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PAPER

Dams and reservoirs in karst? Keep away or accept the challenges

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Abstract
The distribution and flow of groundwater in karstified rocks can be extremely complex and not readily predictable, a far from friendly environment for constructing dams and reservoirs. There have been many expensive failures such as unacceptable leakage rates at and around dams, and/or reservoirs that could not be filled to the design levels. This is never the fault of site geology but always of human mistakes due to inadequate investigation programmes and/or erroneous interpretation of the karst processes at work. Remedial works are expensive, time-consuming and frequently do not justify the money invested. As a result, those undertaking engineering works in karst terrains may approach with two fears—of the exceptional risk and/or of a failure. The key question, so often, is whether to build the dam in karstified rocks or keep away from such a risky environment. However, construction of water storage reservoirs is essential in many karst regions for socio-economic development. The challenge must be accepted. Based on much field experience, the best practices for selection of adequate dam and reservoir sites are defined and illustrated with specific examples from many different climatic, topographic, lithologic and hydrogeologic settings in Europe and Asia. This work emphasises that the amount of certainty or uncertainty in the crucial parameters—geological structure, groundwater regime, intensity and depth of karstification—should be recognized.

Keywords Karst · Engineering karstology · Dam failure · Reservoir leakage · Geomorphology

Introduction

At the end of the nineteenth century and beginning of the twentieth century, understanding of the nature of karstification was very weak from the engineering perspective. At the same time, it was a period of intensive construction of dams and reservoirs all over the world, including in karst regions. The history of dams shows the great benefits to regional socio-economic development that they have conferred all over the world. For their designers, the jaws-like morphology and strong mechanical-bearing capacity of limestone gorges appeared to make them the perfect places for dam construction. However, the carbonate and evaporite rocks are prone to dissolution, i.e. to karstification. The input of geological expertise into the selection of dam sites and reservoirs at that time was not considered an important part of any dam engineering project. As a consequence, there were a significant number of dam failures in karstic regions, and groundwater seepage (or greater leakage) from reservoirs and through dam foundations was frequent. In many cases the reservoirs never filled up to their design levels and they were abandoned. For dam engineers, 'karst' became a bad word, implying likely problems or outright failure. There is also the dilemma that dam construction in karst terrain, necessary for regional socio-economic development, may present a hazard in the often very sensitive karst environment. As time passed, new dams were built higher and higher, and reservoirs larger and larger, making the problems more complicated and riskier.

After some catastrophic failures and instances of unsuccessful remedial works, whether to build any dams in geological formations with such a bad reputation became the question. '*Keep away from karst*' became the message in many planning discussions. However, a large number of the karst regions are rich in hydro-electric power potential. In some countries the socio-economic development of their karstic regions is dependent on this potential. As a consequence, the only way forward was to accept the technical challenges and become familiar with karst, to determine its nature as far as possible. The experience accumulated and lessons learned

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from previous failures, together with the development of many new methods of investigation and technologies for construction and remediation, supported this effort. The role of geological engineers well-trained in karst environments became crucial during selection of proposed dam sites and reservoir areas, during their construction as well as later, during their operation. In comparison with dams built in nonkarstified environments, dams on karst need intensive monitoring and, after their first filling, frequently require additional remedial works throughout their operational life.

The engineering karstology of dams and reservoirs has been a major topic at a number the conferences of the International Commission on Large Dams (ICOLD) and presented in ICOLD bulletins. Important publications include ICOLD Question 58, i.e. "Foundation treatment for control of seepage" (Božović 1985), and "Karst and Dam Engineering" (in Russian) by Lykoshin et al. (1992). Very valuable information on this topic was presented at the International Engineering Geologic Symposium "Engineering Geological Problems of Construction on Soluble Rocks", Istanbul (Turkey) in 1981.

Uncertainties that are consequences of karstification

The following geological features cause the greatest concerns when they are encountered at dam sites and reservoir areas: caverns in the foundation area, swallow holes (ponors) and caves in the reservoir area, any lesser sinkholes in the reservoir floor or close to it, natural groundwater levels that are deep beneath the reservoir (or prior river) floor, possible landslides, large springs and estavelles that will be inundated by the reservoir, thermal springs at the dam site, and the presence of evaporite rocks there or anywhere within the reservoir area.

