing the water balance of poljes.

3.1 GEOGRAPHY, HYDROLOGY AND FLOODING

Planinsko Polje is located about 30 km southwest from Ljubljana (Figure 2) right in the heart of the Classical Karst (Mihevc et al., 2010). This polje belongs to the catchment of the Ljubljanica River and is the lowest in line of a set of cascading poljes located along the Idrija fault zone (Gospodarič & Habič, 1976). The altitude of the polje floor is between 437 m a.s.l. and 460 m a.s.l. and its surface is about 10.9 km^2. Four settlements are located on its margins (Figure 3).

From a hydrogeological point of view, Planinsko Polje is recharged by large springs and estavelles draining water from four recharge areas. The most important spring group is located in the polje southern side and comprise the Unica, Malenščica and Škratovka springs (Figure 2). These springs recharge the polje with water coming from the Pivka Basin in the SW, from the Javorniki Mountain in the S, and from Cerkniško Polje in the SE (Gabrovšek et al., 2010; Ravbar, 2013). The Unica spring is the main flow contributor of the polje and flows out from the cave Planinska Jama (Figure 2). This spring has been daily gauged for flow between 1961 to 1973, with minimum and maximum discharge varying from 0 m^3/s to 106 m^3/s (ARSO, 2022a). The Malenščica spring is located about 820 m eastward (Figure 2), and has been daily monitored since 1961, with 1.1 m^3/s and 11.02 m^3/s as respective minimum and maximum discharge (ARSO, 2022a). The Škratovka spring group (referred hereafter as Škratovka spring) is composed of several temporary springs located about 800 m northeast from the Malenščica spring (Figure 2) activating during flood events. The discharge of this spring has

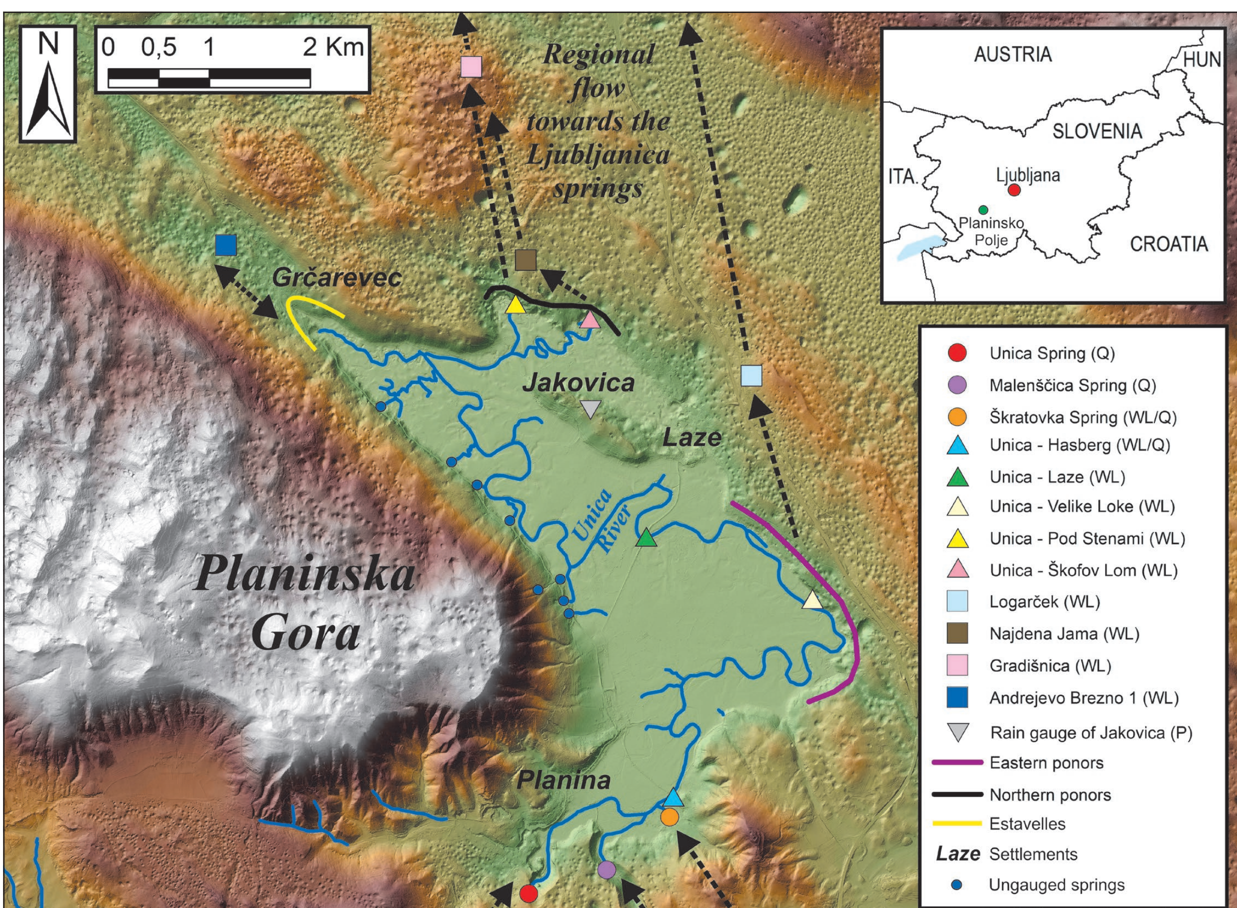

Figure 2: Planinsko Polje and its monitoring network. The springs, ponors' zones and regional flow directions are indicated.

been sporadically monitored before this study, and varies from a few litres per second during low water periods to estimations of 7 m^3/s during high-flow (Putick, 1889). Both period and method of measurement were not specified.

Moreover, Planinsko Polje receives an important water component from a group of estavelles located at its north-western margin (Figure 2). These estavelles provide water from a karst plateau located further NW (Blatnik et al., 2020, 2019). The flow in and out from the estavelles is ungauged, despite a maximum inflow of 24 m^3/s mentioned by Putick (1889) without specifying the period and method of measurement. Finally, a set of small permanent springs is found on the foot of the mountain Planinska Gora (Figure 2). While their contribution to the polje inflow do not exceed a few decilitres per second during low flow conditions, a total maximum inflow of 1-2 m^3/s cannot be excluded during the highest events. Putick (1889) mentions maximum values up to 8 m^3/s.

The Unica, Malenščica and Škratovka springs merge as Unica River. The Unica is daily measured for flow and water level at the Hasberg gauging station since 1954 (Figure 2), with minimum and maximum discharge between 1.09 m^3/s to 90.16 m^3/s (ARSO, 2022a). However, maximum discharge needs to be taken very cautiously, as the rise of water level above the Unica's riverbed might cause consequent error in its rating curves. The Unica River flows across the polje and sinks into two large ponor zones located on its eastern and northern margins (Figure 2). Then, the water flows toward the Ljubljanica springs located 10-15 km north (Gospodarič & Habič, 1976). The groundwater flow between Planinsko Polje and the Ljubljanica springs can be observed in several caves (Figure 2), most of them been located within 2 km distance from the polje margins (Turk, 2010; Blatnik et al., 2019).

Planinsko Polje floods after each notable meteorological event. According to Jelovčan (2019), the Hasberg gauging station is considered as flooded when the water level overtakes the altitude of 447.33 m a.s.l. The analysis of the data recorded at the Hasberg gauging station shows an average flooding duration of 37.5 days/year since 1954 (Ravbar et al., 2018). During this period, 37 floods peaked above 448 m a.s.l., 19 above 449 m a.s.l., 8 above 450 m a.s.l., 2 above 451 m a.s.l. and 1 above 453 m a.s.l. (Ravbar et al., 2021). This event flooded the polje for two months, with a maximum flooded surface of 10.26 km^2 corresponding to a volume of 73.6 10^6 m^3 (Frantar & Ulaga, 2015). While such floods are extremely rare, it is assumed that events of this amplitude were occurring more frequently in the past (Jelovčan et al., 2021). Among others, Gams (1981) reports a flood that reached the altitude of 456 m a.s.l., while Stepišnik et al. (2012) assumed that Holocene floods might have reached up to 50 m above the polje surface.

Regarding the total inflow entering the polje, values of 130 m^3/s are mentioned by Jenko (1959). Similarly, Putick (1889) specified that the total inflow entering the polje was in average of 138 m^3/s, but that maximum values up to 162 m^3/s were possible. The maximum ponor outflow is assumed to be of 60 m^3/s (Jenko, 1959), coinciding with the moment the Hasberg station is becoming flooded. For the Eastern ponors, outflow values of about 17-20 m^3/s have been reported by Jenko (1959), Gams (1981) and Šušteršič (2002), and were confirmed by Acoustic Doppler Current Profiler (ADCP) measurements (Blatnik et al., 2017). Similarly, Jenko (1959) and Šušteršič (2002) assumed that the outflow capacity of the Northern ponors was of 40 m^3/s but could reach maximum up to 60 m^3/s, while outflow values for the estavelles were not mentioned in any of those studies. Because the measurement method employed in these works was not specified, one of the main questions is how the mentioned inflow and outflow values are representative of the polje water balance. The method used in this paper intends to verify it.

3.2 SURFACE - VOLUME RELATIONSHIP

In order to compute the polje surface - volume relationship, a DEM with a resolution of 1*1 m has been used (ARSO, 2022b). The surface area A(h) and cumulative volume V(h) of Planinsko Polje have been calculated with a simple algorithm in the software Surfer® (Golden Software, LLC) between h_{min}= 433.5 m a.s.l. and h_{max}= 460 m a.s.l. as upper limit (Figure 3a). This upper level corresponds to a significant escarpment above the polje surface, and surpasses of 4 meters the highest observed flood. As seen in Figure 3a, the polje cumulative surface has an obvious knickpoint at 447.33 m a.s.l., corresponding to the altitude where the polje banks start to rise sharply. This elevation is also the altitude where the station Unica - Hasberg is considered as flooded (Jelovčan et al., 2021), and represents 80% of the polje cumulative surface and 10.9% of its cumulative volume. The polje volume per vertical unit were computed with a resolution of 10 cm between the altitudes of 433.5 m a.s.l. and 445 m a.s.l. (total cumulative volume of 2.86 10^6 m^3). Then, a vertical resolution of 1 cm has been used from the altitude of 445.02 m a.s.l. to the elevation 460 m a.s.l. (total cumulative volume of 146 10^6 m^3). Similarly to the cumulative surface, the polje cumulative volume has an almost linear rise of volume per vertical unit as soon as the elevation of 447.33 m a.s.l. is surpassed. The use of the DEM implies that the polje surface-volume relationship does not change in time. This assumption is valid as

