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REPORT

Flooding and flood water storage in karst systems of the Mediterranean region

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Abstract

Flooding is a recurring natural phenomenon that can have both life-giving and destructive aspects. In natural environments, floods are often an important element of the seasonal hydrologic cycle that provides water and nutrients to soil, supporting unique, rich and diverse ecosystems. However, flood events can also represent a destructive force that can endanger lives and cause significant damage in urban areas. Karst areas, in particular, are unique because of their special hydraulic characteristics in terms of flood occurrence, the dependence of ecosystems on such events, and attempts to actively store and manage floods. In this article, the hydraulic response of karst aquifers to heavy precipitation events, flood generation, and engineering interventions for flood control are discussed using several examples from karst areas in the Mediterranean region. Flooding mechanisms and regulatory structures in karst poljes are considered using several typical examples from the Dinaric mountain range. In addition, different variants of groundwater abstraction for increasing storage capacity and flood control are presented using examples from France and Montenegro. Managed aquifer recharge in karst areas and adjacent aquifers is demonstrated with examples from Jordan and Algeria. Finally, failed attempts at flood storage in karst reservoirs are presented with examples from Spain and Montenegro. These examples of flood retention in karst areas show the wide range of planning and technical measures and remind us of possible risks and failures in implementation as well as some positive and negative impacts on the environment and especially on ecosystems.

Keywords Flooding · Flood water storage · Carbonate rocks · Karst · Mediterranean region

Introduction

Flooding is a natural phenomenon that is a part of the water cycle and is typically caused by abundant precipitation or snowmelt, but can also be the result of, for example, ice jams in rivers, glacial lake outburst floods, or due to the failure of water infrastructure facilities such as dams or drainage systems (Sene 2012). In most cases, rainfall-induced flash flooding occurs within very short time periods and typically last from a few minutes to a few hours. However, there are also examples where consecutive days of precipitation lead to flooding events. The heavy rainfall flash flooding events often occur locally, mostly in areas smaller than 1,000 km^2, but sometimes much larger areas are affected. The risk of flash floods varies by region at different times of the year, but is likely to become more frequent and severe due to global climate change influencing storm weather systems and river flow dynamics (Pastor and Khodayar 2023; Menna et al. 2022; Yu et al. 2020).

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Besides the precipitation regime, the generation of flood events is also determined by the morphological characteristics of the catchment, the soil properties, and the prevailing geology (Marchi et al. 2010; Zhou 2007). Geology is of particular importance as it determines these infiltration and storage capacity of the subsurface the overall runoff dynamics of the catchment. The hydrological interaction between soil and bedrock is crucial for the formation of preferential flow paths and thus for flood generation. The pre-saturation conditions of the soil controls runoff formation (Marchi et al. 2010), but aquifer permeability and storage capacity are also key factors in flood generation (Vannier et al. 2016), as well as flood attenuation and delay.

In the Mediterranean region, flood events are a frequently observed phenomenon, with extreme flash floods usually occurring in autumn over the western part of the Mediterranean and during the winter in the eastern part. Whereas, in the summer months, the occurrence of flash floods tends to be observed inland (Gaume et al. 2009). In the norther Mediterranean, the Alps and the Dinaric mountains act as a strong orographic barrier, causing high precipitation values in some parts of Italy and the Balkan region. Another strong impact on flooding in these countries arrives from Genoa cyclone, or Genoa low, that formed and developed in the vicinity of the Gulf of Genoa (Ligurian Sea), affecting the Adriatic and Ionian Sea and the Balkan region. Average annual rainfall can vary from 2,000 mm on the Adriatic coast to more than 5,000 mm at an altitude of 1,800 m on Mount Orjen (between Montenegro and Bosnia and Herzegovina). In 1938, for example, the highest annual rainfall ever recorded in Europe was 8,063 mm.

In natural environments, reoccurring flood events are part of the life-cycle of ecosystems and often provide unique conditions for a variety of species. For example, poljes (large closed depressions in karst areas with underground drainage; Pipan et al. 2022) and other ecosystems can contribute to flood regulation by serving as water retention basins (Crossman et al. 2019). However, increasing urbanization of natural landscapes and impairment of natural drainage systems result in flood events that become an increasingly serious climate- and weather-related hazard for people worldwide (Price et al. 2011), and are responsible for significant damage to buildings and infrastructure, as well as loss of life (Terranova and Gariano 2014). In this respect, flood water storage is an important aspect, in order to be able to mitigate the negative consequences of such events and, in the best case, to be able to make this water usable for agricultural purposes or for water supply, especially in water scarce regions.

The occurrence of floods in karst areas requires particular attention, as karst is highly sensitive to precipitation events due to its unique hydraulic characteristics. They exhibit large variations in flow velocity and storage and can therefore respond very quickly to precipitation events, resulting in rapidly rising groundwater levels or spring discharges. However, in the case of their large effective porosity, i.e. cavernousness, karst can provide a 'buffer' that attenuates the effect of heavy rainfall by slowing down the discharge of newly infiltrated water (Stevanović et al. 2015). Another important factor is the distinctive flow behaviour in the epikarst, the thin, heavily karstified upper zone. It usually has a much higher permeability than the underlying aquifer and often forms a perched aquifer (Bakalowicz 2004a, b). As the soil and epikarst subsystems can provide an important storage function in catchments (Perrin et al. 2003), they can contribute in a particular way to the generation of flood events. However, in contrast to impermeable rock formations where surface runoff is generated much more rapidly they have also unique buffering properties and flood mitigation potential. All these issues imply that, the contribution of karst groundwater flow to surface runoff needs to be assessed on a case-by-case basis (Jourde et al. 2007).

In this study, four categories of flood water storage and management examples are presented and discussed on the basis of selected case studies to raise awareness of karst-specific hydrological responses to heavy rainfall events and flood generation and to contribute to a better understanding of flood management. The case studies are a selection of natural karst settings and their characteristics in relation to the occurrence of flood events, engineering measures to manage them as well as general surface storage and active karst aquifer management. This study specifically focused on the hydraulic functioning and response of systems to heavy precipitation events and associated management measures, and to aspects of water quantity, whereas aspects of water quality were not considered.

- Flood mechanisms and regulatory structures in karst polje are discussed on the basis of three examples. These are the unregulated river flow and flood dynamics in the Planinsko Polje in Slovenia, the regulated river flow and dam construction in the Popovo Polje in Bosnia & Herzegovina, and the anthropogenic factors that stimulate flooding in the Cetinjsko Polje in Montenegro.
- Variants of groundwater abstraction from karst to increase storage capacity and protect against flooding are discussed using the example of flash flood mitigation by overpumping the aquifer at Lez spring, France, and a mobile abstraction point to prevent flooding of the captured groundwater at Bolje Sestre spring, Montenegro.
- Managed aquifer recharge in karst and adjacent aquifers is demonstrated with the examples of stored flood-induced recharge at Wadi Wala, Jordan, and underground dams at Laghouat, Algeria.
- Failed attempts to store flood water in karst reservoirs are also discussed, using the example of an unsuitable reser-

voir site at Montejaque, Spain, and an attempt to control enormous leakage from reservoirs at Nikšić, Montenegro.

Karst hydrogeology and flooding

The development of floods in karst areas is very different from that of other drainage basins because of the unique hydraulic characteristics of karst. Precipitation or surface runoff in karst areas generally infiltrates rapidly into the subsurface, diffusely through cracks, fissures, or by point recharge through ponors (swallow holes; Gutiérrez et al. 2014). Allogenic recharge processes (runoff from adjacent non-karstic areas) is generally reflected in the rapid response of spring discharge, whereas autogenic recharge (rainfall on karst areas) controls baseflow in the spring when the low-permeability portions of the saturated zone are drained. Thus, spring discharge behavior, reflects the interaction of precipitation supply, surface catchment size, and karstification degree of the karst groundwater basin, and thus its storage potential and infiltration-water retention capacity (El-Hakim and Bakalowicz 2007; White 2019). However, the size of the karst groundwater basin may increase (or decrease) due to changes in groundwater levels when adjacent dry karst systems are activated by rising groundwater levels, or vice versa (Bonacci 1987; Ravbar and Goldscheider 2009; Bonacci and Andrić 2015; Stevanović 2015). The combination of fast infiltration, rapid aquifer drainage, but low storage capacity can quickly lead to excess infiltration and thus surface runoff (Maréchal et al. 2008). Thus, when the infiltration rate exceeds the runoff capacity of the epikarst structures, or the vertical infiltration pathways are blocked, flooding occurs once the storage capacity of the epikarst is exceeded (Jones 2013; Bakalowicz 2019a, b). A similar situation occurs when underground channels and cave systems are completely filled with water and the maximum discharge capacity of springs is reached. This causes the water table in the aquifer to rise upgradient, eventually making further percolation at the surface impossible. This can also lead to the activation of temporary overflow springs (Zhou 2007; Bonacci et al. 2006). In eastern Herzegovina, for example, an enormous rise in groundwater levels of more than 90 m in just 24 h was recorded (Milanović 2000, 2021). Another example was a three day rainfall event in the Iška River catchment (Slovenia) in 2010, which caused a massive flood event with a peak discharge of 59.3 m^3/s after rapid transmission through the karst terrain. Recorded small, near-surface earthquakes that destroyed the deposits in the riverbed (Gosar and Brenčič 2012) possibly accompanied the subsequent rapid infiltration of almost all of the river water.