The common potential problems and failures during operation are: endangering the stability of the dam, leakage through and under it, physical damage to it, dam collapse (with the likelihood of a disastrous flood wave), unacceptably large leakage losses from the reservoir, negative impacts on downstream springs, creation of new swallow holes, creation of new collapses in the reservoir and its vicinity, progressive erosion in caverns and damage to grout curtains, progressive increase of leakage, deterioration of water quality in the karst aquifer, induced seismicity, pollution of surface reservoir water due to contact with evaporites in the floor and banks, and environmental impacts endangering sensitive endemic fauna.

Due to the highly specific, widely differing nature of karstification at different sites, in many cases the impacts noted in the preceding are unpredictable, and they can sometimes occur instantaneously. Collapses of the dam structures themselves are rare in karst and have mostly occurred due to presence of evaporites at the sites. Well-known examples include the Quail Creek Dike (Payton and Hansen 2003) and St. Francis Dam (Rogers 2006) in the USA, and the San Juan earth dam in Spain (Gutierrez et al. 2003). The Mosul Dam, on the River Tigris in Iraq, in operation since 1986, has been declared to be one of the most dangerous dams in the world due to problems with gypsum in the foundations (Adamo et al. 2015).

Characterisation of geology associated with dams in karst regions

In carbonate rocks, both physical erosion and chemical corrosion occur with varying intensity and they cause permanent changes to the prevailing conditions. The key regulatory factories the evolution of the karst aquifer by the progressive adaptation of groundwater flows towards attaining the least expenditure of energy.

In the selection of acceptable dam sites or reservoir areas, the essential requirement is to understand the evolution of the karst aquifer at the regional and local scale. However, due to the complexity created by the wide range of lithologic, structural, tectonic, hydrogeologic, geomorphologic, and climatic conditions, plus orogenic mobility and any new tectonic activity, a wide range of different parameters needs to be considered and their values determined. Based on more than 100 years of experience of dam construction and operation in different karst regions, there are a number of lessons to be learned and general concepts to be applied. One key conclusion is that each karst region must be treated as geologically unique because the processes of karst evolution depend on such a large number of parameters that truly similar situations are seldom, if ever, to be found (Milanović 2002).

To select the least risky places for dam and reservoir construction, the following parameters have to be taken into account: the characteristics of the regional geological structure(geosyncline or platform); location, extent and form of local structures (anticline, syncline, overthrust, etc.); lithostratigraphic properties (carbonates, evaporites, both); the karstification processes (epigene or hypogene or a mixture); geomorphic form (deep gorges, wide valleys, karst poljes, etc.); location of the local and regional base levels for discharge of groundwater (whether they are inside the dam site catchment area or in adjacent catchments); and the likelihood of new tectonic movements as the karst aquifer evolves in response to load being added at the dam and in the reservoir. In the first stage of dam site selection, the geomorphological properties, geological structure and groundwater regime are particularly important.

Evaporites are particularly vulnerable if they are present in the foundation of dams or in abutments of the reservoirs (Milanović et al. 2019). Worldwide, more than 60 dams have been affected by gypsum and salt dissolution problems and needed rehabilitation. The best examples are: Anchor Dam (Wyoming, USA, Jarvis 2003); Mosul Dam, (Iraq, Guzina et al. 1991); Kamskaya Dam (Russia, Maximovich 2006) and San Juan Reservoir (Spain, Gutierrez et al. 2003).

Geological structure and reservoir watertightness

One of the most important aspects of dam site analysis is assessment of the geomorphology. Analysis of the significance of any narrow canyons, sinkholes, karst poljes, dry valleys, river terraces, landslides and paleo-slides, is a crucial starting point in selecting a safe and acceptable site. All of these features depend on the interaction of many parameters and processes but mostly are the consequence of interrelations between geological structures, fluvial erosion and new tectonic movement.