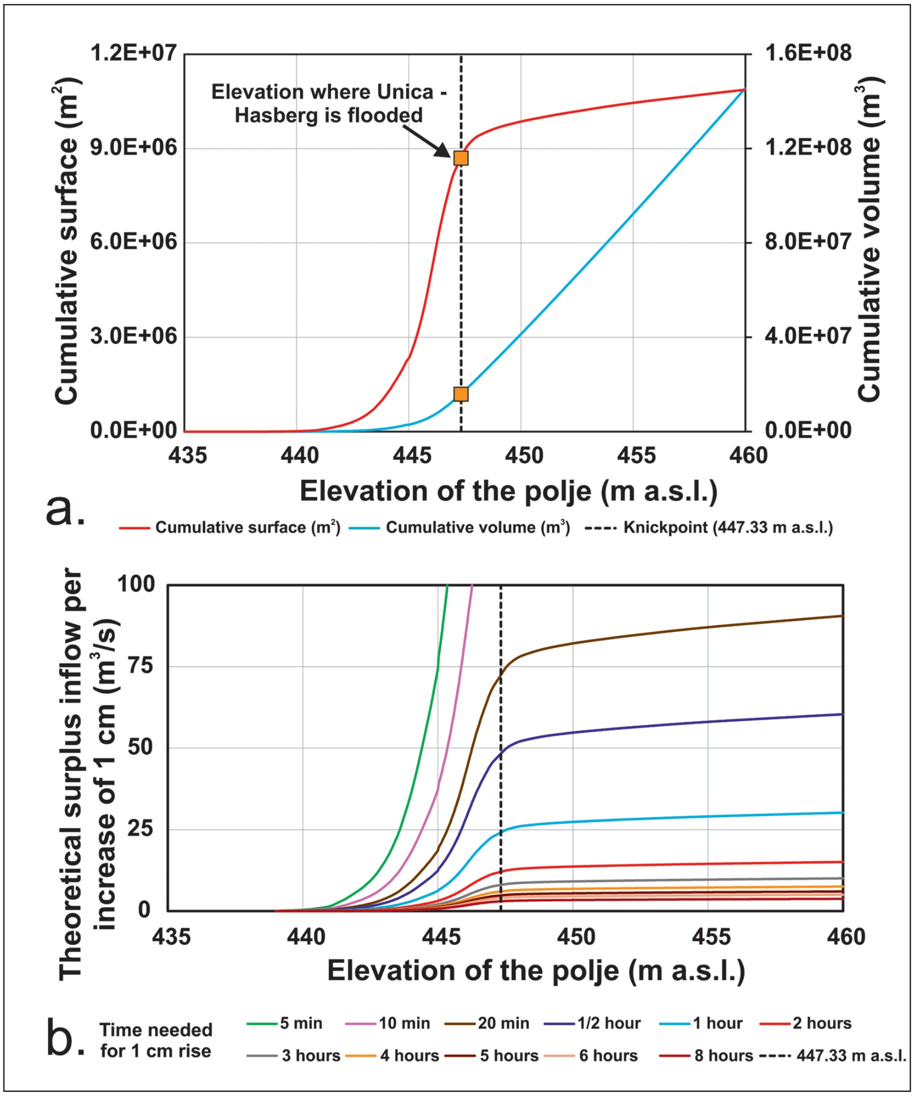

Figure 3: (a) Cumulative surface and volume of Planinsko Polje as a function of its elevation. (b) Theoretical surplus inflow to increase the water level of 1 cm in Planinsko Polje for different speed of increase.

long as the polje is not massively modified by any human intervention within the measurement period.

Figure 3b presents the theoretical surplus inflows necessary to increase the water level in Planinsko Polje for 1 cm, depending on the elevation and on the speed of increase. As it can be observed, the amount of theoretic surplus inflow turns from a strongly rising limb to almost constant one as soon as the knickpoint of 447.33 m a.s.l. is reached. This significates that the polje will flood at higher elevations even if the quantity of surplus inflow is minimal. Thus, a water level at the elevation of 447.33 m a.s.l. rising uniformly above the polje surface at the speed of 1 cm per hour would take approximately 53 days to reach 460 m a.s.l. The corresponding theoretical surplus inflow values would range from 24.15 m^3/s to 30.19 m^3/s (Figure 3b). If the maximum level reached would be of 450 m a.s.l., it would take only 11 days under the same conditions. Frantar and Ulaga (2015) made similar computation for two large floods that occurred in the polje in February and November 2014.

3.3 MONITORING NETWORK

A monitoring network has been installed all over the surface of Planinsko Polje and its surrounding aquifer (Figure 2). This included two water level stations at the terminal ponors zones (Unica - Pod Stenami and Unica - Škofov Lom), two water level stations in the polje central part (Unica - Laze and Unica - Velike Loke) and two stations at the springs Unica and Škratovka. In addition, four water level stations were installed inside the caves Najdena Jama, Gradišnica, Logarček and Andrejevo Brezno 1 located on the polje outflow side (Blatnik et al., 2019). Finally, the stations Unica - Hasberg (water level and flow) and the Malenščica spring (inflow) located in the polje upper part and managed by the Slovenian Environmental Agency ARSO (ARSO, 2022a) have been used. The meaningful repartition of the monitoring stations allow catching accurately the flood dynamic from the event beginning to its end. While all stations were not working together all the time, the density of the monitoring network allowed recording each flood with a minimum of three water level stations. The only exception is February 2017 where only Unica - Hasberg and Unica - Pod Stenami were active (Table 1).

3.4 RECORDED FLOOD EVENTS

During the period from January 2016 to January 2020, nine significant floods were recorded. The hourly and half-hourly data were compensated for barometric pressure and reselected at a 6 hours frequency to avoid regular 1 cm oscillation in the recorded signal. This interval was found to be the most optimal after comparing signals at frequencies of 2, 4, 6 and 12 hours, as it allows removing measurement uncertainties and noise from the data, but keep in the meantime the main hydrological information at high accuracy.

As shown in Table 1 the floods can be classified by amplitude and duration. Thus, the four highest floods occurred in December 2017, November 2019, March 2016 and September 2017. The station Unica - Hasberg was flooded from two to six weeks, and minimal head difference between Unica - Hasberg and the ponors zones were recorded. Conversely, the flood of October 2018 was the smallest of the monitored period (0 days above Unica - Hasberg), followed by the flood of May 2019 (3 days above Unica - Hasberg). Because these events had

Table 1: Maximum water levels registered at the stations installed across the surface of Planinsko Polje during the nine monitored events. Flood durations at the station Unica - Hasberg and level difference between Unica - Hasberg and the ponors stations are also indicated.

Event	Days above 447.33 m a.s.l. at Unica - Hasberg	Unica - Hasberg (m a.s.l.)	Unica - Laze (m a.s.l.)	Unica - Pod Stenami (m a.s.l.)	Unica - Škofov Lom (m a.s.l.)	Unica - Velike Loke (m a.s.l.)	Difference Hasberg - ponors (cm)	Uniformed level is reached
March 2016	18.75	448.24	-	448.25	-	448.26	-1	Yes
February 2017	3.75	447.44	-	447.21	-	-	23	Yes
September 2017	14.25	447.73	447.59	447.73	-	-	0	Yes
December 2017	42	449.62	449.62	449.45	-	-	17	Yes
March 2018	6	447.48	447.34	447.14	447.14	-	34	Yes
October 2018	0	447.29	445.85	444.29	443.75	-	354	No
February 2019	4.5	447.59	447.49	447.62	447.33	-	26	Yes
May 2019	3	447.72	446.83	446.81	446.90	-	91	No
November 2019	19.75	448.58	448.54	-	448.62	-	-4	Yes

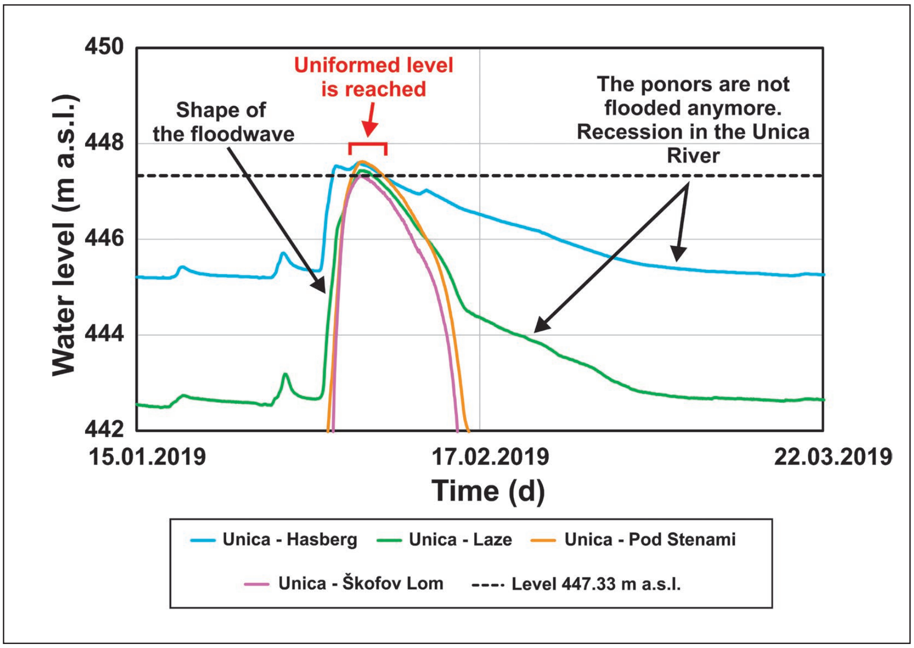

Figure 4: Water levels recorded in Planinsko Polje during the flood of February 2019.

respectively more than 3.5 m and 0.9 m level difference between Unica - Hasberg and the ponors, it can be considered that uniformed level was not reached. For all other floods, the duration where the water level was above Unica - Hasberg was rather short (less than 6 days). This implies that uniformed level was reached only during a short time interval, as evidenced by the water levels of the flood of February 2019 (Figure 4).

For this event, the variations of water level were very similar for the stations Unica - Laze, Unica - Pod Stenami and Unica - Škofov Lom during the event rise, while Unica - Hasberg merged with them after uniformed level was reached. Conversely, the stations Unica - Pod Stenami and Unica - Škofov Lom behaved identically during the recession, while the water level reached the bottom of the riverbed for the stations Unica - Hasberg and Unica - Laze. This difference in water level variation shows that it is fundamental to install monitoring stations both at the polje terminal ponors and higher elevated parts to record properly the flood dynamics.

4. WATER BALANCE OF PLANINSKO POLJE

4.1 EQUATION

The water balance equation of Planinsko Polje is developed from Equation 1 with:

$$Q_{In} = Q_{Unica} + Q_{Malenščica} + Q_{Škratovka} + Q_{Estavelles} + Q_{Other\ inflows}$$

$$Q_{Out} = Q_{Eastern\ ponors} + Q_{Northern\ ponors} + Q_{Estavelles}$$

And: $Q_{Other\ inflows} = Q_{Other\ Ungauged\ Springs} + Q_{Precipitations}$

While inflow data of the Malenščica spring are already available (ARSO, 2022a), a rating curve of the Unica spring has been established using water levels recorded at the entrance of Planinska Jama and ADCP flow measurements carried out under different hydrological situations (Kogovšek, 2022). Therefore, the polje two main inflows (named measured inflow hereafter) are assessed during the complete analysed period. Besides, the inflow from the Škratovka spring has been measured only four times (Table 2). This is insufficient to make a rating curve, but provides information on how the spring behaviour is related to the Unica and Malenščica springs (Kogovšek, 2022). While precipitation data are obtained from the Jakovica rain gauge (Figure 2), other inflows entering the polje remain ungauged. They include the estavelles as well as any other permanent or temporary springs activating during the flood, such as the springs from Planinska Gora.