Flood-promoting conditions in karst are mostly the result of complex systems of hydraulic interaction. For example, karst aquifers with high storage capacity and a deep base of karstification may dampen the storm hydrograph response to heavy rainfall events. In contrast to the two aforementioned cases, Stevanović et al. (2015) present several examples from the Mediterranean and the Middle East where heavy rainfall events do not lead to extreme flooding due to the high storage capacity of karst aquifers. The high permeability and caverns within the karst bedrock, and the absence of epikarst, allowed all precipitation to quickly infiltrate and percolate into deeper aquifer sections. At Kameno more ("Stone Sea") above the Boka Kotorska bay (Montenegro), for example, more than 300 vertical shafts have been recorded in an area of only 8 km^2 (Milanović 2005). Precipitation in this area, which is known to be the highest in Europe, never results in surface runoff, instead precipitation quickly percolates downwards and discharges to the Adriatic coast.

The heterogeneity of karst aquifer systems can therefore results in two contrasting scenarios. In one case, the karst aquifer reacts almost immediately with an increase in groundwater flow, rapid surface and subsurface drainage and activation of temporary overflow springs. In the other case, where karst is characterized by large effective porosity and groundwater storage, the aquifer provides high storage and sufficient base flow for groundwater-dependent ecosystems and can better attenuate significant rainfall/runoff variations and therefore feature a higher resilience to climate change relative to other types of aquifers.

The Mediterranean karst setting

Karst landscapes in the Mediterranean region are widespread (Xanke et al. 2024; Fig. 1) and their occurrence is closely related to tectonic processes since the late Mesozoic and primarily influenced by the Alpine orogeny (Cavazza and Wezel 2003; Duggen et al. 2003). As a result, a long mountain belt stretches along the European Mediterranean region from Spain to Turkey, whereas the African and Arabian regions are less tectonically deformed and in many regions wide horizontal plateaus are prevailing. Extensive karst landscapes can be found on the Iberian Peninsula, in southern France and in the Alpine region from where karst formations extend across the Dinaric karst landscapes to Greek Hellenides. Taurides of central and southern Turkey is also known for its distinctive karst landscapes, which extend along the coast through Syria and Lebanon to Israel. A large part of the North African Mediterranean region is covered by extensive karst landscapes that stretch from Egypt to Libya to the Atlas Mountains in Algeria and Morocco (Xanke et al. 2024; Goldscheider et al. 2020; Mari and Telbisz 2018).

The climate of the Mediterranean region is generally strongly influenced by latitude and geomorphological features, so that regional differences in temperature and precipitation can be observed both throughout the year and

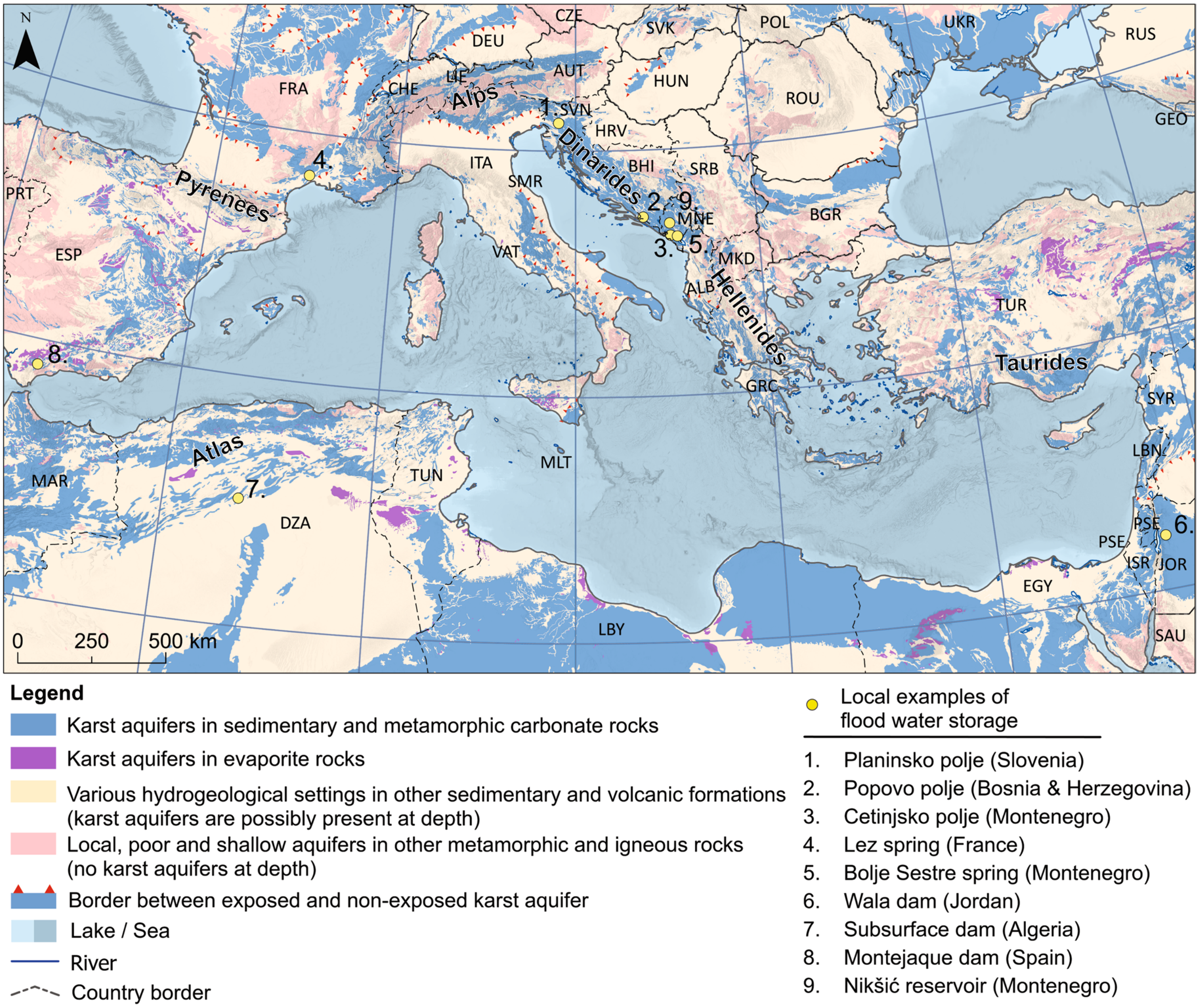


Fig. 1 Mediterranean karst aquifer map (modified after Xanke et al. 2024) providing the locations of the nine examples of flood water storage and management

seasonally. Thus, four climatic zones are distinguished ranging from arid, temperate and cold to tundra zones, with the latter occurring only in the European part and there only at high altitudes (Peel et al. 2007). These different climatic conditions have shaped the karst landscapes in very different ways. In regions with higher precipitation rates, there is usually stronger karstification and the development of typical karst geomorphological features such as sinkholes, dolines or poljes (e.g. in the Dinaric region) relative to predominantly dry regions, such as the Middle East and North Africa (MENA) region. Likewise, tectonic stress plays a role in karstification, as highly fractured areas provide more water flow pathways leading to a greater extent of rock-water interaction. The temporary but almost complete drying up of the Mediterranean Sea during the Late Mesozoic, about 6 to 5 million years ago (Messinian salinity crisis; Roveri et al. 2014), and subsequent water level changes of about 70 m below the present sea level, due to Quaternary glacial and interglacial periods, led to deep karstification at various levels, but especially in the coastal area of the Mediterranean Sea. Thus, some of the karst systems are now located below the current sea level and often act there as submarine springs. Also, inland springs and caves are found at different elevations (Stevanović, 2020; Bakalowicz 2018; Stevanović and Milanović 2023) throughout the Mediterranean. Here, springs near the coast are often subject to seawater intrusion and may feature high salinity values, as described by Sanz et al. (2023).

The different karst landscapes, the availability of water as a result of the prevailing climate are finally decisive in the extent to which local efforts of active karst aquifer management take place. The Mediterranean region is well-known as a cradle of modern water supply management. The Romans were the first to manage long-distance transportation of high-quality water, primarily from karst aquifers. At the height of the Roman Empire, several aqueducts from springs located up to 90 km from the city, delivered about 13 m^3/s of water to the center of Rome (Lombardi and Corazza 2008; Stevanović 2015). Many centuries later the construction of dams as typical and established measure to control surface water in karst terrains, had also been firstly and successfully applied in the Mediterranean region (Milanović 2002). Examples of surface water reservoirs can be found in most karst areas around, numerous of them in Bosnia & Herzegovina, Montenegro, Turkey or in Algeria (Fig. 1). Adapted measures of flood control to special natural structures such as to poljes are only found in the regions where they occur, as in the Dinarides (Milanović 2000, 2002; Stevanović and MIlanović 2023). Active management of groundwater abstraction is also a common measure, although the focus is usually on water harvesting. Targeted measures such as managed aquifer recharge are a rather less commonly used form of surface water and groundwater management in karst terrains in terms of flood water control (Daher et al. 2011).