As a consequence of aforementioned processes, rivers tend to change direction, i.e. create a number of bends. If the dam site is located between the upstream and downstream sections of a river band, the river channel downstream of a dam site will be the erosional base level for the water at the upstream river section (i.e. for a potential reservoir area).The difference of elevation between upstream and downstream sections of a river can be a few tens up to more than 100 m if channel entrenchment is occurring. If there are karst-prone rocks between these sections, there can be a very rapid karstification process creating underground short-cuts for the flow across the meander-like band, especially at its neck. As a consequence, upstream sections of river valleys become risky spots for water storage. The following examples are selected to illustrate this common situation.

In the Zalomka River Valley, Herzegovina (the southern region of Bosnia and Herzegovina), a site with very suitable topography and geotechnical properties was selected for dam construction (Fig. 1a). Downstream of the dam, the Zalomka River changes its direction from east → west to west → east/south. The difference of elevation between the potential reservoir area and the downstream river bed is 50–60 m, while the distance is only 4–5 km, i.e. a gradient of >10 m/km. It was feared that there would be rapid karstification, to create an underground short-cut between the potential reservoir floor (ponor zone) and the spring zone (local erosion base level). To avoid this dangerous possibility the dam site was shifted upstream from the sinkhole area on to much safer dolomite.

A similar situation was a cause of long-lasting investigations in the case of the Ilarion Reservoir in the Allakmon River Valley, Greece. The site is situated mostly in watertight schists (phillites); however, a small part of the reservoir at its upstream end, in the Elati area, is in contact with a karstified limestone marble formation that extends to contact the same river 11 km downstream (Fig. 1b). The difference in elevation between leakage at Elati and the Rimnion springs is about 60 m. The groundwater level (GWL) at the Elati area is 50 m beneath the reservoir floor. Very slow filtration between the reservoir and springs was confirmed by tracer testing. To block leakage towards the Rimnion springs, a grout curtain about 480 m long and 200 m deep was constructed in the right bank of the reservoir.

At the Karun 3 dam site in Iran, the W → E river valley is oriented almost perpendicularly to a large limestone anticline. Immediately downstream of the dam site, the river changes direction to east→ west (Fig. 2). The dam is located in the south-west sector of the anticline. The difference in elevation between the reservoir bottom and downstream section of Karun River is about 20 m (Fig. 2a). Immediately after reservoir filling began, leakage was observed along the strike of the anticline, following the bedding planes, particularly those in pure limestone beds (Fig. 2b). Depending on the level of water in the reservoir, leakage ranges from 0.3 to 1.0 m^3/s.

Similar situations where river channels downstream of a dam serve as erosion base levels for reservoirs upstream are seen in the instances of Seymareh Dam (Iran), Salakovac Dam

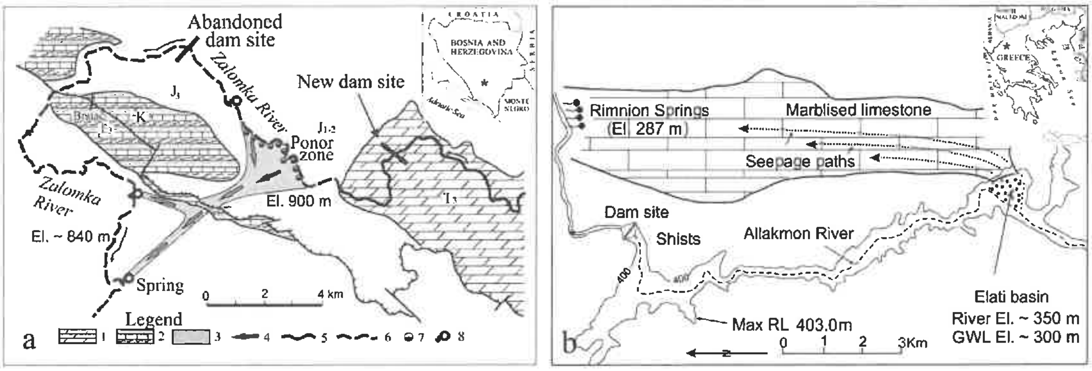

Fig. 1 **a** Nevesinjsko Polje, Herzegovina (the southern part in Bosnia and Herzegovina). Legend: 1 dolomite; 2 flysch; 3 concentrated groundwater flow; 4 direction of groundwater flow; 5 permanent surface water flow; 6 temporary surface water flow; 7 ponor; 8 temporary spring. J refers to karstified limestone. **b** Elati Basin in Greece, with potential leakage routes. RL reservoir level