Regarding the outflow, the ADCP measurements made by Blatnik et al. (2017) provide a reliable estimation of the outflow capacity of the Eastern ponors, with a value around 18 m^3/s. The polje maximum outflow, the outflow of the Northern ponors as well as the outflow of the estavelles are not determined.

4.2 SURPLUS INFLOW AND DEFICIT OUTFLOW

Figure 5 shows the water levels recorded in Planinsko Polje for the floods of December 2017 and November 2019. From that, the variation of flooded volume determines both surplus inflow and deficit outflow. For the flood of December 2017 (Figure 5a), uniformed level is reached at an elevation of 447.73 m a.s.l. on 13.12.2017 at 00:00. The maximum surplus inflow at that time is of 88.83 m^3/s (1). When looking at the three secondary flood peaks occurring after, maximum surplus inflows of 62.33 m^3/s on 28.12.2017 at 18:00 (2); 31.61 m^3/s on 02.01.2018

Table 2: Inflow from the Škratovka spring with corresponding measured inflow and hydrological conditions at the Unica and Malenščica springs.

Time	**10.03.2017** 12:30	**17.03.2017** 12:30	**10.11.2019** 13:00	**10.12.2020** 15:30
Škratovka spring (m^3/s)	1.66	0.03	4.53	2.84
Measured inflow – Unica and Malenščica springs (m^3/s)	34.92	15.00	52.05	59.81
Hydrological conditions during the measure	During the recession	End of recession	High water	High water

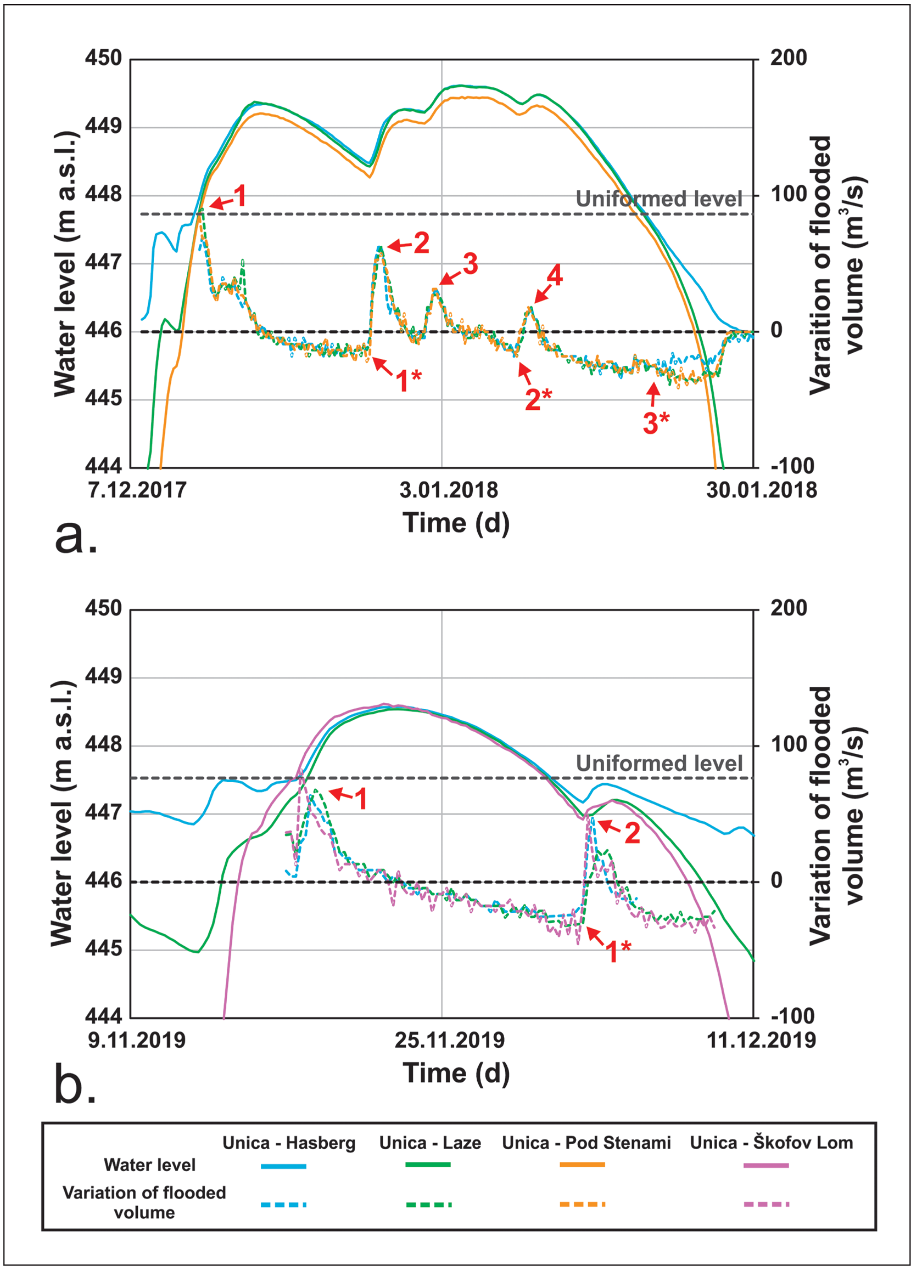

Figure 5: Water level and variation of flooded volume for (a) the flood of December 2017 and (b) the flood of November 2019. Dashed grey lines indicate uniformed levels. Red bold numbers indicate the inflection points for surplus inflow and deficit outflow (marked by a star) described in the text.*

Table 3: Maximum water levels, surplus inflow and deficit outflow at Unica - Hasberg for the 8 highest floods recorded in Planinsko Polje since 1954. Six-hourly values were employed for the floods of December 2008, September 2010 and December 2010. Other floods were based on daily values.

Event	March 1970	November 1992	November 2000	December 2008	September 2010	December 2010	February 2014	November 2014
Maximum water level (m a.s.l.)	451.03	450.67	450.84	450.12	449.49	450.15	453.24	450.3
Maximum surplus inflow (m^3/s)	63.20	75.10	58.24	87.69	86.44	98.56	92.74	111.73
Maximum deficit outflow (m^3/s)	-37.20	-32.35	-34.78	-38.72	-38.72	-31.31	-39.14	-38.74

at 12:00 (3) and 18.07 m^3/s on 10.01.2018 at 18:00 (4) can be derived. For deficit outflow, maximum values of -21.95 m^3/s, -18.07 m^3/s and -32.86 m^3/s occurred respectively on 27.12.2017 at 12:00 (1*); 09.01.2018 at 06:00 (2*); and 22.01.2018 at 00:00 (3*). These observations are confirmed during the flood of November 2019 (Figure 5b), where uniformed level was reached at the elevation of 447.53 m a.s.l. on 17.11.2019 at 12:00. Maximum surplus inflows were respectively of 67.84 m^3/s and 49.05 m^3/s on 18.11.2019 at 12:00 (1) and 02.12.2019 at 12.00 (2). For deficit outflow, a maximum value of -28.91 m^3/s occurred on 30.11.2019 at 18:00 (1*). An interesting observation is related to the difference of behaviour between both surplus inflow and deficit outflow: while the surplus inflow peaks to high values and decreases rapidly after, the deficit outflow increases slowly and tend toward end values around -32/-35 m^3/s. The explanation is due to the difference of hydrological situation in the polje and its surrounding aquifer. In one case, the polje fills with important quantities of floodwater arriving from its recharge areas, while water is slowly drained through the ponors into the saturated aquifer in the second case.

Furthermore, even if these events are the highest recorded during the observation period, floods can reach much higher levels. Table 3 shows the maximum water levels, surplus inflow and deficit outflow at Unica - Hasberg during the eight highest floods recorded in the polje since 1954. As it can be seen, the maximum surplus inflow increases twofold, with values between 58 m^3/s and 111 m^3/s. Conversely, the deficit outflow does not differ so much, with maximum values around -35/-40 m^3/s, in agreement with data from the floods of December 2017 and November 2019. These values could emphasize the effect of a limited drainage capacity, either directly at the ponor zones or further below in the saturated aquifer.

4.3 OUTFLOW

The determination of the outflow is crucial to reconstruct the polje water balance. However, as it is practically impossible to measure the quantity of water flowing through all ponor zones, an indirect estimation has to be made. The main idea consists to identify the moments where the variation of flooded volume is equal to 0, which corresponds to situations where the inflow entering the polje is equal to the outflow (Figure 1). Assuming that the majority of the inflow at that time is provided by the Unica, Malenščica and Škratovka springs and by the estavelles, the measured inflow of Unica and Malenščica could cover a major part of the inflow signal. While the Škratovka spring has no rating curve, measurements in Table 2 show that the discharge is not more than a few m^3/s during the event recession. On the meantime, the contribution of the estavelles can be known by computing the hydraulic gradient between the aquifer they are draining and the polje. To do so, water levels recorded at the ponors Unica – Pod Stenami and Unica – Škofov Lom and in the cave Andrejevo Brezno 1 are used, while the distance taken is assumed being the linear distance between the estavelles and the cave Andrejevo Brezno 1 (about 1.1 km apart; Figure 2). This cave proved to be directly connected to the polje and follow the hydraulic behaviour of the estavelles (Blatnik et al., 2019). When the hydraulic gradient estavelles - polje is equal or near 0, the estavelles have a minimal effect on the water balance and the aquifer drained by the estavelles is at equilibrium with the polje. Therefore, the inflow entering the polje at that time can be reduced to the contribution of the measured inflow and the Škratovka spring, which is assumed negligible. Figure 6 presents this analysis for the flood of December 2017. In both situations, only recession periods are considered, as important water level variations makes harder to determine the exact moment when the variation of flooded volume become equal to 0 during the rise. The moments when the variation of flooded volume is equal to 0 (Figure 6a), and when the hydraulic gradient estavelles-polje is equal to 0 (Figure 6b) are marked by blue dots. They occur in a relatively similar time interval, allowing concluding than the effect of the estavelles on the polje water balance can be considered as minor when the variation of flooded volume is equal to 0.

Table 4 shows the measured inflow during eight flood events (the cave Andrejevo Brezno 1 was not monitored in March 2016) when the variation of flooded volume is equal to 0. The corresponding gradient estavelles - polje is also indicated. Results show that measured inflow is very similar from one event to the other when the gradient estavelles – polje is close to 0 (between -0.0005 and 0.0005). On the meantime, the floods of February and May 2019 have a lower measured inflow but receive a non-negligible contribution of the estavelles, as indicated by respective gradient values of 0.0072 and 0.0029. Therefore, the inflow during these events should include an important contribution from the aquifer drained by the estavelles in addition to the measured inflow and the Škratovka springs. Conversely, the low value of measured inflow during the flood of October 2018 can be explained by the fact that uniformed level was not reached (Table 1). When the measured inflow in Table 4 is averaged, a value of 63.62 m^3/s is found. If only situations with a gradient between -0.0005 and 0.0005 are considered, the value is of 66.96 m^3/s. This should be close to the real outflow value, keeping in mind that the inflow of the Škratovka spring is not taken into account.