Flooding mechanism and regulation structures in karst poljes

Although karst poljes can be found in karst areas all over the world, they are a representative landscape feature of the Dinaric Arc. A karst polje is a large, closed depression, with a flat bottom (corrosional lowering) and steep slopes. The hydrology of a polje is usually characterized by springs at one side and ponors at the other side. According to Milanović (2000), there are about 130 poljes in the Dinaric karst region, where surface water regularly drains through ponors located along the polje perimeter and at the polje bottom in unconsolidated sediments or exposed carbonates. If the capacity of the ponors is insufficient to absorb the runoff water, the polje is at risk of flooding. Flooding is not only connected to the limited outflow capacities, but also to groundwater level rise. In order to control the frequent and prolonged flooding of many karst poljes due to the insufficient storage capacity of the ponors, dam and reservoir projects have been completed in the Mediterranean region, many of which are located in the Dinaric karst. In this region, the dynamic water regime and the large variations in discharge and changes in groundwater levels have a negative impact on aspects of human life and lead to the instability of ecosystems. For this reason, many efforts have been made in the past to regulate the water regime. The first dams in the Dinaric Karst were built at the end of the nineteenth century, following the projects of Austrian engineers. Today, the major rivers of the region, the Cetina, Neretva, Trebišnjica, Zeta and Drini Rivers, are dammed for hydroelectric power generation. The latter three rivers are karst polje rivers. The Dinaric Karst is thus becoming an important reference area for the successful completion of dams in karst landscapes, which tend to be problematic with respect to catchment water losses (Milanović 2000, 2002).

Example 1: Non-regulated river flow and flooding dynamics Planinsko Polje, Slovenia

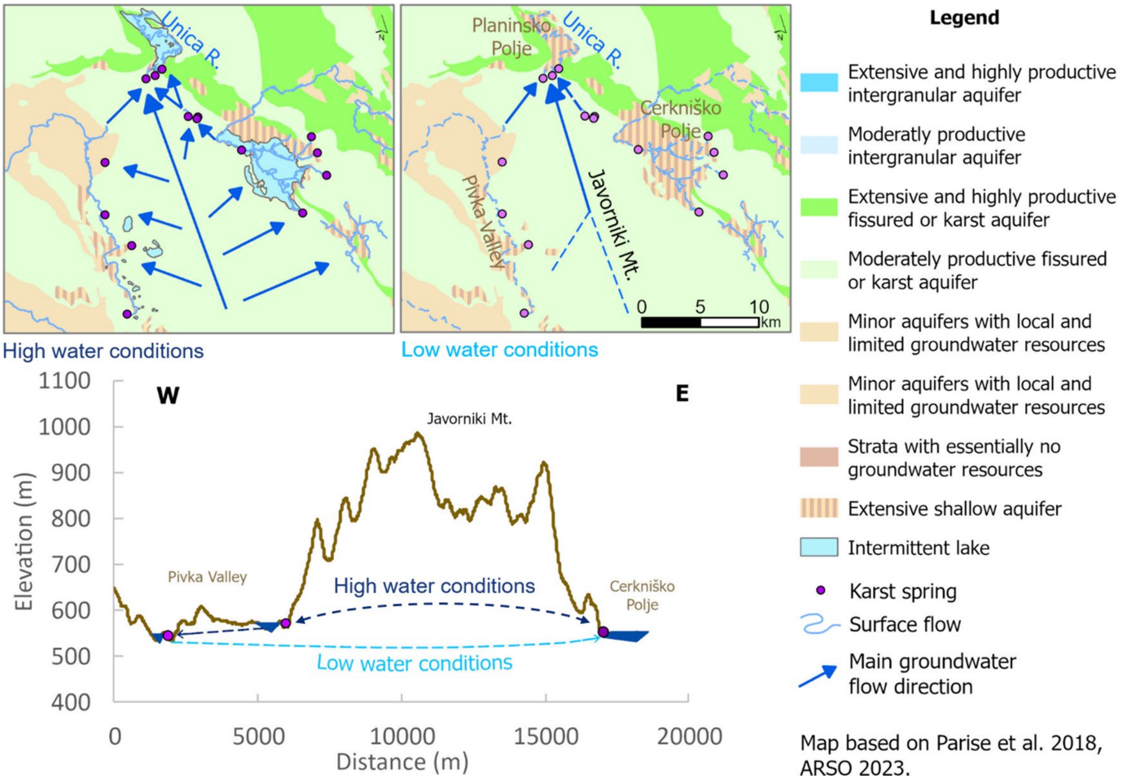
The Planinsko Polje is considered a typical example of karst polje formation and development (Gams 1978; Ford and Williams 2007). It is a depression about 5 km long and 2.5 km wide with a flat bottom where two large and several smaller springs are located on the southern and western edges of the polje. The water converges in a common watercourse, the Unica river, which crosses the polje and sinks into the eastern, northern, and northeastern edges. The Planinsko Polje (Fig. 2a,b) represents the confluence of waters from several contributing sub-catchments. It is the lowest in a chain of consecutive karst poljes that follow each other downstream, and in which the same water sinks and reappears several times. In addition, the polje drains adjacent mountains with karstic and fractured aquifers and indirectly

Fig. 2 **a**) Planinsko Polje at low and **b**) high water (Photo accreditation: Matej Blatnik)

drains an allogenic river basin with flysch bedrock (Kovačič and Ravbar 2010). Several studies, including artificial tests and natural tracer tests (Gabrovšek et al. 2010; Petrič et al. 2020; Ćuk Đurović et al. 2022) and water balance analyses (Mayaud et al. 2023), have confirmed the existence of groundwater flow connections.

The polje is characterized by extensive surface–groundwater interactions and flood cycles (Fig. 2b). As groundwater levels rise (Fig. 3c), spring discharge increases by many orders of magnitude, intermittent springs become active, and estavelles act as springs (under normal conditions, water seeps into an estavelle and it acts as a ponor. After heavy rainfall, the pressure conditions in the karst system change and the estavelle takes on the function of a periodically discharging karst spring.). The maximum recharge capacity of springs can exceed 140 m^3/s, and then the inflow to the polje significantly exceeds the capacity of the ponors, which ranges from 65 to 75 m^3/s (Mayaud et al. 2023). Floods occur with highly variable magnitude and periodicity, but are generally associated with intense or prolonged precipitation in late autumn, during winter rains and snowmelt. On average, the polje is flooded 38 days a year and water levels can rise up to eight meters. Extreme floods result from simultaneous high water conditions in recharge areas (Fig. 3a, b). When these conditions occur in phases, floods of lower amplitude and longer duration occur, which can last for several weeks. The volume of water during extreme floods can exceed 80 million m^3 (Frantar and Ulaga 2015; Mayaud et al. 2019; Ravbar et al. 2018, 2021). The transition from drought to flood can be rapid, followed by a decline in water levels and the formation of wetlands.

For flood control purposes, detailed hydrogeological studies and hydrological monitoring have been carried out in the area since the late nineteenth century, as well as pioneering speleological and karst research. In the past, only minor interventions such as the widening of ponors, the construction of a small floodgate in an upstream polje and the like have been carried out, and Planinsko Polje has remained in a relatively natural state. Today it acts as a natural flood reservoir, alleviating flooding in downstream areas. One of the springs that feed the polje is a regionally important water source (Petrič 2010). Due to its high biodiversity, the polje is recognized as an important karst groundwater-dependent ecosystem (Pipan et al. 2022), as are many other poljes in the Dinaric region (Sackl et al. 2014).



Map based on Parise et al. 2018, ARSO 2023.

Fig. 3 Schematic presentation of temporal variability under different hydrological conditions with **a**) high water conditions and **b**) low water conditions and **c**) a schematic profile of the supposed water level in the area recharging the Planinsko Polje (based on Parise et al. 2018)

Example 2: Regulated river flow and dam constructions at the Popovo Polje, Bosnia & Herzegovina

The Popovo Polje is the largest intra-mountain depression in eastern Herzegovina, with an area of about 68 km^2 and a width varying between 1 and 2 km (Fig. 4a, b). It is crossed by the Trebišnjica River, one of the largest sinking river in Europe, which is canalized along about 65 km. The thickness of the alluvial deposits is only 1 to 2 m in the upper part and 15 to 20 m downstream. More than 500 ponors, estavelles and temporary springs have been registered in the Popovo Polje. The total swallowing capacity of numerous ponors in the riverbed, but also along the edges of the polje, is more than 300 m^3/s. However, even this capacity was not sufficient to absorb the flood waters, and prior to the implementation of a hydropower plant (HPP) regulation project, the polje was flooded on an average of 253 days per year. During the maximum extent of flooding, 7,500 ha were under water (Milanović 2000).

The construction of the multi-purpose Trebišnjica hydrosystem began in the late 1960s and has not yet been completed. The construction of two successive dams on this river (Grančarevo and Gorica) enabled the creation of the Bileća reservoir and the Gorica regulating reservoir. This has enabled the construction of several HPPs jointly operated by Bosnia & Herzegovina and Croatia with Trebinje I at Grančarevo dam (180 Megawatt), Trebinje II at Gorica dam (8 Megawatt), Čapljina (420 Megawatt) and Dubrovnik in Plat (210 Megawatt; Fig. 4a).

Despite the doubts of some experts that a reservoir as large as Bileća, impounded by the Grančarevo Dam, would never be filled with water due to the highly porous karst rocks, the resulting water losses are negligible. Losses from the downstream Gorica regulating basin are between 3 and 4.5 m^3/s, depending on the level of the basin (Milanović 2021). These losses occur mainly downstream of the Gorica Dam, which guarantees the ecological flow of the Trebišnjica River through the urban area of Trebinje. Downstream of Trebinje, its 65 km long riverbed flowing through Popovo Polje is covered with 5 cm thick reinforced shotcrete, which prevents river water losses.