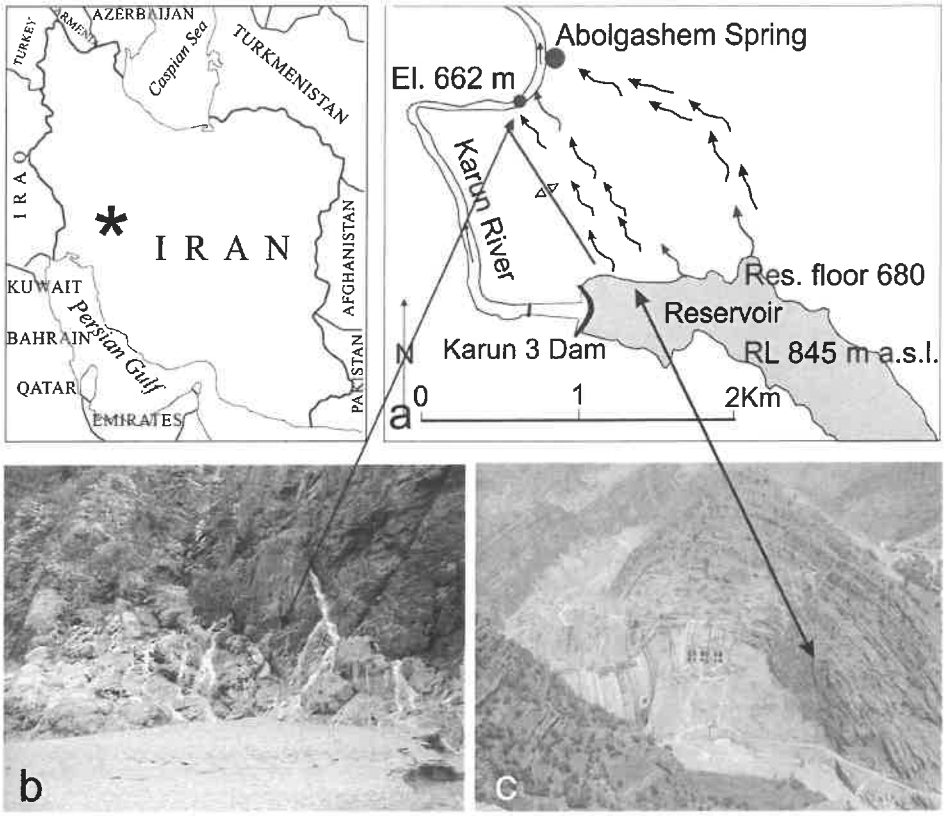

Fig. 2 **a**–**c** Dam and reservoir at Karun 3, Iran. **a** Leakage paths developed between the upstream and downstream sections of the entrenched, meandering Karun River channel. New seepage springs (clean water **b**) and increasing of seepage at Abolghasem Spring (muddy water), refer to section 'Leakage concerns' **c** Seepage zone at the dam site, right bank

(Herzegovina), Haditha (Iraq; Kondratyev 1979), and Keban (Turkey). In these cases, however, the leakage water is not lost from the catchment area. If the water is being used for power production, any reservoir leakage losses can be used at downstream run-of-the-river power plants (Milanović 2018).

There is a different situation at the Akköprü Reservoir in Turkey. Approximately 2 km upstream from the dam, the floor of the reservoir (115–125 m asl) and left bank are in a belt of extremely karstified limestone marbles about 800 m wide. A number of vertical karst shafts extending down to modern sea level have been detected. Water sinking in them flows directly to a spring zone at the sea coast outside of the reservoir catchment area. To prevent seepage, a thick reinforced concrete slab on the surface was linked to a 40–60-m-deep cut-off wall (Günay and Milanović 2005).

As noted, the presence of swallow holes, sinkholes, caves and springs inside a reservoir area indicates risky and leakage-prone hydrogeological conditions. However, due to the variability of karst, this is not an absolute rule. If there is an impervious geological structure between the reservoir and a lower erosion base level, the situation can be significantly different. Based on the geometry and spatial location of the impervious barrier, a given reservoir area can be declared to be a *hydrogeologically closed structure*. The best example is the Bileća Reservoir in Herzegovina (Fig. 3).