The second approach consists to assume that if the measured inflow corresponds to the most important part of the inflow entering the polje during the recession; its combination with the deficit outflow should provide a reliable estimation of the outflow (Bonacci, 1987; López Chicano et al., 2002; Kovačič, 2010). Figure 7 presents this approach for the floods of December 2017 and November 2019. In both cases, the polje outflow is represented by a horizontal line with values oscillating around 70 m^3/s for each station.

Table 5 summarizes the results for all 9 measured events. An interesting observation is that the outflow changes with the flood amplitude and duration but also depends of the station location. Indeed, the values of Unica - Hasberg are lower compared to all other stations, especially for events of lowest intensity. This is because this station is located in the polje upper parts, which floods significantly only during the highest and longest events (Table 1). Similarly, the flood of October 2018 did not reach uniformed level and show therefore the lowest outflow values. Thus, if October 2018 and the values of Unica - Hasberg are excluded, an average outflow around 69.33 m^3/s is found (Table 5). This value is in good agree-

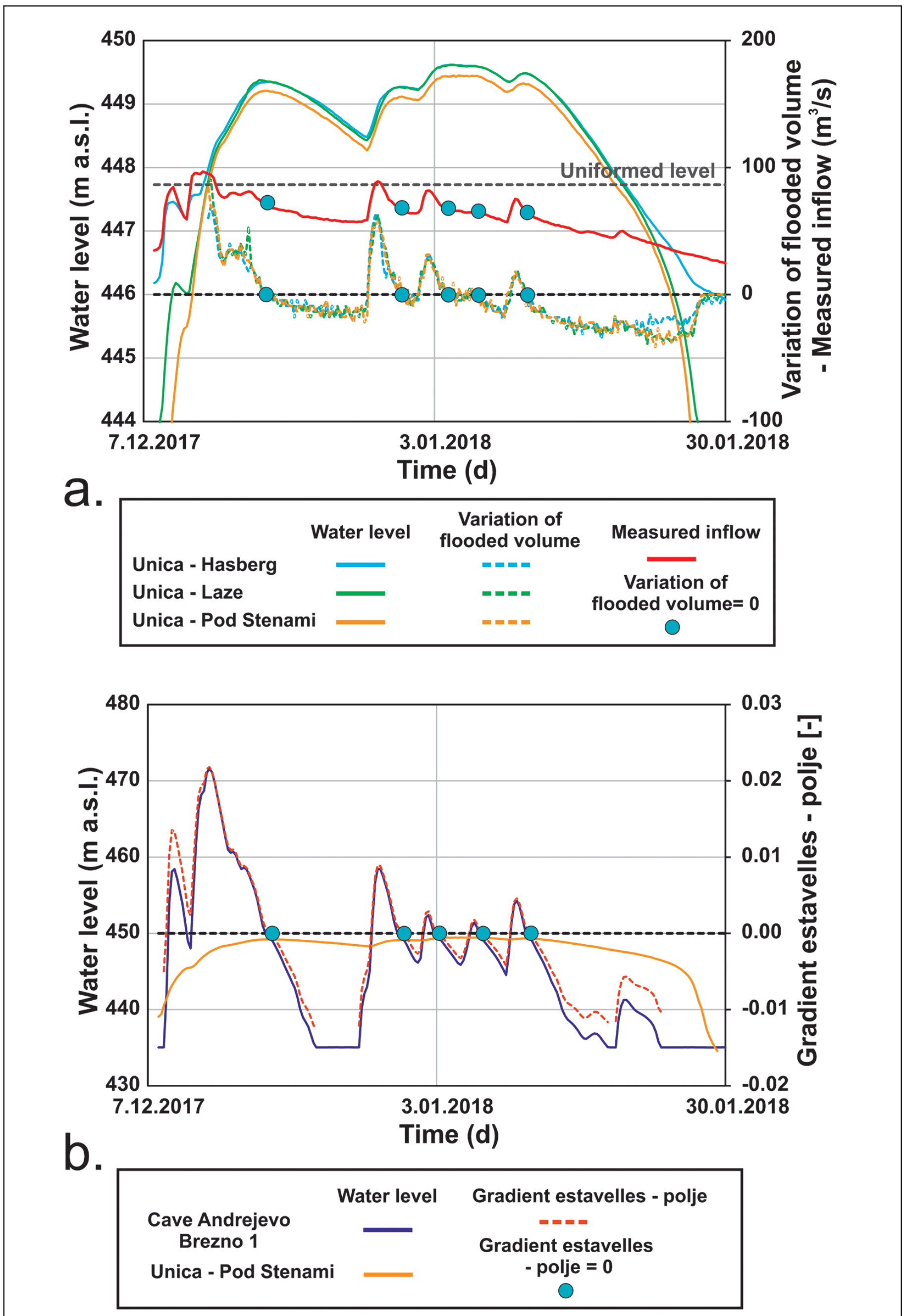

Figure 6: (a) Water levels, variation of flooded volume and measured inflow entering Planinsko Polje during the flood of December 2017; (b) Water level measured at the ponor Unica - Pod Stenami, in the cave Andrejevo Brezno 1 and gradient estavelles - polje during the same event.

Table 4: Values of measured inflow when the variation of flooded volume is equal to 0. Corresponding gradient estavelles - polje and hydrological situation between the cave Andrejevo Brezno 1 and the polje are indicated.

Event	Datum when the variation of flooded volume is equal to 0		Measured inflow – Unica and Malenščica springs (m³/s)	Gradient estavelle - polje [-]	Dynamic estavelle - polje
February 2017	8.02.2017	00:00	64.87	0.0045	The estavelles provide water to the polje
September 2017	22.09.2017	00:00	65.65	0.0003	Minimum impact
December 2017	18.12.2017	18:00	69.11	-0.0004	Minimum impact
	31.12.2017	00:00	65.74	-0.0001	Minimum impact
	4.01.2018	18:00	66.78	-0.0026	The polje drains toward the estavelles
	6.01.2018	18:00	65.07	0.0013	The estavelles provide water to the polje
	11.01.2018	12:00	65.24	0.0005	Minimum impact
March 2018	20.03.2018	00:00	62.96	0.0007	The estavelles provide water to the polje
October 2018	5.11.2018	00:00	56.92	-0.0013	The polje drains toward the estavelles
	7.11.2018	06:00	60.42	-0.0007	The polje drains toward the estavelles
February 2019	5.02.2019	18:00	60.07	0.0072	The estavelles provide water to the polje
May 2019	31.05.2019	18:00	56.63	0.0029	The estavelles provide water to the polje
November 2019	22.11.2019	18:00	69.03	-0.0003	Minimum impact
	4.12.2019	00:00	62.23	0.0012	The estavelles provide water to the polje

ment with the average outflow found when applying the first method. Again, the contribution of the Škratovka spring is not directly considered due to the absence of a rating curve. However, it can be assumed that this spring does not provide more than a few m³/s during the recession, in agreement with the values in Table 2.

Despite being computed by two different methods, the results are in good agreement with each other and tend toward an outflow ranging between 65 and 75 m³/s. This value can fluctuate from an event to the other depending on the drainage capacity of the ponor zones, on the maximum water level in the polje, as well as on the permeability of the main restrictions in the aquifer draining the polje (Mayaud et al., 2019).

As the outflow is determined, it becomes possible to estimate how much water is drained out through each ponor group. Thus, if the 18 m³/s measured at the Eastern ponors is assumed to be close to the maximum outflow that can be drained through this ponor zone, the remaining amount of about 50 m³/s should be drained by the Northern ponors and the estavelles. However, it has to be kept in mind that the estavelles have a minimal impact on the outflow at the beginning of the recession, as the gradient estavelles - polje is close to 0. Therefore, floodwater should be at first exclusively drained through the Northern ponors, while the outflow capacity of the estavelles increase as soon as the recession advances.

Table 5: Outflow values for each water level station during the nine recorded events. The event of October 2018 was not considered in the column computing the average per event without Unica – Hasberg.

Event	Unica - Hasberg	Unica - Laze	Unica - Pod Stenami	Unica - Škofov Lom	Unica - Velike Loke	Average per event (m³/s)	Average per event without considering Unica - Hasberg (m³/s)
March 2016	69.60	-	71.45	-	70.45	70.50	70.95
February 2017	60.12	-	70.12	-	-	65.12	70.12
September 2017	64.37	67.83	69.32	-	-	67.17	68.58
December 2017	70.53	71.12	71.18	-	-	70.94	71.15
March 2018	59.83	65.99	67.07	67.37	-	65.07	66.81
October 2018	61.42	58.64	56.02	56.39	-	58.12	-
February 2019	56.77	65.35	69.09	66.65	-	64.47	67.03
May 2019	54.69	62.82	68.70	70.99	-	64.30	67.50
November 2019	70.16	70.70	-	72.49	-	71.12	72.49
Average per station (m³/s)	62.54	66.06	67.87	66.78	70.45	66.31	69.33