Example 3: Anthropogenic factors promoting flooding at Cetinjsko Polje, Montenegro

In some high mountain karst areas without perennial streams or with a deep water table, reducing drainage through ponors is a traditional way of saving some rainwater or prolonging the existence of a temporary swamp or lake. However, if clogging of ponors (complete or partial) is done unintentionally, it can cause flooding in the upstream area or complicate natural dewatering downstream. One such example is the Cetinjsko Polje in Montenegro, which covers a small area of about 4 km^2 at the foot of Mt. Lovćen (Fig. 5a) and is fully urbanized. (Fig. 5b). It is a typical Dinaric type of polje with a temporary spring emerging from a large cave on one side and a cave ponor (swallow hole) on the other (Fig. 5c). This completely closed structure is situated at an

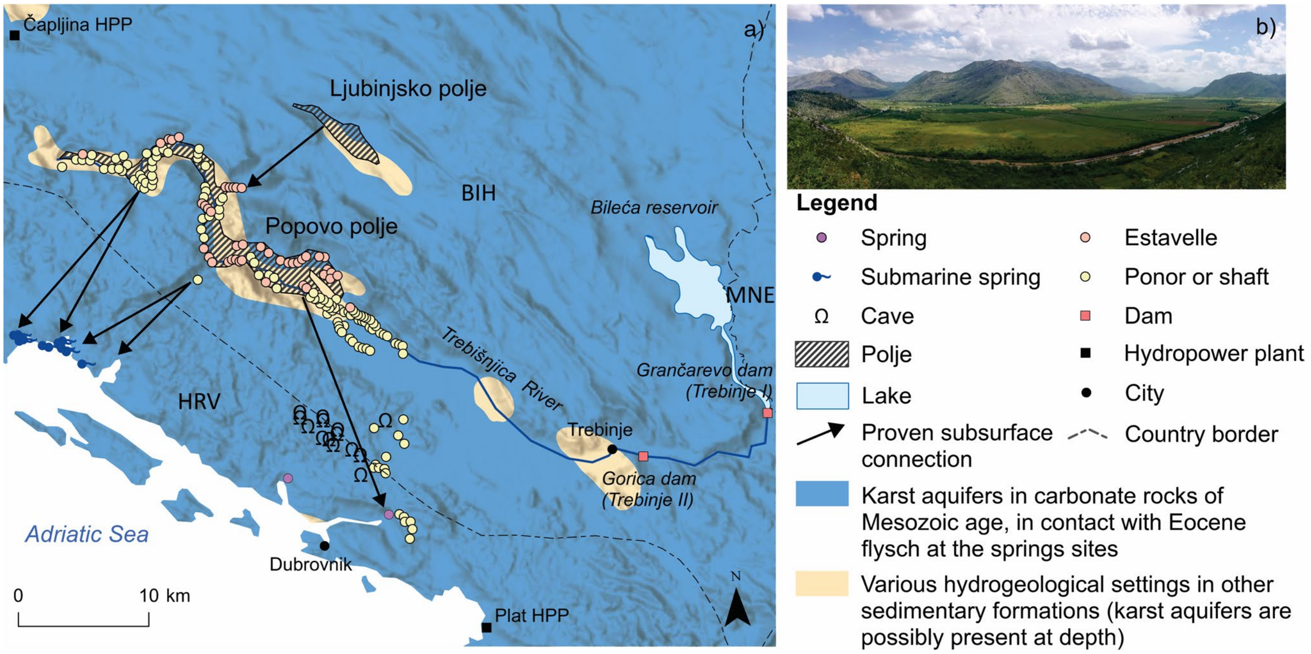


Fig. 4 **a**) Location of Popovo Polje in eastern Herzegovina and proven connection of its ponors with the springs located along Adriatic Coast (modified after Milanović 2000) and **b**) the canalized Trebišnjica River (Photo: Zoran Stevanović)

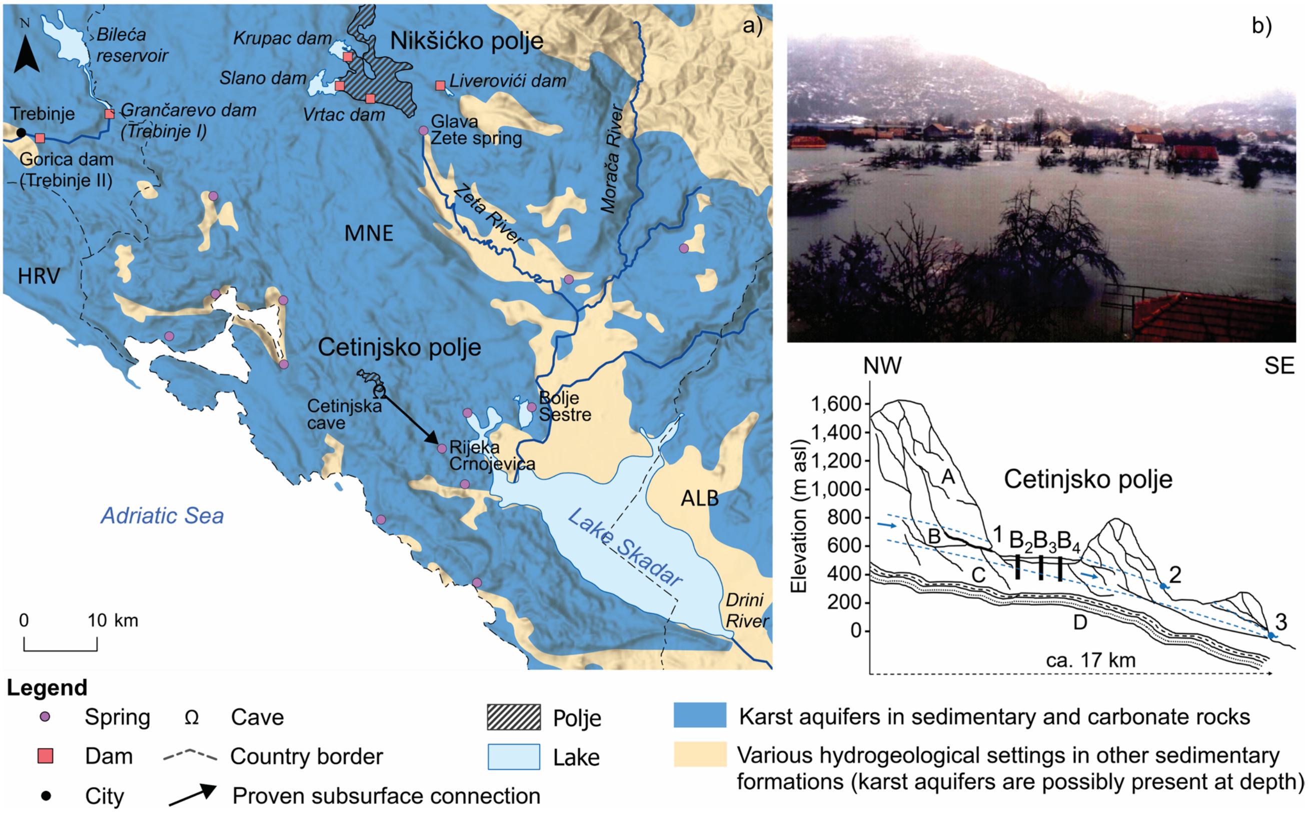


Fig. 5 **a**) Schematic hydrogeological map of the Adriatic basin of Montenegro. The locations of the examples 3, 5 and 6 are indicated (extract from the Digital hydrogeological map of Yugoslavia, Stevanović & Jemcov, 1995, modified; Input data based on Hydrogeological map of Montenegro by Radulović, 2000). **b**) Submerged houses in the lower part of Cetinjsko Polje during the flood of February 1986 (photo Mićko Radulović,). **c**) Cross-section over Cetinjsko Polje (modified after Radulović 2000) with A. Dry zone with vertical water percolation, B. Zone of groundwater fluctuations, C. Saturated zone, D. Zone under base of karstification. $B_{2\text{-}4}$ are exploratory boreholes

altitude of 750–635 m above sea level and is drained exclusively by a temporary sinking stream through the ponor. The sinking water percolates under the lower Dobrsko Polje and reappears six hundred meters below the ponor in the Obod cave, which is also the source of the Rijeka Crnojevica river. This conceptual model (Fig. 5c) was confirmed by a tracing test carried out in March 1938. The linear distance of 7 km between the ponor and the spring was traced with an apparent speed of 4 cm/s (Radulović 2000).

Between 16 and 18 February 1986, rainfall of 670 mm and rapid snowmelt caused the spring of the Cetinjska cave to start discharging about 50 m^3/s and with the addition of smaller streams, the total flow at the entrance to the cave reached 60 m^3/s, while its swallowing capacity is about half of that (Radulović 2000). However, the flooding of the polje was greatly exacerbated by solid waste deposited in the cave and its channels, with serious consequences for the population and their property. The waste was deposited during the flood, but also illegally prior to the flood. This material inhibited drainage towards the erosion base and the source of the Rijeka Crnojevica River. After this flood, systematic cleaning of the cave's main cavities and some engineering interventions, including the reconstruction and maintenance of the rainwater drainage channel, have helped to prevent a similar accident from happening again.

Abstracting karst groundwater to increase storage capacity and prevent flooding

Example 4: Flash flood mitigation through aquifer over-pumping at the Lez spring, France

The city of Montpellier and the surrounding area are regularly affected by flooding from the Lez River, which was first recorded in 1394. In the twentieth century, the most severe floods occurred in 1933, 1976, 2003 and 2005. In 1976, a rainfall event of more than 300 mm in 24 h caused severe flooding and damage in Montpellier. Following this catastrophic event, several studies were carried out, leading in particular to the rehabilitation and damming of the Lez River. In addition to these infrastructures, several studies were launched in 2002, 2003 and 2005 to better understand the dynamics of flooding in the upper Lez catchment. The results show that in such karst-dominated catchments (Fig. 6a), the rapid contribution of groundwater to streamflow can generate specific peak flood discharges of more than 5 $m^3/s/km^2$ (Camarasa-Belmonte and Segura-Beltrán 2001) and locally even very briefly up to 20 $m^3/s/km^{2\cdot}$ as happened in September 2002. According to Delrieu et al. (2005) there are indications of opposing hydrological behaviours which, together with the karst-specific geomorphological factors, led to this event. However, peak discharges twice as high as those expected from surface runoff alone are possible (Jourde et al. 2007).