Between the upstream sector of the Trebišnjica River (the Bileća Reservoir) and its downstream, much lower, reaches, there is a regional anticline structure with an impervious core. After crossing the anticline, the river turns from north–south to east–west. Underground flow between the reservoir and lower channel is prevented by the core, which consists of grusified and compressed Triassic dolomite. This is the reason why all underground flow in this large catchment discharges through the huge Trebišnjica Spring (Qav > 80 m^3/s), which is upstream of the anticline. The spring is now beneath 75 m of water in the reservoir. Active karstification processes are "trapped" inside the reservoir and its banks, and more than ten ponors have appeared in the reservoir bottom as a consequence. Discharge from the reservoir is possible only as surface flow through a river gorge. The Grančarevo Dam is constructed in that gorge, on the flank of the anticline, where the low-permeability foundations consist of Jurassic limestones with shale and shaly-coal interbeds. The efficiency of the clay-cement grout curtain is perfect. Even though the 75–100-m-deep reservoir is located entirely on well-karstified carbonates, leakage from it and at the dam site is less than 50 L/s. This is negligible for a reservoir with a capacity of 1.3 billion m^3.

A high base of karstification prevents leakage from the Bileća Reservoir (normal water level, NWL 400 m asl) toward

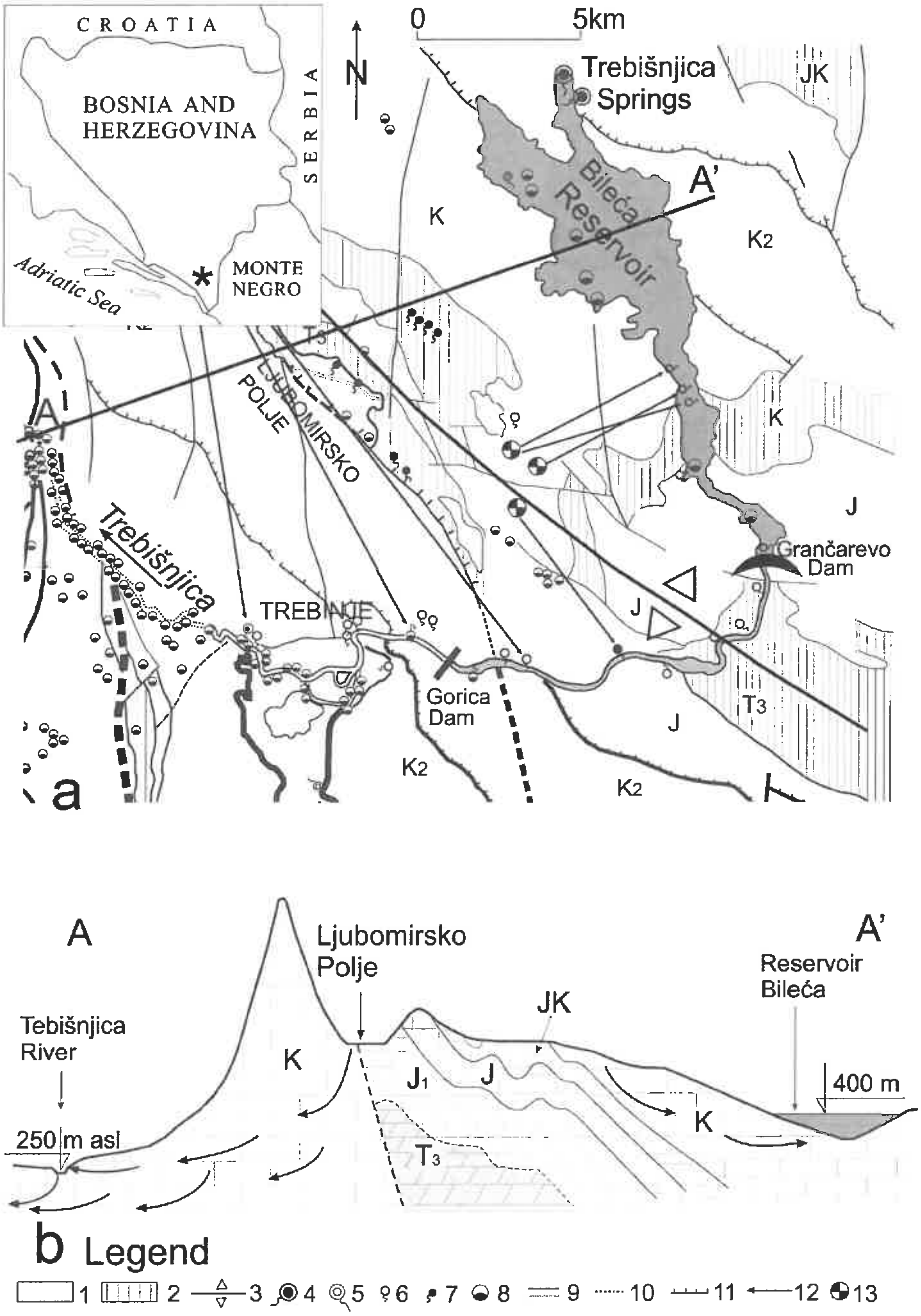

Fig. 3 Bileća Reservoir, Herzegovina. **a** Hydrogeological map and **b** cross section. Legend for **a**: 1 karstified limestone; 2 dolomite; 3 anticline axis; 4 karst spring; 5 large temporary spring; 6 small temporary spring; 7 small permanent spring; 8 ponor; 9 geological boundaries; 10 intermittent river; 11 overthrust; 12 underground connections; 13 boreholes