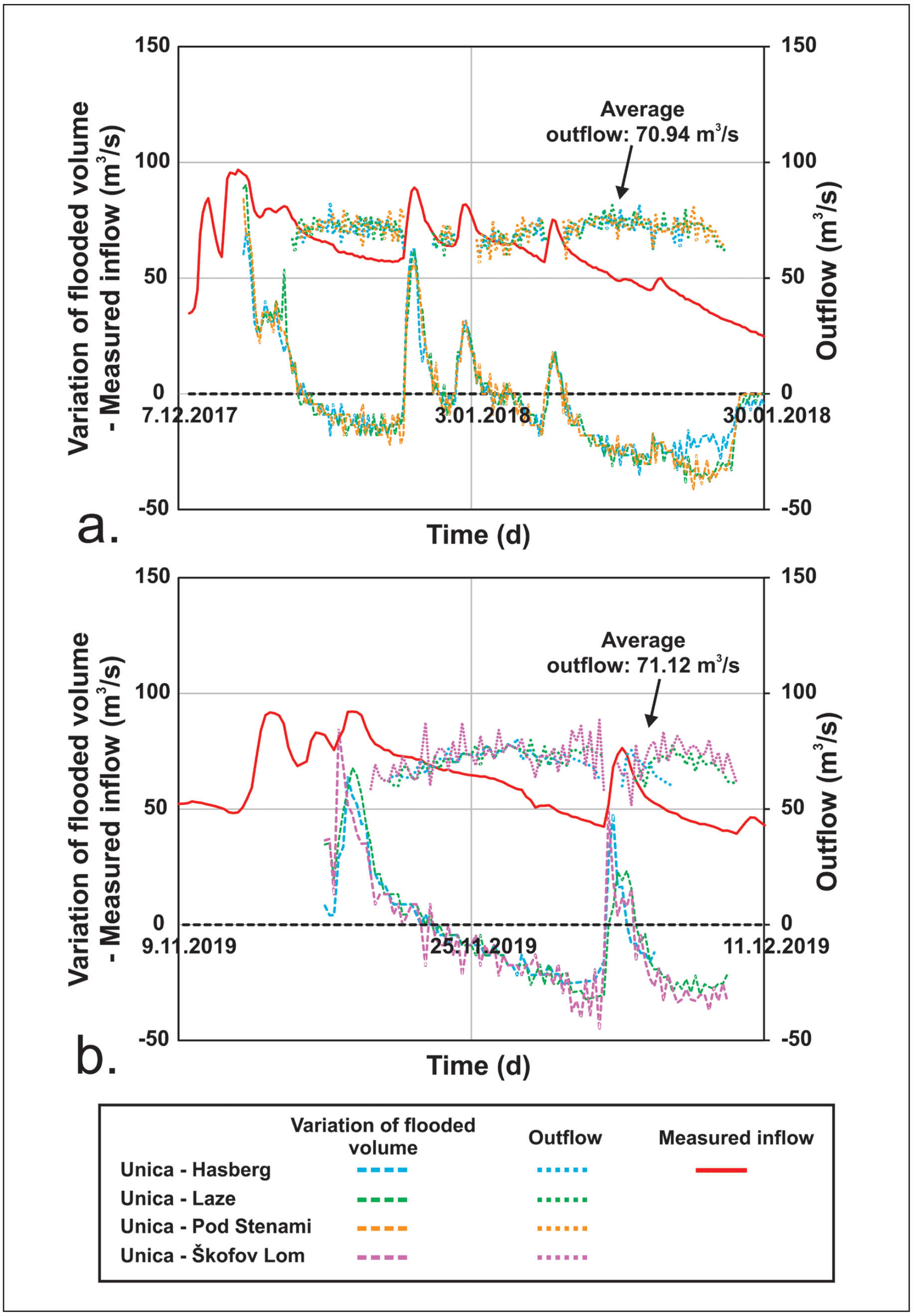

Figure 7: Variation of flooded volume, outflow and measured inflow during (a) the flood of December 2017; (b) the flood of November 2019.

4.4 TOTAL INFLOW

The total inflow entering Planinsko Polje during the floods of December 2017 and November 2019 (Figure 8) is reconstructed by adding the variation of flooded volume to the outflow determined in Table 5. Because uniformed level was not reached at the event beginning, the first part of each signal cannot be reconstituted. However, it is possible to estimate this amount using surplus inflow values of other extreme floods presented in Table 3. As an example, the floods of December 2010 and November 2014 had important flood peaks with maximum surplus inflow reaching respectively 98 m^3/s and 111 m^3/s. Assuming that the outflow at that time was identical to the value found in part 4.3, the total inflow would reach values between 165 and 180 m^3/s. Such amounts of surplus and total inflow are in agreement with the respective precipitation quantities and maximum water levels (Table 3) that were recorded during these events. Therefore, the same reasoning can be transposed to the floods of December 2017 and November 2019 (Figure 8), keeping in mind that the missing data at the event onset can approach, but not overtake such extreme total inflows.

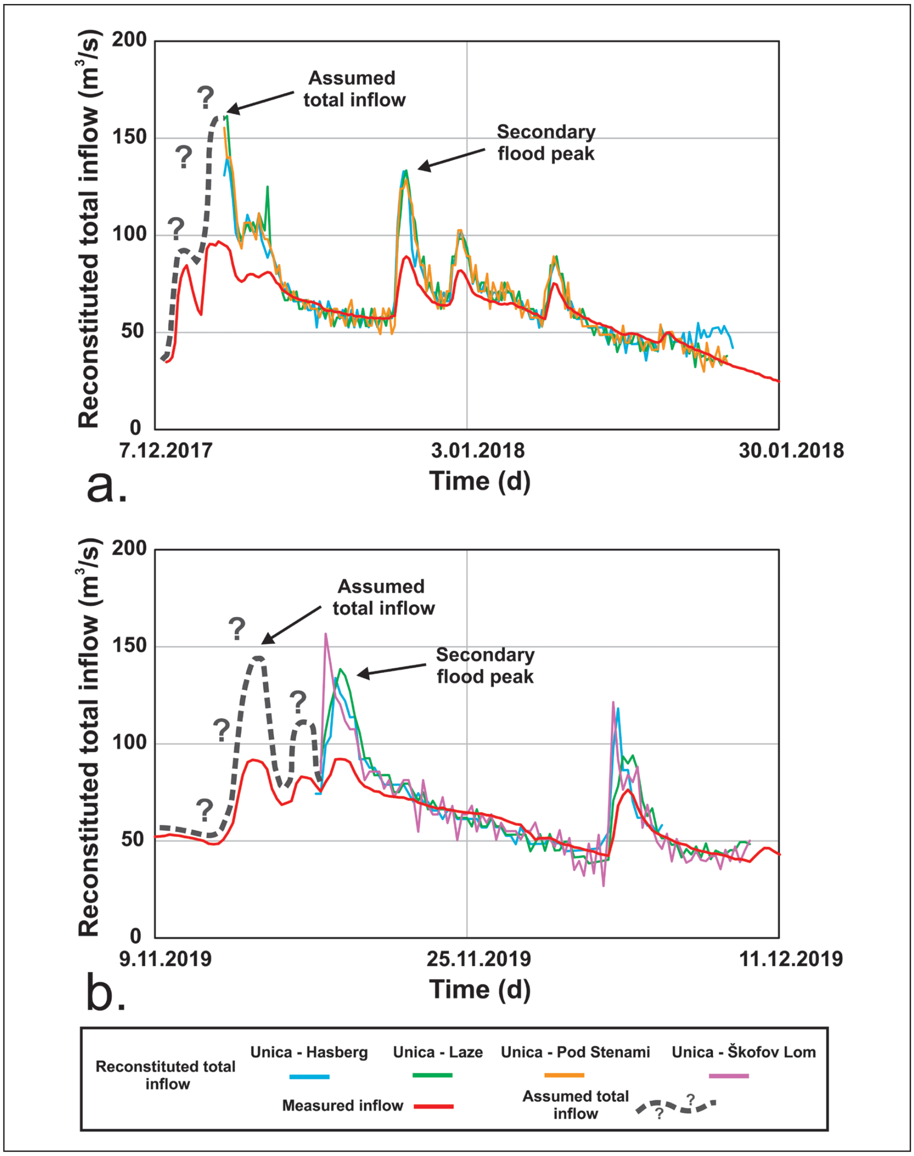

Figure 8: Total inflow entering Planinsko Polje during (a) the flood of December 2017 and (b) the flood of November 2019.

When looking the reconstituted total inflows of December 2017 and November 2019 (Figure 8), it is visible that both events have an important secondary flood peak occurring after reaching uniformed level. In both cases, the values were comparable, with total inflow around 130 - 140 m^3/s. Such numbers are consistent with the hydro-meteorological conditions at that time. They support the assumption that higher total inflow may occur at the event onset and also agree with the maximum inflow values mentioned by Putick (1889).

4.5 UNGAUGED INFLOW

An assessment of the ungauged inflow entering the polje is obtained by subtracting the measured inflow from the total inflow. The ungauged inflow comprises contributions from the Škratovka spring, the estavelles, the rain falling on the polje surface as well as any other spring discharging into the polje. In addition, it can contain measurement uncertainties made during the implementation of the rating curves of the Unica and Malenščica springs. Figure 9 presents the total amount of ungauged inflow during the floods of December 2017 and November 2019, focusing solely on analysing secondary flood peaks. For December 2017 (Figure 9a), maximum values of about 43 m^3/s, 20 m^3/s and 10 m^3/s were reached on 28.12.2017 at 12:00 (1), 02.01.2018 at 12:00 (2) and 10.01.2018 at 12:00 (3). This corresponds respectively to approximately 1/3, 1/5 and 1/8 of the total inflow recharging the polje at that time. For November 2019 (Figure 9b), maximum values of about 40 m^3/s and 20 m^3/s occurred on 18.11.2019 at 12:00 (1) and 03.12.2019 at 12:00 (2), and correspond respectively to 1/3 and 1/4 of the total inflow entering the polje. Therefore, it can be assumed that the quantity of ungauged inflow increases with the event intensity. Conversely, values of ungauged inflow are slightly negative (between -2.5 m^3/s and -5 m^3/s) during both event recessions. This shows that the measured inflow is probably a good approximation of the total inflow entering the polje at that time; while the effect of both Škratovka spring and the estavelles is of secondary importance, compensating each other during the recession. Nonetheless, as an important part of the inflow is ungauged during the event onset, it would be meaningful to know if the proportion is similar to the results presented above. If the answer is affirmative, an amount of ungauged inflow up to 50-60 m^3/s could be expected during the first wave of both floods. This would result in a total inflow of 140-150 m^3/s entering Planinsko Polje at that time, as assumed in part 4.4. However, it has to be kept in mind that assumptions on both inflows of the Škratovka spring and the estavelles have been made to assess the outflow. This means that the reconstruction of the total inflow and the assessment of the ungauged inflow are surely within a range of uncertainties.

The identification and separation of all different signals comprised in the ungauged inflow is highly challenging. However, the following observations can be made:

(1) The computation of the hydraulic gradient between the cave Andrejevo Brezno 1 and the polje allows knowing the estavelles hydrological behaviour. Thus, gradient values equal to 0 imply a minor contribution of the estavelles on the water balance (Table 4); regardless they function as spring or ponor. Such situations occur mostly at the beginning of the flood recession (Figure 6b). Conversely, maximum and minimum gradient values occur during the event on-