The management of the Lez aquifer consists of pumping water directly from the karst conduit below the karst spring (Fig. 6d), withdrawing less water than is replenished by natural groundwater recharge (Avias 1995). During low flow conditions, the groundwater level drops below the level of the spring overflow (Fig. 6b), and large drawdowns (up to 30 m) are observed in the catchment when the pumping rate exceeds the natural discharge of the karst aquifer. This creates an "available storage volume" that is at its maximum at the end of the low flow period until precipitation events occur, generally in late summer or early autumn, and refill the karst aquifer (Fig. 7). At the Lavalette gauge, where the Lez reaches the city of Montpellier, the catchment area is about 116 km^2 and peak discharges of up to 500 m^3/s can be observed after extreme rainfall events (Fig. 7). An analysis of different flood events with a peak discharge of 100 m^3/s or more at Lavalette showed that the volume available for water storage in the epiphreatic zone (before the flood) controls the occurrence and intensity of large flash floods (Jourde et al. 2014).

This suggests that much of the precipitation can be stored in the epiphytic zone of the aquifer (Fig. 7) when the karst aquifer is depleted after a long period of low flow (usually in late summer), thereby mitigating downstream flooding. This explains the much larger peak flows (Fig. 7), but also the larger flood volumes that contribute to surface flooding, when the groundwater level is high, thus storage is not available and precipitation causes a general rise in the groundwater level above the spillway surface (Fig. 6c). Since the installation of the underground pumping station for Montpellier's water supply in 1981, part of the groundwater pumped is returned to the river Lez downstream in order to preserve the ecosystem during the low water period (no flow at the spring). This "ecological discharge" was around 160 l/s until 2018 and has been set at 230 l/s after 2018.

The groundwater level at the Lez spring is now used by the flood forecasting service (SPC Méditerranée Ouest) to assess the state of saturation of the karst aquifer and to predict the hydrodynamic response of the karst aquifer to precipitation events. It can also be used as a key parameter in hydrological models to predict flash floods. In the case of the Lez river, it has been shown that karst groundwater

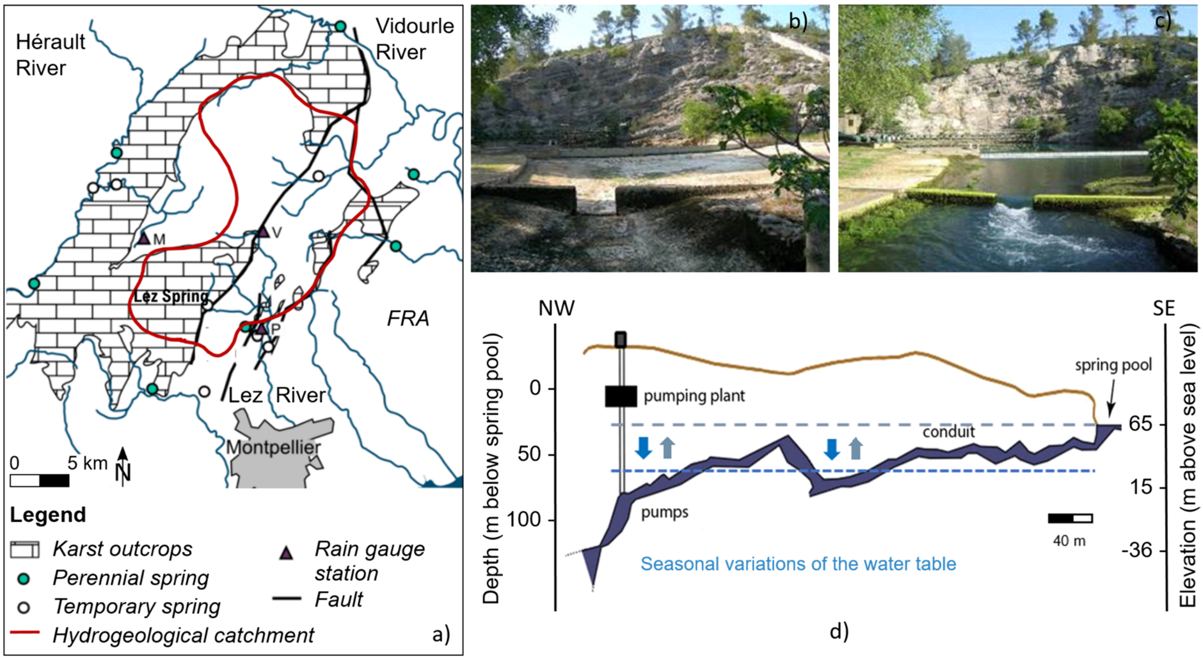
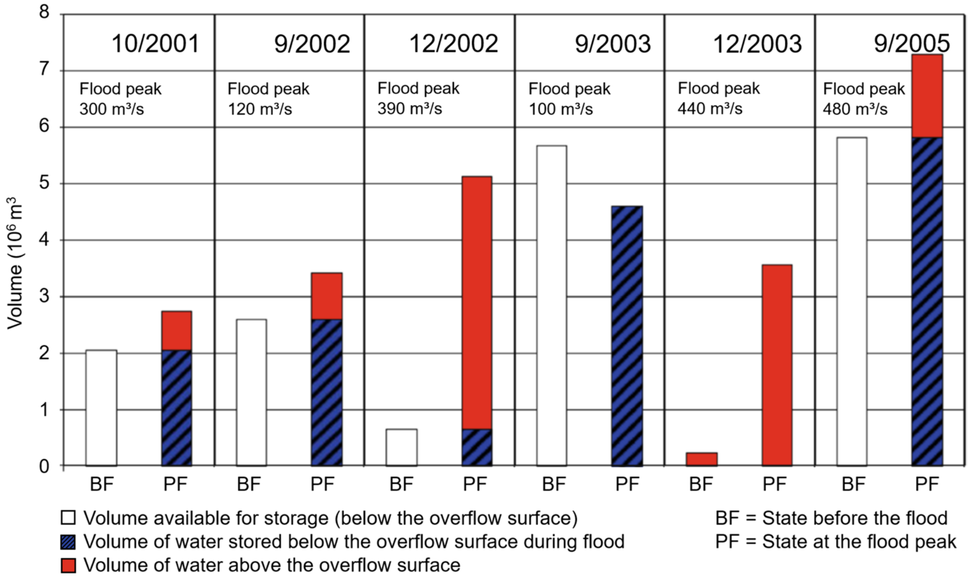


Fig. 6 **a**) Simplified hydrogeological setting of the Lez Karst aquifer and hydrogeological catchment (modified after Mazzilli 2011) with b) Lez spring during low-flow and **b**) under regular discharge conditions. **c**) Simplified topography of the terminal karst conduit of the Lez spring and seasonal variation of the water level due to high flow pumping (after Mazzilli 2011 by P. Rousset from the G.E.P.S. diving group, 1972)

Fig. 7 Different volumes of storage at the Lez aquifer system from 2001 to 2005. Low available storage (12/2002) leads to severe flooding while high available storage (09/2003) leads to no flooding



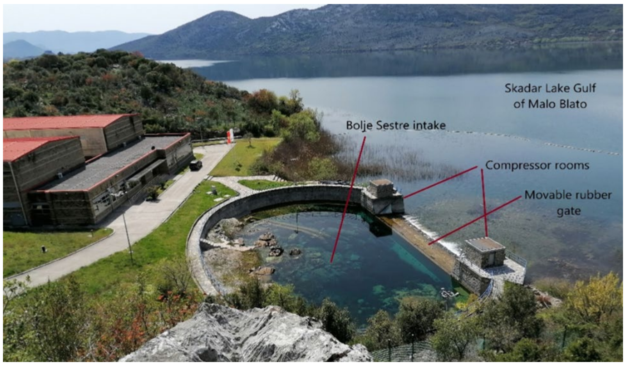


Fig. 8 Bolje Sestre intake on the shores of Lake Skadar. In this photo, the movable gate is lowered to allow the free flow of non-captured spring water. Photo accreditation: Zoran Stevanović

can contribute to flash floods when the water table is high, but also that the karst aquifer can mitigate the floods that occur after a period of pronounced low water due to the specific management of the groundwater resource (Jourde et al. 2014).

Example 5: Movable intake to prevent flooding of the Bolje Sestre spring, Montenegro

Intensive overpumping of karst aquifers can lead to both deepening and enlargement of the cone of depression, which, as in the case of the Lez Spring, can create new storage space for future floods. A very different approach is to create a protective mechanism against flooding. One such example is the damming of the Bolje Sestre spring in the Skadar Basin (Fig. 5a), which supplies the entire Montenegrin coast with karst water. Bolje Sestre is one of many sublacustrine springs (Fig. 8) on Lake Skadar that were flooded during the ice and interglacial periods in the Pleistocene. While some of these springs originate at the bottom of the lake, Bolje Sestre is one of the shallowest with main drainage "veins" only 1 to 2 m below the minimum lake level. Lake Skadar is the largest lake in the Balkans with an average area of about 475 km^2, of which 60% belongs to Montenegro and 40% to Albania. The pronounced water level fluctuations between 4.6 and 9 m are the result of long-term flooding by the tributaries, but can also occur randomly when water accumulated in the reservoirs on the Drini River in Albania is quickly drained, as happened in December 2010. To tap the fresh karst groundwater before it mixes with the lake water and to prevent it from backing up into the intake, an elliptical concrete structure—a cofferdam—was designed and built in 2009. It has an area of about 300 m^2 and is the largest of its kind in the Mediterranean built in the last half century (Stevanović 2010). Considering the importance and influence of the lake's water fluctuations on the inflow, a special removable spillway (rubber slider) was designed and installed on the top of the dam. The two automatic and remotely controlled compressors are used to feed air into a rubber hose and activate the gate when needed (Fig. 8). When the lake level is low and the spring discharge is "normal", the gate is lowered to allow the unused spring water to flow freely into the lake (Stevanović 2010).