the Bregava River spring zone at an elevation of 110–130 m asl.

The Karun 4 Reservoir in Iran is also located within a geological structure with good hydrogeological retention conditions. The reservoir flooded the narrow canyons of Karun and Bazuft rivers with bottom elevations of about 860 m asl, rising upstream. Downstream of the dam, the river changes direction by almost 180° (Fig. 4) and is 60–89 m lower in elevation than the reservoir.

Between the Bazuft and the downstream Karun lies the long and continuous Safid-Kuh anticline, trending parallel with both rivers (Fig. 4a). The anticline core consists of the impervious Pabdeh (marl, marly limestone, shale) and Gurpi (marl, marly limestone and shale) formations. This 2-km-wide core serves as a good hydrogeological barrier between the reservoir and the channel downstream. Karstification in the north-east flank of the anticline was limited and directed into the Bazuft channel only. A number of caverns were found in

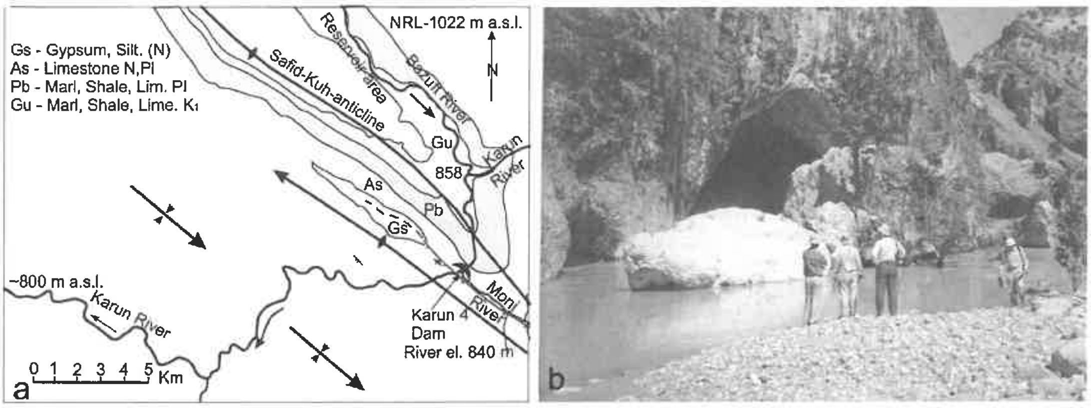

Fig. 4 Karun 4 Dam (Iran). **a** Sketch of the reservoir area; **b** caverns in the reservoir floor, now inundated. For country map refer to Fig. 2

the right bank of the reservoir and in the canyon bottom (Fig. 4b). However, due to their origin as underground tributaries discharging to the canyon, they do not permit any leakage from the reservoir; however, the Asmari Limestone at the dam site itself is tectonically deformed, and karstified by both epigene and hypogene groundwaters (Fig. 4c). In contrast to the watertight reservoir, the hydrogeological conditions at the dam site required complex preventive measures.