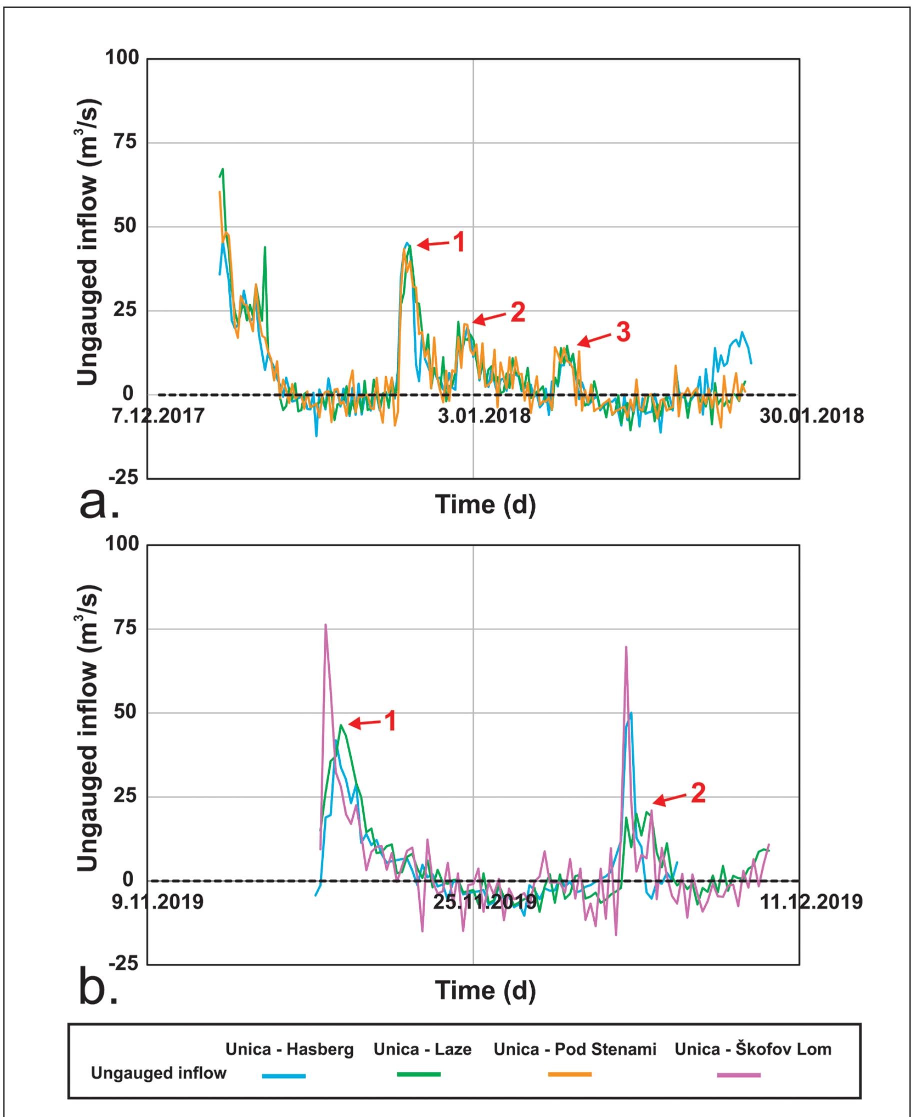

Figure 9: Ungauged inflow entering Planinsko Polje during: (a) the flood of December 2017 and (b) the flood of November 2019. Red bold numbers indicate inflection points described in the text.

set and late recession (Figure 6b), proving that the estavelles are a non-negligible contributor of the polje water balance in such periods (Blatnik et al., 2019). Therefore, an accurate quantification of the estavelles in- and outflow should be subject of future work.

(2) Despite the absence of a rating curve, the effect of the Škratovka spring can be estimated via the measurements presented in Table 2. This spring is assumed to discharge at its maximum capacity during the event rise, while the inflow should be of less importance during the recession. Future works should attempt to establish its rating curve.

(3) The rainfall falling over the polje surface can be converted into inflow using the theoretical variation of surplus inflow per level increase (Figure 3b). As the rain gauge of Jakovica was out of service in December 2017, the analysis is only made for November 2019. The sum of the rainfall at a six hourly time step leads to maximum rain amounts of 29.4 mm/6 hours and 12.8 mm/6 hours at the event onset. If these values are correlated to the corresponding water level in the polje at that time, converted value of theoretical surplus inflow of about 12.14 m^3/s and 4.13 m^3/s are found. This shows that direct inflow from the rain may have a high impact on the flood at the event onset, but that it lasts only during a very short time interval (Kovačič, 2010). Therefore, the difference between the total ungauged inflow and these quantities lead to remaining ungauged inflow values of 14.31 m^3/s and 31.55 m^3/s. These numbers comprise contribution from the estavelles, from the Škratovka spring as well as from all other ungauged springs active at the event onset.

(4) The inflow of the remaining ungauged springs could be either gauged, or indirectly identified by measuring the inflow of the Škratovka spring and the estavelles.

Future works will have to focus on improving characterization techniques to assess and separate all ungauged signals going in and -out Planinsko Polje.

5. DISTRIBUTED NUMERICAL MODELLING

A numerical model was implemented to validate the water balance of Planinsko Polje. The software Storm Water Management Model (SWMM) is selected to simulate the flood dynamics in the polje and its surrounding aquifer. The model setting is made of a realistic configuration of pipes and reservoirs based on the works of Blatnik et al. (2019) and Mayaud et al. (2019), keeping the conduit geometry as simple as possible and considering only the most important water active caves in the area (Figure 2). The model surface - volume relationship is based on the curve shown in Figure 3a, with the polje bottom defined at 444 m a.s.l. and a 10 cm vertical resolution until the altitude of 452 m a.s.l. Conversely to Blatnik et al. (2019) and Mayaud et al. (2019), the head in the cave Andrejevo Brezno 1 is defined as a prescribed head boundary using the water levels recorded in the cave. This allow putting a constraint on the flow entering and leaving the polje via the estavelles. The period investigated goes from the 09.09.2017 to the 08.03.2018 (180 days). It comprises a flood of small amplitude and long duration (September 2017) and a flood of large amplitude and long duration (December 2017). The model input and reporting time steps are 6-hours long similarly to recorded data. The calibration focuses on reproducing the water levels fluctuations in the polje (Unica - Hasberg) and in its neighboring caves (Najdena Jama, Gradišnica and Logarček). Simulated water levels are evaluated against the recorded data using the Nash Sutcliffe Efficiency NSE (Nash & Sutcliffe, 1970). In addition, values of modelled outflow are analyzed in light of previous studies (Jenko, 1959; Šušteršič, 2002; Blatnik et al., 2017) to confirm the model robustness.

The numerical simulations compare the model reaction to two different input signals. The first signal (1) is the reconstituted total inflow presented in this work. This signal is defined as the sum of the variation of flooded volume with the outflow during flood periods and as the measured inflow during low flow conditions. The variation of flooded volume recorded at each station are averaged together to remove noise, while the part that cannot be determined at the event onset is extrapolated based on results in Figure 8 and Table 3. Because the contribution of the estavelles is delivered by the prescribed head boundary in the cave Andrejevo Brezno 1, it has to be removed from the input time series. The flow provided by the estavelles is assumed to be a third of the ungauged inflow, which is seen as a realistic amount. The second signal (2) tested is the sum of the discharge measured at Unica - Hasberg with the flow provided by the estavelles. This allows verifying if the flow recorded at Unica - Hasberg is representative to simulate the flood dynamics. The model geometry and values of hydraulic parameters are identical in both simulations. Therefore, the sole effect of the two input signals is compared, while model calibration is based on changing conduit diameters and ponor elevations.

Figure 10 presents the modelled water levels for both simulations. As it can be seen, the model with the reconstituted inflow signal reproduces the flooding dynamics in the polje and its surrounding caves in a better way than the model using Unica - Hasberg and the estavelles as input. This is especially visible for the water levels in Planinsko Polje, which are overestimated for more than 3.5 m if the flow at Hasberg and the estavelles is used. This can be explained due to the rating curve of Hasberg, which delivers constant flow values as soon as the station is flooded. For the simulation implemented with the reconstituted inflow signal, NSE values are of 0.96 for Unica - Hasberg, 0.84 for Najdena Jama, 0.92 for Gradišnica and 0.82 for Logarček. Conversely, values of NSE are very poor if the inflow is assumed to correspond to the discharge of Unica - Hasberg and the estavelles, with -0.72 for Unica - Hasberg, 0.47 for Najdena Jama, 0.51 for Gradišnica and 0.52 for Logarček. These notable differences confirm that the flow recorded at Unica - Hasberg is not suitable to model the flood, as the flooding of the Unica River over its banks make important approximations in its rating curve.

Figure 11a shows the outflows of the model that has been computed with the reconstituted inflow as input signal (1). For the modelled period, the polje total outflow is comprised between 69 and 77 m^3/s. This is in good agreement with the values of measured inflow summarized in Table 4, and highlights how the estavelles behaviour affects the polje total outflow. In the same way, the functioning of the northern ponor zone is in agreement with measured water levels, while the modelled values around 50 m^3/s are in the range described by Jenko (1959) and Šušteršič (2002). The eastern ponor zone is always active and shows a maximum outflow of 18.6 m^3/s similar to the values measured by Blatnik et al. (2019). Finally, the flow going through the estavelles is realistic, with a maximum modelled inflow of 11.3 m^3/s and a maximum modelled outflow of 8.5 m^3/s during the event of December 2017. Figure 11b shows the reconstruction of both input signals tested by the numerical model using the modelled water levels and outflow time series. As it can be seen, the reconstituted inflow is identical to the input that have been given into the model. This result proves that the water balance theory presented in this paper is valid for the numerical model, and implies that the same reasoning should be also valid for the real system.

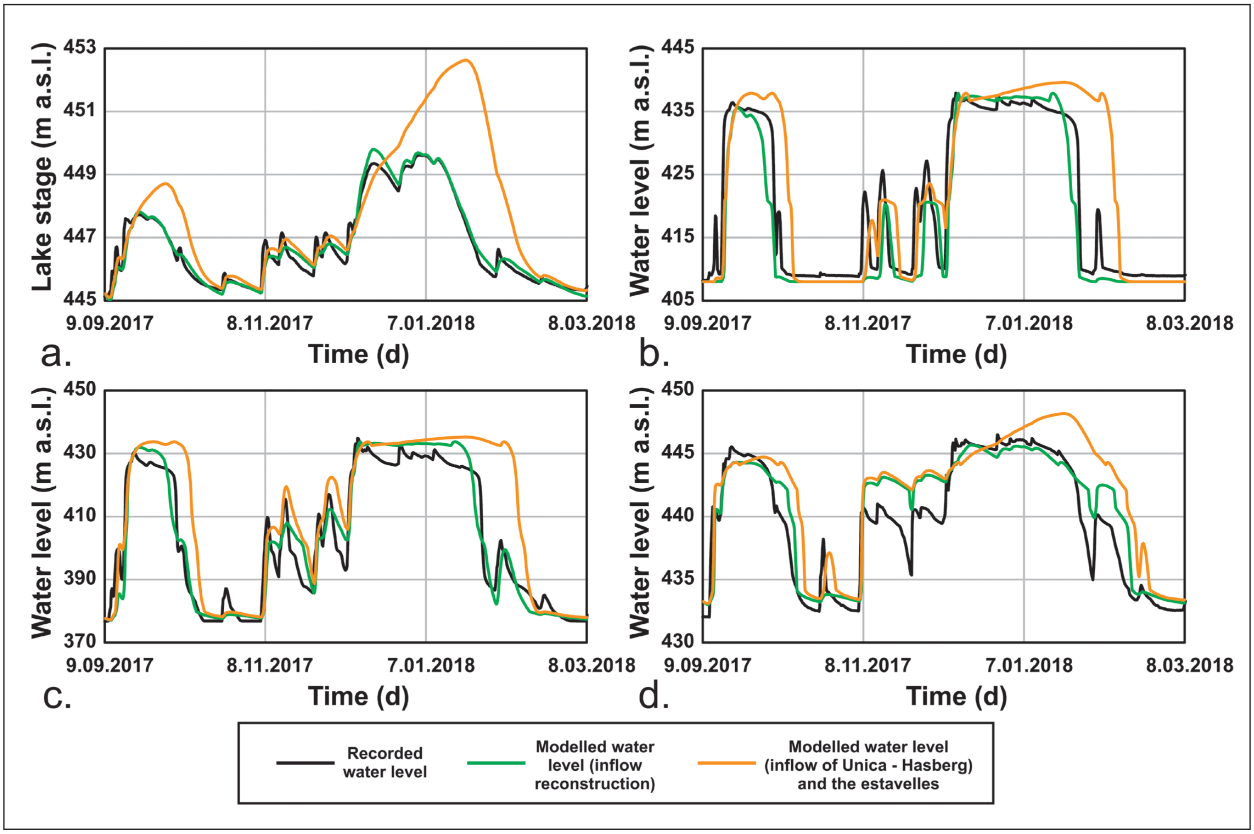

Figure 10: Measured and simulated water levels during the floods of September and December 2017 for (a) Planinsko Polje; (b) Najdena Jama; (c) Gradišnica; (d) Logarček.