Managed aquifer recharge in karst and adjacent aquifers

Example 6: Flood storage and induced groundwater recharge at Wadi Wala, Jordan

Several flash floods have been recorded in Jordan in recent decades, causing significant damage to people and infrastructure, especially in the Wadis that drain toward the Jordan Valley or the Red Sea (Al-Qudah 2011; Obeidat et al. 2021). To control these flash floods and make the water usable, dams have been constructed in many of the larger wadis in recent decades, including in Wadi Wala in 2002 (Fig. 9a). Runoff dynamics in the Wadi Wala are diverse, reflecting the climate gradient in the catchment, which extends east of the reservoir and covers an area of about 1,770 km^2 with elevations ranging from about 1,000 m asl in the east and down to about 500 m asl at the reservoir. Due to the high potential evapotranspiration rates, most of the rainfall evaporates and only a small proportion infiltrates into the sequence of Upper Cretaceous and Eocene sedimentary rocks (predominantly limestone, dolomite and chalk) and only 0.5 to 10% generates surface runoff. This surface runoff collected in the reservoir is usually of a few hundred thousand m^3 on certain days during the winter months, adding up to an average of about 12.4 million m^3 (2002–2012) per year (Fig. 10). However, during extreme rainfall events, runoff can reach several million m^3 in a very short period of time. (Fig. 9b; Xanke et al. 2015).

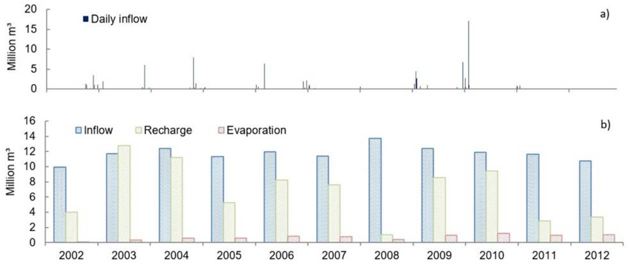


Fig. 10 **a**) Daily inflow and **b**) mean annual water balance of the Wala reservoir (2002–2012)

The special feature of the Wala reservoir is that it is built on carbonate rock and that a large proportion of the flood water naturally infiltrates into the underlying aquifer, while a small proportion can be injected via recharge wells. This water supplements groundwater flow to a wellfield 7 km downstream.

The dam was built at the confluence of two dry valleys, a sort of bottleneck in this large catchment area, which means that significant amounts of water flow into the reservoir. As a negative side-effect, large amounts of sediment have been carried into the reservoir over the years. This has not only reduced the reservoir's storage capacity and increased the risk of overtopping, but has also significantly reduced natural infiltration (Xanke et al. 2015). Efforts to flush or

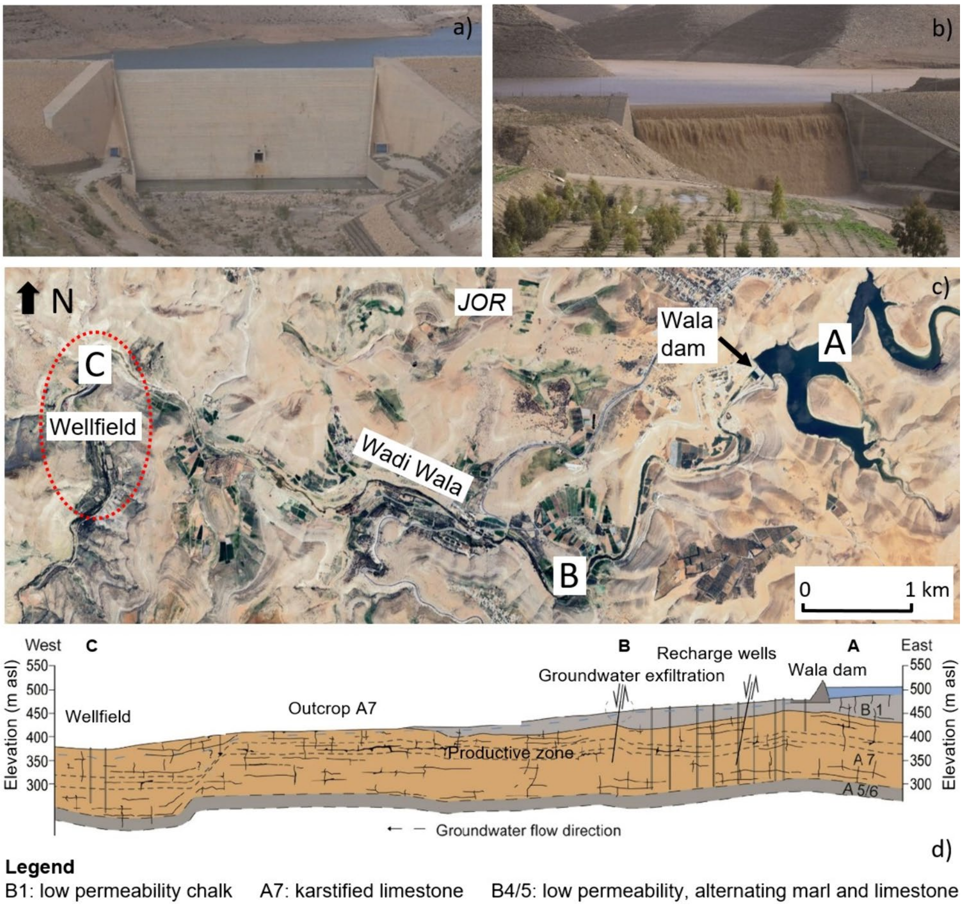


Fig. 9 **a**) View of the Wala Dam, which stores flood waters in the winter season and recharges the underlying karst aquifer (Xanke et al. 2015). **b**) Periodic overspill of the dam shows the tremendous runoff volumes after heavy rainfall events (photo: Xanke et al. 2015). **c**) Plan view of the study area (source: Google Earth 2023). **c**) Schematic geological profile along the Wadi Wala (Xanke et al. 2015) with B1 layer of low permeable chalk, A7 layer of karstified limestone aquifer and A5/6 layer of low permeable alternation of marl and limestone

excavate the sediments have so far failed, and only the construction of smaller dams and sedimentation basins upstream could provide a long-term solution. In addition, some of the recharge wells are lost functionality because they are clogged, this is likely due to the wells not being connected to larger karst conduits.

Example 7: Subsurface dam near Laghouat, Algeria

Numerous underground dams, also known as 'sand dams', have been constructed in countries in the Middle East and North Africa (MENA region; Stevanović 2016) to store flood water or temporary river water. Short flood periods and rapid dispersion of water through highly porous alluvial deposits are the main reasons why such systems, with barriers above the excavated riverbed that prevent water from flowing downstream, can be considered a viable solution. As these underground dams are constructed in alluvial deposits, recharge of adjacent or underlying karst aquifers can be considered as an indirect benefit, or in other cases as an intended benefit.

Some of these dams were built in the first half of the twentieth century in the foothills of the Atlas and on the northern edge of the Sahara. The Tadjemout impermeable barrier with a system of underground filtration pipes was built on the Oued M'zi, the temporary river near Laghouat (Algeria), which has a catchment area of 6.800 km^2 (Fig. 11a). The main purpose of the dam is to control the flow of alluvial groundwater during rare but intense floods (Fig. 11b). For this purpose, the Tadjemout impermeable barrier, 300 m long and 5 m deep, was constructed across the bed of the Oued M'zi (Fig. 11c). These structures and the stored flood water also benefit the associated Turonian limestone aquifer through enhanced recharge, which is intensively used by several well fields in the wider area.