Beside geological structures, the water tightness of reservoirs in karst can be aided where the *local base of karstification* is shallow in the terrain between the reservoir and the erosion base level. Where karstification is governed by two different erosion base levels, the land between them may not be affected by karstification. Negligibly karstified or hard, compact carbonate rock tends to minimise or prevent hydraulic connection between the adjoining base levels: the high base (shallow depth) of karstification here plays the role of underground watershed between two river basins. Due to this role, *the base of karstification* can be defined as a distinct hydrogeological structure.

In the example of the Geheyan Reservoir, China, the impounding capability of the reservoir is reliant on the very compact nature of the carbonate formations in the mountain spur between the reservoir and the river canyon downstream (Fig. 5; Ruichun and Yan 2004). In a number of cases, the base of karstification in the dam foundations is accepted as the beginning of a lower-permeability rock mass where the grout curtain will be tight.

Groundwater levels: a crucial source of diagnostic information

Among the many diagnostic hydrogeological properties of karst aquifers, knowing the groundwater regime is of key importance for estimating the risk levels at dams and reservoirs. The regime depends on the intensity and depth of karstification, location of the principal conduits, hydraulic properties of host rocks, and similar. The minimum and maximum GWL and the regime of the fluctuation between them is particularly important. Deep groundwater levels indicate a deep base of karstification. Long experience with the problems that can arise where groundwater levels are deep beneath the reservoir demands particular care and analysis before there is a final decision on feasibility of a project. Evaluation of the designs and methods needed for an effective sealing approach will be exceptionally complex. Deciding between emphasizing surface or underground sealing applications is particularly difficult.

In a number of cases the GWL in natural conditions has been found to be deep beneath the proposed dam foundations or reservoir floor: Lar, Iran (200–300 m); Mornos, Greece (~200 m, Pantzartzis et al. 1993); Akkoprü Reservoir, Turkey (116 m); Hutovo Reservoir, a karst polje in Bosnia and Herzegovina (>100 m); Buško Blato karst polje in Bosnia & Herzegovina, (Nikolić et al. 1976); Perdikas, Greece (70 m, Heitfeld and Krapp, unpublished repot, 1972); Abolabas, Iran (60 m); Tang Ab, Iran (40–60 m); Ourkis Dam site, Algeria (40–60 m, Milanović et al. 2007); Elati Basin, Ilarion Reservoir, Greece (40–50 m); Slano Reservoir, a karst polje in Montenegro (40 m); Boqaata, Lebanon (36 m); Havasan, Iran (20–35 m); Vrtac karst polje in Montenegro (10–20 m);the Taka Lake polje in Greece; and Montejacque Dam polje in Spain (Therond 1972).

From present experience, the concept of sealing the surface has advantages compared to sealing underground. Due to deep GWL some reservoirs have been abandoned (Montejaque, Vrtac), some dam sites shifted to less risky places (Havasan), and others operated with acceptable amounts of leakage—Lar, Slano, Tang Ab (underground treatment applied); BuškoBlato (both underground and surface treatments were applied). Surface treatment on its own has been successful at Hutovo, Ourkis and the Akkoprü Reservoir.