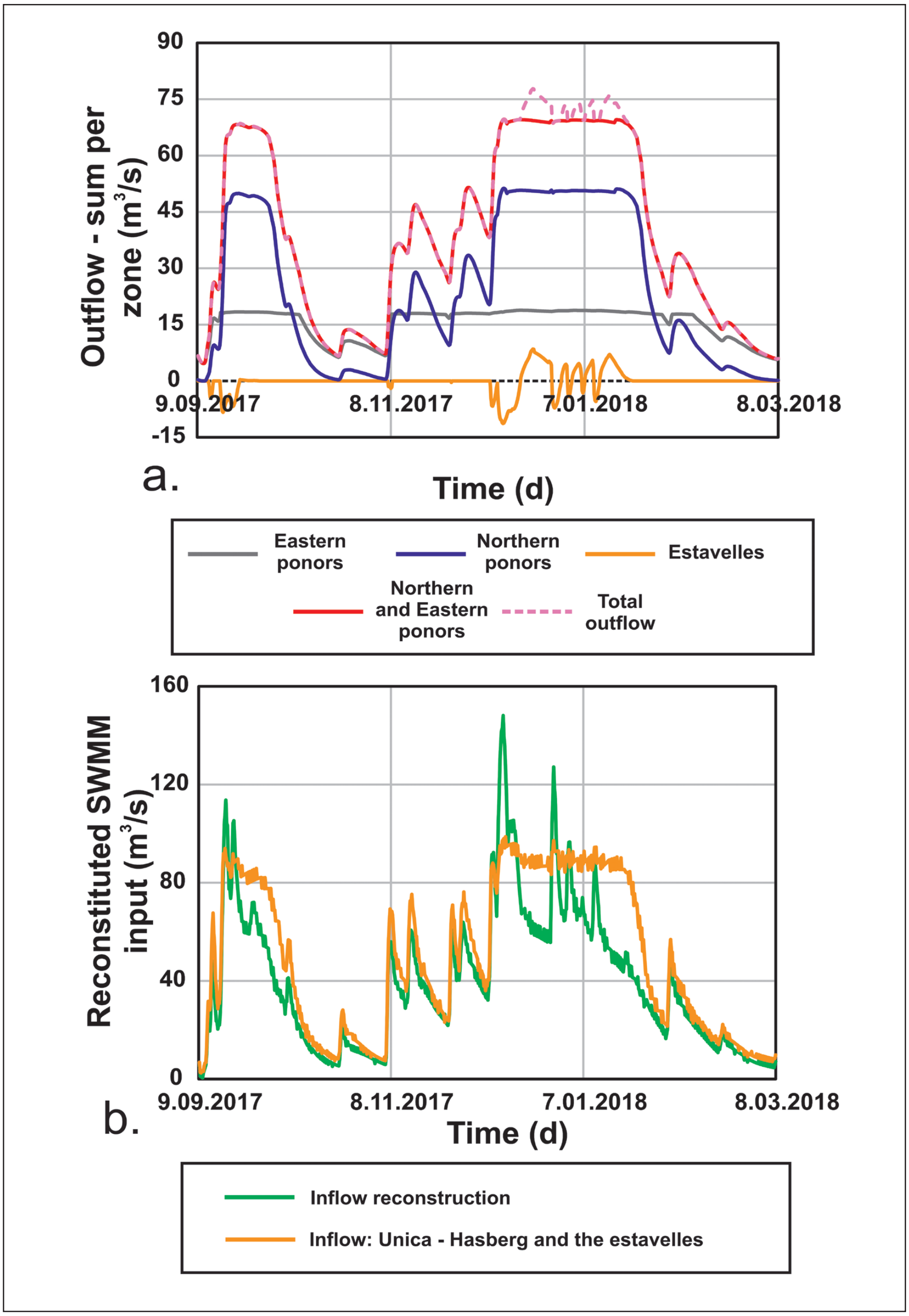

Figure 11: (a) Total and individual outflow at each ponor zone for the model simulated with the reconstituted inflow. (b) Reconstituted inputs based on the variation of flooded volume and outflow of both numerical models.

6. DISCUSSION

6.1 WATER BALANCE IMPLEMENTATION

The water balance of Planinsko Polje has been assessed using a network of stations installed in the polje and its surrounding aquifer. While the method proved to be helpful to characterize the polje inflow and outflow, time and budget restrictions do not allow to collect a similar dataset in every polje. Therefore, several recommendations can be made to ensure an accurate estimation of the water balance, even if less data are available.

The polje surface-volume relationship is crucial to compute the water balance. This implies the use of a DEM, which is generally available in state-managed geographical portals at a relatively modest cost. While a 1 m resolution DEM has been used in this work, coarser pixel resolutions up to 10 m could be probably employed without losing too much accuracy on the cumulative volume.

The existence of notable water level differences between the polje upper parts and terminal outflow zones implies the meaningful installation of measuring stations over the entire surface to catch properly the flood dynamics. Whenever possible, a minimum of two water level stations installed in the lowest ponor zone and in the polje higher part is recommended, while the polje main inflow should be gauged. In addition, monitoring the caves located on the polje outflow side is important to record the aquifer response. If financial restrictions prevent installing such network, the theoretical surplus inflow per increase of 1 cm can be used to estimate the inflow. This technique requires only a few water level measurements during the most important moments of the flood (start, beginning and end of uniformed level, flood peak, end of recession etc.). It allows extrapolating the inflow depending on the speed of filling.

A hydrological time series containing a sufficient number of floods of different amplitudes and durations is necessary. Ideally, the minimum-recorded period should cover one to two hydrological years, and comprise a flood of high amplitude to estimate the highest possible values of surplus inflow and outflow. In addition, available maximum water levels of past extreme floods can be used. Finally, it is recommended to record the hydrological time series at a high frequency (e.g., hourly) and to remove noise from the signal depending on the oscillation of the variation of flooded volume.

The quantification of the outflow is challenging, as an important proportion of the inflow entering the polje might be ungauged. This work assessed the outflow by two ways based on water level and flow records of the polje main springs. While the results showed to be in good agreement with each other, it should be kept in mind that the outflow might be underestimated using such approach as gauging all inflows entering the polje is practically impossible. In addition, as the outflow might also depends on the maximum water level reached and on the quantity of material accumulated at the ponor zones (López-Chicano et al., 2002; Frantar & Ulaga, 2015; Mayaud et al., 2019) it may vary from one flood to another.

Finally, characterizing the behaviour of estavelles is of high importance, as they contribute to both polje inflow and outflow. In this work, water level measurements in a cave located nearby a group of estavelles helped to understand their functioning, and proved to be very useful to assess the outflow.

6.2 UNCERTAINTIES WITHIN THE APPROACH

The assessment of the water balance of a complex system such as Planinsko Polje comprises several uncertainties. The first one is related to the quality of the dataset collected, with possible measurement errors made by the monitoring stations and during the implementation of the rating curves, as it is challenging to measure accurately high discharges. Then, the determination of the polje outflow relies on the assumption that the measured inflow approximates the inflow entering the polje when $dV/dt = 0$. This is only valid if the contribution of the estavelles (when the hydraulic gradient is equal or close to 0) and of the Škratovka spring are neglected. While the approach is probably correct, it should be also reminded that the computation of the gradient between the estavelles and the polje relies on the assumption that water level at the estavelles and at the ponor zones should be almost identical. Therefore, any difference in water level would affects the assessment of both total and ungauged inflow, and put the determined values within a range of uncertainties. Furthermore, the total inflow entering the polje at the event onset is extrapolated based on secondary flood peaks recorded during the highest floods and should be interpreted carefully. Finally, the conceptual hydrogeological model of the polje and its surrounding aquifer is made using all knowledge of the field area, but is still a partial representation of the real system.

The numerical model used in this work aimed validating the results from the water balance analysis of Planinsko Polje. Because the plausibleness of the inflow signal is tested, model calibration was reached by adapting the elevation and outflow/drainage capacity of the ponors zones and observing the respective water level variations in the polje and three of its surrounding caves. In addition, modelled ponor outflows were compared to estimated values. Modelling results showed the validity of the approach, and confirmed that the values of inflow and outflow found via the data analysis were highly realistic. However, it is important to remember that numerical modelling comprises always a subjective part depending on the user. This significates that equifinality cannot be excluded. Nevertheless, the results of the analysis tend to support the conceptual hydrological model and water balance approach tested, and should reduce the risk to obtain similar results with a geometrical configuration radically different from the one presented.

7. CONCLUSIONS

This work presented a method to assess the water balance of a typical Dinaric polje flooding by a complex interaction of spring inflow with a rise of the regional groundwater level. To do so, a 1 m DEM of Planinsko Polje was used with water levels measured in the polje surface and surrounding caves, and combined with inflow data of the main two springs. This allowed determining the variation of flooded volume and estimating the outflow. The total inflow entering Planinsko Polje could be reconstructed and the proportion of ungauged inflow quantified. The in- and outflow values were used as input data in a numerical model aiming reproducing the hydrological dynamics in the polje and its surrounding aquifer. The model validated the numbers found by the water balance analysis, the conceptual hydrological model and the water balance method tested. The results show that while it is impossible to measure individually each signal entering or leaving poljes, combining water levels and flow measurements with a DEM allows assessing the water balance in an accurate way. Because monitoring network is sparse or absent in many poljes, a discussion on the hydrological points to be equipped in priority was implemented. The method presented in this work is seen to be straightforward, and can be applied to any other polje flooding on the same principle. At a regional scale, it opens important perspectives for flood forecasting. The inflow entering Planinsko Polje during past severe floods could be reconstructed, and the polje reaction to extreme hydrological events driven by climate change could be studied. Finally, the characterization of the outflow of Planinsko Polje provides a relevant contribution to better understand the hydrological behaviour of the karst aquifer located between the ponors and the Ljubljanica springs 15 km northward.

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REFERENCES

Anderson, M.P., Woessner, W.W., Hunt, R.J., 2015. Applied Groundwater Modeling. Simulation of Flow and Advective Transport. Second Edition. Academic Press.