Unsuccessful attempts to keep flood water in reservoirs in karst

Example 8: Inappropriate flood water storage *at Sierra* de Líbar, Spain

The Montejaque reservoir is located in the northeast of the Sierra de Líbar (Fig. 12c), which belongs to the outer zone of the Betic alpine orogen and is characterized by Jurassic dolomites and limestones and Cretaceous marls and marly limestones (Martín-Algarra 1987). The construction of the dam (Fig. 12a) began in 1922 to regulate the water of the Gaduares River for the generation of electricity in a hydroelectric plant at the entrance to the Hundidero Gato cave system. This network of karst passages had not been explored before. It was generally assumed that the two large

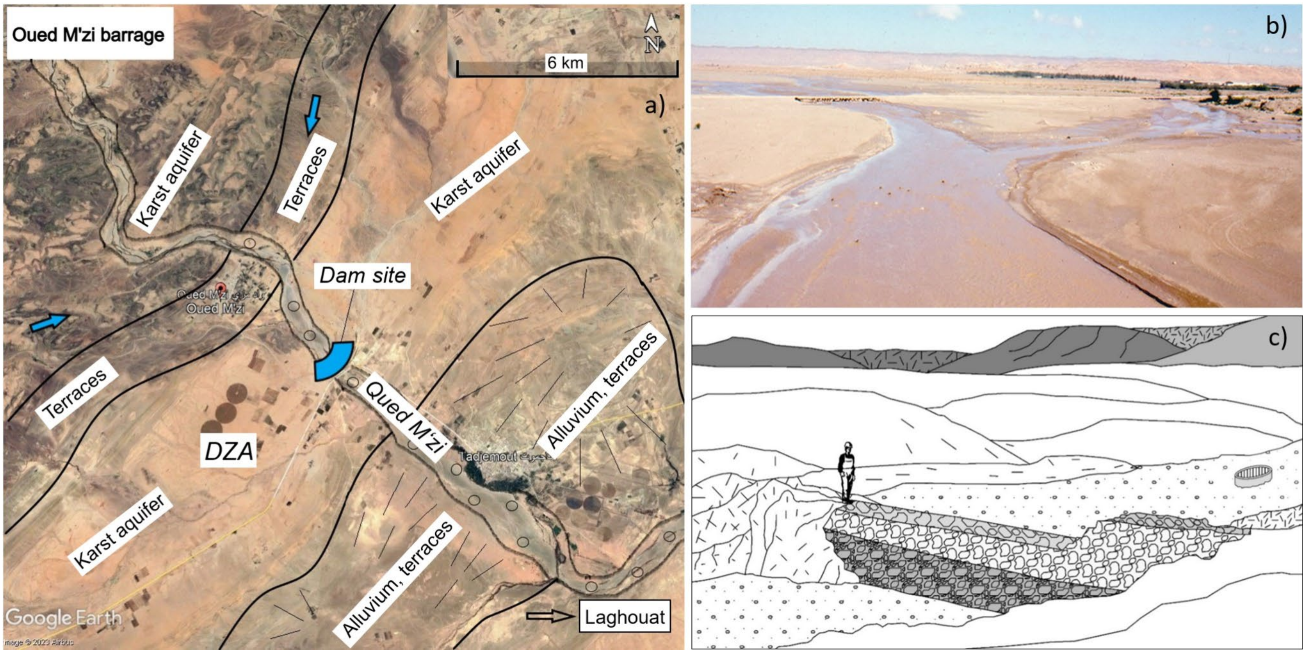


Fig. 11 **a**) Schematic hydrogeological map of Tadjemout dam site near Laghouat (Algeria). Dam (300 m long and 5 m deep) is placed across alluvial deposits of Oued M'zi to store flood waters generated in Turonian karst aquifer and Quaternary deposits to enable its further use for irrigation purpose. **b**) Temporary river Oued M'zi with flooded riverbed and banks after heavy rains (springtime 1985; Stevanović, 2016, Springer copyrights). **c**) Schematic illustration of a subsurface dam in the alluvium, which recharges the adjacent aquifers as an indirect (or desired) effect when the water level in the upstream section is raised (modified after Stevanović 2016)

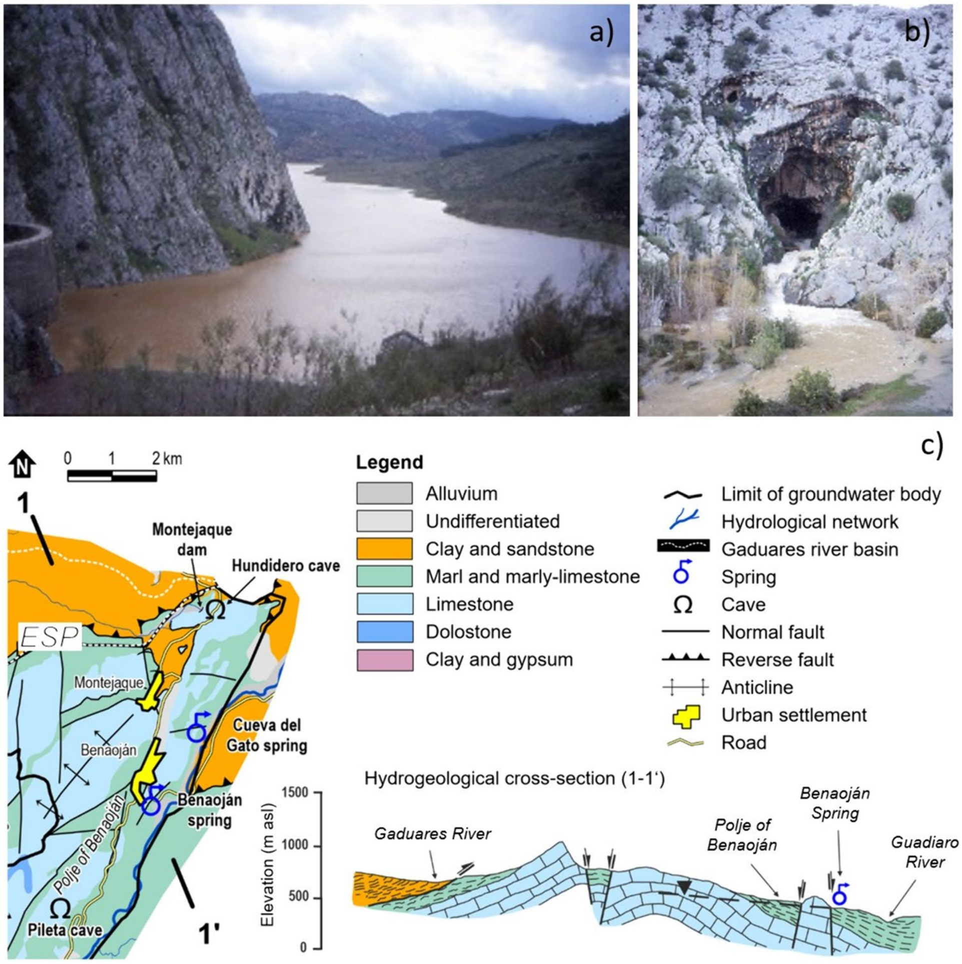


Fig. 12 **a**) The Montejaque dam and the Gaduares River after a period of rain, **b**) entrance to the Gato Cave and its spring (Photo accreditation: Archive of the Hydrogeology Centre of the University of Málaga). **c**) Hydrogeological map of the Sierra de Libar carbonate karst aquifer (adapted from Jiménez 2007). The dam is located at the northeastern edge of the karst system, close to the Hundidero cave, which, together with the Cueva del Gato spring, forms the Hundidero-Gato cave system, as referred to in the text

cave openings represented an independent development of the endokarst system and that the orography of the endorheic catchment, the impermeable lithology (rock layers of flysch formations) and the regularity of the annual discharge (25 hm^3 on average; Álvarez and Arias 1992) were favourable conditions (Algora and Álvarez 2000).

The Montejaque dam is 83 m high and 73 m wide (arch length), with a storage capacity originally estimated at 36 million m^3, making it the first arch dam and the highest water storage facility in Spain at the time (Gruner 1927; Bestué-Cardiel and Moreno 2017). Only one year after the completion of the works, several cracks appeared in the concrete mass at the bottom and sides of the dam, which, according to initial estimates, led to a water leakage of 3.1 m^3/s (Álvarez and Arias 1992). Although concrete, blocks and gravel were used to reduce the losses at the dam by up to 1.3 m^3/s, the reservoir continued to lose water. Several salt tracer tests conducted between 1930 and 1933 revealed the complexity of the dam's leakage system and the associated connections, but also proved that the stored surface water infiltrated mainly into the Hundidero-Gato cave system (60–70%; Álvarez and Arias 1992; Fig. 12b). Since then, initial knowledge of the karst function of the Sierra de Líbar has been obtained through speleological explorations, measurements of groundwater inflow into the cave and tracer tests in the field, but these have been used to solve engineering problems rather than to gain fundamental knowledge for the evaluation of cave connections.

The project was finally abandoned because the reservoir was never fully filled with sufficient water to generate hydroelectric power and attempts to seal (most of) the concrete wall failed, resulting in constant leakages at the base and lower sides (i.e. due to the result of a piping effect that accelerated the opening of cracks due to karstification upstream and in the depth of the dam). Subsequently, no investments were made for the rehabilitation of the dam, probably due to the poor design and location of this hydraulic infrastructure more than a century ago, but also due to the lack of detailed hydrogeological and geotechnical studies to repurposed the dam for water supply or flood risk mitigation. Today, this unique water infrastructure is unusable and forms part of Spain's hydraulic heritage. The Montejaque dam is not the only one that remains empty after its construction. Milanović (2015) provides a catalogue of such unsuccessful works, dividing them into several groups: catastrophic failures, abandoned dams, reservoir failures after many years of operation, dams and reservoirs with soluble karst rocks, reservoirs with unsuccessful or partially successful remedial works. The "successful" group includes reservoirs with acceptable seepage, dams with no need for remedial works and dams with successful remedial works.

Example 9: Control *of major* leaks from a water reservoir in Nikšić, Montenegro

Nikšicko Polje is the largest karst polje in Montenegro, with an area of 65 km^2 (Fig. 5a). Approximately 880 ponors and estavelles have been registered in this polje, 851 of which are located along its southern edges. In order to control the frequent floods, but also to exploit the hydroelectric potential of the Zeta River, a major construction project was started in the late 1950s. In natural conditions, the sinking Zeta River delivers its water to the springs (Glava Zete, Oboštica) located 600 m below the Ponors, and this concept was kept as the basis of the project. Finally, three artificial reservoirs, Slano (Figs. 5a and 13a), Krupac and Liverovići, and a shallow retention basin (Vrtac) were built in the Nikšić polje, while three large pipes divert water to the Perućica hydroelectric power plant (307 MW), which is located next to the natural Glava Zete spring, which still discharges some of the submerged water from the polje. The total capacity of these reservoirs is ca. 1×10^9 m^3 of water.