ARSO, 2022a. Archive of hydrological data. Ministry of the Environment and Spatial Planning, Slovenian Environment Agency. Available online: http://vode.arso.gov.si/hidarhiv/. [Accessed 21 April 2022].

ARSO, 2022b. Lidar data network. Ministry of the Environment and Spatial Planning, Slovenian Environment Agency. Available online: https://gis.arso.gov.si. [Accessed 21 April 2022].

Blatnik, M., Frantar, P., Kosec, D., Gabrovšek, F., 2017. Measurements of the outflow along the eastern border of Planinsko Polje, Slovenia. Acta Carsologica, 46(1): 83–93. https://doi.org/10.3986/ac.v46i1.4774.

Blatnik, M., Mayaud, C., Gabrovšek, F., 2019. Groundwater dynamics between Planinsko Polje and springs of the Ljubljanica River, Slovenia. Acta Carsologica, 48(2): 199–226. https://doi.org/10.3986/ac.v48i2.7263.

Blatnik, M., Mayaud, C., Gabrovšek, F., 2020. Supplement to the paper "Groundwater dynamics between Planinsko Polje and springs of the Ljubljanica River, Slovenia" from Blatnik et al. (2019) published in Acta Carsologica 48(2). Acta Carsologica, 49(1): 143-147. https://doi.org/10.3986/ac.v49i1.8967.

Bonacci, O., 1987. Karst hydrology: with special reference to the Dinaric karst. Springer-Verlag, Berlin, 184 pp. https://doi.org/*10.1007/978-3-642-83165-2*.

Bonacci, O., 2013. Poljes, ponors and their catchments. In: Shroder, J. (Editor in Chief), Frumkin, A. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 6, Karst Geomorphology, 112–120. *https://doi.org/10.1016/b978-0-12-374739-6.00103-2*.

Duran, L., Gill, L., 2021. Modeling spring flow of an Irish karst catchment using Modflow-USG with CLN. Journal of Hydrology, 597: 125971. https://doi.org/10.1016/j.jhydrol.2021.125971.

Ford, D., Williams, P., 2007. Karst Hydrogeology and Geomorphology. John Wiley & Sons, 562 pp.

Frantar, P., Ulaga, F., 2015. Visoke vode Planinskega polja leta 2014. Ujma, 29, 66–73.

Gabrovšek, F., Kogovšek, J., Kovačič, G., Petrič, M., Ravbar, N. & J. Turk, 2010: Recent results of tracer test in the catchment of the Unica River (SW Slovenia). Acta Carsologica, 39(1): 27-37. https://doi.org/10.3986/ac.v39i1.110.

Gabrovšek, F., Peric, B. & G. Kaufmann, 2018: Hydraulics of epiphreatic flow of a karst aquifer, Slovenia-Italy.- Journal of Hydrology, 560: 56-74. https://doi.org/10.1016/j.jhydrol.2018.03.019

Gams, I., 1981. Poplave na Planinskem Polju. Geografski Zbornik XX.

Gill, L.W., Naughton, O., Johnston, P., 2013. Modelling a network of turloughs in lowland karst. Water Resources Research, 49(6): 3487-3503. https://doi.org/*10.1002/wrcr.20299*

Gill, L.W., Schuler, P., Duran, L., Morrissey, P., Johnston, P.M., 2021. An evaluation of semidistributed-pipe-network and distributed-finite-difference models to simulate karst systems. Hydrogeology Journal, 29: 259–279. https://doi.org/10.1007/s10040-020-02241-8

Gospodarič, R., Habič, P. (Eds.), 1976. Underground water tracing. Investigations in Slovenia 1972–1975. Institute for Karst Research, Ljubljana, Slovenia. 309 pp.

Jelovčan, M., Žigon, T., Brenčič, M., 2021. Zgodovina in rekonstrukcija meritev vodostajev na Planinskem polju - History and reconstruction of water level measurements on the Planinsko polje. Geografski vestnik, 93(1). https://doi.org/10.3986/GV93103

Jenko, F., 1959. Hidrogeologija in vodno gospodarstvo krasa. Državna založba Slovenije. Ljubljana. 237 pp.

Kogovšek, B., 2022. Characterization of a karst aquifer in the recharge area of Malenščica and Unica springs based on spatial and temporal variations of natural tracers. [PhD thesis]. University of Nova Gorica, 242 pp.

Kovačič, G., 2010. An attempt towards an assessment of the Cerknica Polje water balance. Acta Carsologica 39 (1), 39-50. https://doi.org/10.3986/ac.v39i1.111

Kovačič, G., Ravbar, N., 2010. Extreme hydrological events in karst areas of Slovenia, the case of the Unica River basin. Geodinamica Acta, 23(1-3): 89-100. https://doi.org/*10.3166/ga.23.89-100*

López-Chicano, M., Calvache, M.L., Martín-Rosales, W., Gisbert. J., 2002. Conditioning factors in flooding of karstic poljes - the case of the Zafarraya polje (South Spain). Catena, 49: 331– 352.

Lučić, I., 2014. General aspects of the Karst Poljes of the Dinaric Karst. In: Sackl P., Durst R., Kotrošan, D., Stumberger, B., 2014. Dinaric Karst Poljes - Floods for Life. EuroNatur, Radolfzell.

Mayaud, C., Gabrovšek, F., Blatnik, M., Kogovšek, B., Petrič, M. & N. Ravbar, 2019: Understanding flooding in poljes: a modelling perspective. Journal of Hydrology, 575: 874-889. https://doi. org/10.1016/j.jhydrol.2019.04.092

McCormack, T., O'Connell, Y., Daly, E., Gill, L.W., Henry, T., Perriquet, M., 2017. Characterisation of karst hydrogeology in Western Ireland using geophysical and hydraulic modelling techniques. Journal of Hydrology: Regional Studies, 10: 1–17. https://doi.org/10.1016/j.ejrh.2016.12.083

Mihevc, A., Zupan Hajna, N., Prelovšek, M., 2010. Case studies from the Dinaric Karst of Slovenia. In: Mihevc, A., Prelovšek, M., Zupan Hajna, N., (Eds.) 2010. Introduction to the Dinaric Karst. Karst Research Institute at ZRC SAZU, Postojna.

Milanović, P., 2004. Water resources engineering in Karst. CRC Press. Boca Raton. 328 pp.

Morrissey, P.J., McCormack, T., Naughton, O., Johnston, P.M., Gill, L.W., 2020. Modelling groundwater flooding in a lowland karst catchment. Journal of Hydrology, 580: 124361. https://doi.org/10.1016/j.jhydrol.2019.124361

Morrissey, P., Nolan, P., McCormack, T., Johnston, P., Naughton, O., Bhatnagar, S., and Gill, L., 2021. Impacts of climate change on groundwater flooding and ecohydrology in lowland karst, Hydrology Earth Systems Sciences, 25: 1923–1941. https://doi.org/10.5194/hess-25-1923-2021.

Myhre, G., Alterskjær, K., Stjern, C.W.,. Hodnebrog, Ø., Marelle, L., Samset, B.H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M,. Stohl, A., 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. Scientific Reports, 9: 16063. https://doi.org/10.1038/s41598-019-52277-4

Naughton, O., Johnston, P.M., Gill, L.W., 2012. Groundwater flooding in Irish karst: The hydrological characterization of ephemeral lakes (turloughs). Journal of Hydrology, 470-471: 82-97. https://doi.org/10.1016/j.jhydrol.2012.08.012

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, part I: a discussion of principles. Journal of Hydrology, 10: 282–290. https://doi.org/10.1016/0022- 1694(70)90255-6

Pagnozzi, M., Coletta, G., Leone, G., Catani, V., Esposito, L., Fiorillo, F., 2020. A Steady-State Model to Simulate Groundwater Flow in Unconfined Aquifer. Applied Sciences, 10(8): 2708. https://doi.org/10.3390/app10082708

Putick, W., 1889. Die hydrologischen Geheimnisse des Karstes und seine unterirdischen Wasserläufe: auf Grundlage der neuesten hydrotechnischen Forschungen. Himmel und Erde.

Ravbar, N., 2008. Naravne in ekološke nesreče na Krasu. In: Zorn, M., Komac, B., Pavšek, M., Pagon, P., (Eds.) 2008: Naravne nesreče v Sloveniji : zbornik povzetkov : 1. trienalni znanstveni posvet, Ig (Izobraževalni center za zaščito in reševanje Republike Slovenije). Ljubljana: Založba ZRC.

Ravbar, N., 2013: Variability of groundwater flow and transport processes in karst under different hydrologic conditions. Acta Carsologica, 42(2-3): 327-338. https://doi.org/10.3986/ac.v42i2.644

Ravbar, N., Petrič, M., Kogovšek, B., Blatnik, M., Mayaud, C., 2018. High waters study of a Classical Karst polje – An example of the Planinsko Polje, SW Slovenia. Symposium Karst 2018 – Expect the Unexpected. Proceedings, 417-424. Trebinje.

Ravbar, N., Mayaud, C., Blatnik, M., Petrič, M., 2021. Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping. Hydrogeology Journal, 29(1): 213-228. https://doi.org/10.1007/s10040-020-02268-x

Schuler, P., Stoeckl, L., Schnegg, P.A., Bunce, C., Gill, L., 2020. A combined-method approach to trace submarine groundwater discharge from a coastal karst aquifer in Ireland. Hydrogeology Journal, 28: 561-577. https://doi.org/10.1007/s10040-019-02082-0

Stepišnik, U., Ferk, M., Gostinčar, P., Černuta, L., 2012. Holocene high floods on the Planina Polje, Classical Dinaric Karst, Slovenia. Acta Carsologica, 41(1): 5-13. https://doi.org/10.3986/ac.v41i1.44

Šušteršič, F., 2002. Where does Underground Ljubljanica Flow? RMZ Materials and Geoenvironment, 49(1): 61-84.

Tabari, H., 2020. Climate change impact on flood and extreme precipitation increases with water availability. Scientific Reports, 10: 13768 . https://doi.org/10.1038/s41598-020-70816-2

Tramblay, Y., Somot, S., 2018. Future evolution of extreme precipitation in the Mediterranean. Climatic Change, 151: 289-302. https://doi.org/10.1007/s10584-018-2300-5

Turk, J., 2010. Dynamics of underground water in the karst catchment area of the Ljubljanica springs. Založba ZRC, Ljubljana 136 p. ISBN 978-961-254-233-7 (Carsologica 11).

Worthington, S.R.H., 2009. Diagnostic hydrogeologic characteristics of a karst aquifer (Kentucky,USA). Hydrogeology Journal, 17(7): 1665–1678. https://doi.org/10.1007/s10040-009-0489-0

Worthington, S.R.H., Smart, C.C., Ruland, W., 2012. Effective porosity of a carbonate aquifer with bacterial contamination: Walkerton, Ontario, Canada. Journal of Hydrology 464-465: 517-527. https://doi.org/10.1016/j.jhydrol.2012.07.046