All the reservoirs in the Nikšićko Polje were built in highly karstified rocks. The Slano and Krupac reservoirs required intensive and expensive anti-infiltration works from the very beginning. First, some ponors were excavated at the Krupac margin, then 247 m of grout curtain was constructed, while the curtain reached a length of 1085 m over time (Vlahović 2020). The grout curtain along the southern rim of Slano is one of the longest in the world. It has a length of 7,011 m, a depth of 57 m and a surface area of about 396,000 m^2 (Vlahović 2020). In contrast to these two, the Vrtac retention, which is the last in the sequence towards the HPP spillway, has never been filled with water, except during a few extreme floods, despite intensive grouting and regulation of small ponors by concrete immersion (Fig. 13b). The average water loss from this retention is estimated to be 25 m^3/s.

The system in the Nikšićko Polje, which is designed to receive and attenuate the effects of floods and to use this water for energy production, is still functioning well, despite its shortcomings caused by the nature of the karst. The struggle for free space for new water and the attempt to keep every drop for the production of electricity is still going on and remains one of the main challenges for local engineers.

Discussion

Floods, and especially flash floods, are difficult to control because the triggering heavy precipitation events are difficult to predict in terms of their temporal and spatial occurrence. However, the topographical and climatic environment often provides indications of their ability to develop. For example, neuralgic topographical bottlenecks and places where large areas drain are often the cause and subject of floods. Flood management is therefore usually based on knowledge of regional and local hydrogeological conditions in the long term and on weather forecasts in the short term.

Flooding in the Mediterranean karst regularly occurs in closed depressions (karst poljes and similar endorheic areas) as a common erosional base for water drainage. The main cause of flooding in these areas is the imbalance between input (rainfall) and output (drainage via ponors, sinking streams). However, karst also often acts as a "buffer" because it can absorb large amounts of water that can be stored in epikarst sections or in its deeper cavities, joints and fissures. Especially in karst areas, it is essential to understand the elements of the water balance and, in particular, the factors that determine the dynamics of effective infiltration of rainfall,

Fig. 13 **a**) Slano dam and reservoir and **b**) special cylindrical valves to prevent water sinking

surface runoff, groundwater level fluctuations and spring discharges, in order to develop management concepts adapted to local conditions. Therefore, for heterogeneous aquifers such as karst, each management case is unique and requires a specific solution. Although it is difficult to develop suitable transferable approaches for managing such events, general knowledge can often be used to develop new approaches or improve existing ones.

Floods affect human life, cause damage to infrastructure and alter the habitat of ecosystems by forcing them to adapt to these conditions. For this reason, the attempt to control floods by building dams and reservoirs has been widely applied in the Mediterranean area during the last century. The benefits, such as the generation of electricity and the opening up of new prospects for the population, should be balanced against the negative effects on the environment (e.g. desertification, disturbance of ecosystems). Civil engineering works in karst areas are always site-specific, but they are also subject to a risk of failure that can never be completely excluded, even with today's modern investigation techniques. In the past, this was particularly true for the construction of dams and their main purpose of surface storage and the problem of leakage and seepage into the subsurface (Milanović 2011). The problem of leakage is usually solved by grouting and blocking the waterways.

With regard to flood control and flood water storage, especially in arid regions, Stevanović (2016) proposes the construction and use of underground dams, distinguishing between two types of dams where 'leakage' can even be a welcome feature. One is built in the karst (for direct recharge), the other in the alluvial aquifer associated with the karst (for indirect recharge). Successful examples can be found in the Middle East or the Horn of Africa, but also in the southern Mediterranean (North Africa). However, karst poses significant risks to the construction and stability of dams, where it is present either above or below ground e.g. as a result of the dissolution of easily soluble evaporitic sediments beneath them (Milanović 2015; Stevanović and Milanović 2015; Stevanović 2015). Siltation of reservoirs is also a known problem, reducing storage capacity and blocking infiltration pathways (Xanke et al. 2015).

The use of a reservoir for flood control has been demonstrated in several examples, which mainly differ in their purpose. Some have worked very well since they were commissioned, such as the Trebišnjica Hydrosystem (Bosnia & Herzegovina), whereas others have failed, such as the Montajaque Dam (Spain), designed to store surface water and generate electricity. In this case, insufficient knowledge of the karst bedrock led to the infiltration of large volumes of water in a short period of time. In the case of the Wala reservoir (Jordan), however, this was a welcome development, as only a limited amount of water can be injected into the local recharge wells, thus increasing the volume of groundwater storage at a faster rate. Attempts to plug the leaks in the Montejaque dam or the Vrtac reservoir (Montenegro) were unsuccessful, while sedimentation in the Wala reservoir had the same, but unwanted, effect over the years. Nevertheless, these structures serve to store flood water and prevent severe runoff events. For the sake of completeness, it has to be acknowledged that these two examples are very large structures and that both positive and negative impacts have much greater consequences than for small-scale measures. In this context, Milanović (2015) recommended narrow canyons as less risky locations for dams and reservoirs compared to wider valleys and karst poljes. This is true for the example of Planinsko Polje (Slovenia), which is well studied and understood. Instead of major engineering works, only minor measures such as widening of ponors and construction of a small gauging station for flood control were implemented. Smaller measures have also been very effective at the Bolje Sestre spring (Montenegro), where a dam protects this water source from flooding and allows for better use. The coastal springs affected by seawater intrusion mentioned by Sanz et al. (2023) could also be made more usable, e.g. by smaller dams.

The occurrence of floods is widespread, and local people are dealing with it by focusing on knowledge and prevention, and by taking targeted local measures. This has also helped to preserve the natural state of e.g. poljes and their ecosystems, such as at Planinsko Polje. The example of the Lez spring and river in France illustrates the complex interaction between groundwater levels, rainfall infiltration and runoff that can lead to flooding. It is essential to understand the hydraulic behaviour of the karst system under different conditions in order to act accordingly. Controlling groundwater levels is key to increasing storage capacity, allowing more rainfall to infiltrate into the aquifer, thereby reducing surface runoff and flooding. Opening new space for infiltration of heavy rainfall and its storage in deeper parts of the karst aquifer is therefore a regulatory measure and could also be considered as managed aquifer recharge (Stevanović 2015), although the latter is generally considered as intentionally induced recharge. Flood water storage can make a significant contribution not only to preventing the catastrophic effects of floods, but also to balancing the water regime and sustainable water use for the benefit of the whole ecosystem.

However, there is almost no intervention to change nature for the benefit of mankind that has absolutely positive effects on an ecosystem and all its elements (Stevanović and Milanović 2023). In the case of the construction of dams and reservoirs, some negative effects are foreseeable and can be prevented or mitigated by appropriate measures. Others, however, such as the flooding of cultivated fields, the relocation of small villages, the drying up of the soil along the canalized (or concreted) riverbeds, the reduction of wildlife and endemic fish, are sometimes unavoidable. With regard to engineering solutions, it must be emphasized that nature-based solutions with minimal intervention in the original state should always be preferred to methods that cause major changes in the environment. Solutions should always aim to protect and preserve the hydrological and ecological conditions of individual sites. People must adapt to nature and seek nature-based solutions. Finally, despite a good knowledge of the nature of highly developed or 'mature' karst, such as that of the Dinarides, numerous problems were still to be expected as a result of the imposed, but often unavoidable, technical measures.

The examples shown in this study demonstrate that flood storage and management in karst areas is feasible where there is a very good knowledge of regional hydrological and hydrogeological conditions and, especially, of the local hydraulic properties. The main risks of failure lie in the absence or inadequate consideration of karst-specific characteristics. At the same time, karst offers unique topographical and hydraulic structures and thus individual solutions for creative implementation of management measures and technical solutions to prevent or reduce flood events and to store water.

Conclusions

Karst aquifers play a special role in flood generation and storage due to their unique hydraulic properties. While the prediction and magnitude of flood events in karst are often more difficult to estimate than in other hydrogeological areas, karst offers high infiltration capacities and certain buffering properties that can also be actively used for flood mitigation. Several examples of flood management and flood storage in karst areas were studied and the following main conclusions are made. The contribution of a karst aquifer and karst groundwater flow to flooding must be assessed on a case-by-case basis. This means that good results in flood management always go hand in hand with a very good understanding of the local and regional hydrological conditions and, in particular, the hydraulic properties of the karst aquifer. This knowledge often indicates in advance possible risks of failure of the planned measures, but also often shows which measures are promising. The following individual conclusions can be added:

- Natural floodplains, such as poljes, act as buffers for flood events and are often home to unique ecosystems. Engineering interventions are therefore more likely to be avoided, as even small measures often have unpredictable negative effects. Appropriate risk management therefore often appears to be sufficient to cope with flood events.
- Surface storage by dams is an extensive engineering measure that can store large volumes of water and provide additional benefits such as electricity generation, drinking water supply and irrigation, in addition to flood control, but it is always likely that leakage will occur in a karst environment.
- Targeted surface drainage or plugging of siphons can be successful local measures if they have been carefully designed to exclude unintended effects.
- Managed recharge of karst aquifers by surface infiltration or direct injection is a promising method for reducing flooding and increasing groundwater reserves. This requires a good knowledge of the local hydraulic properties.
- Targeted groundwater pumping to manage aquifer storage is another promising method of flood control. This also requires a good understanding of local hydraulic properties to maintain the balance between artificially draining the aquifer, increasing infiltration capacity and maintaining natural conditions.

The examples presented here and the lessons learned are important for future sustainable management of karst aquifers, especially in the face of increasing pressure on groundwater resources due to population growth and climate change.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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