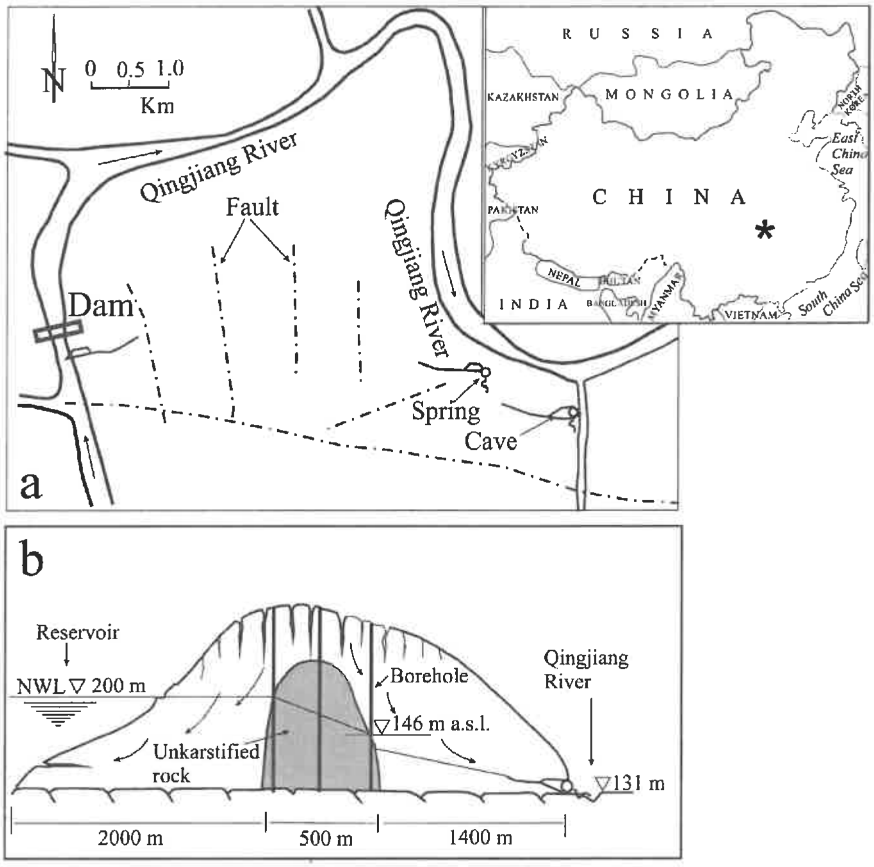

Fig. 5 Geheyan Reservoir, China. **a** Layout and **b** cross section (Ruichun and Yan 2004)

Leakage concerns

Leakage from a reservoir is a key problem in engineering karstology—for example, as many as 644 reservoirs suffer from significant leakage losses in the karst regions of Guangxi Province, China, according to Yuan (1991). Leakage can remain local, meaning that water is not lost from the catchment, or the leakage may be discharged entirely outside the catchment. In the first case, the water lost from a reservoir returns somewhere downstream in the same river, while in second case, the leakage is a definite loss to the water balance in the catchment.

After dam construction and during the ensuing filling of the reservoir, the karstified rock mass is exposed to unnaturally large and rapid increases of pressure. The main purpose of dam and grout curtain construction is to prevent hydraulic connections developing between the surface and underground waters that are upstream and those that are downstream. When filling starts, the gradients between these two parts of the aquifer increase rapidly. In a majority of cases, grout curtains are not perfectly watertight underground structures. Occurrence of weak and leakage-prone points in the grout curtain is not the exception; in karst it is the most frequent case. The weak points are places where the grout mix could not penetrate into the some of the open joints and other cavities. If the curtain does not form a 'positive cut-off structure', the increased water pressure can extend beneath and/or around the curtain. In these circumstances, the process of sediment wash-out (silt, clay) from any karst conduits and caverns will begin and be immediately followed by increased leakage of water. Old karst channels formed in earlier karst cycles come back to life, i.e. their ancient water transfer functions are reactivated. This process usually begins immediately after the first-time filling of a reservoir, and can be very fast—for example, "the Hales Bar Dam, Tennessee (USA), is a notorious example of a simple and immediate response to raising the water table, because there was leakage directly under the dam where the hydraulic gradient is greatest", Ford and Williams 2007.

The amount of clayey and sandy particles washed out in the water can be more than 10% w/v. Sometimes this appears at the surface as a muddy suspension (Fig. 6). In other cases, the process is slow and takes some years. In the case of the Višegrad Dam (Bosnia and Herzegovina), due to progressive erosion, leakage increased from 1.4 m^3/s during first filling in 1986 up to 9.4 m^3/s in 2003 (Milanović 2004). Despite a few intensive grouting campaigns, it further increased to 13.92 m^3/s in 2008 (Milanović et al. 2015). During this period, more than 10,000 m^3 of clayey-sandy sediments were washed

Fig. 6 Karun 3 Dam, Iran. Abolghasem Spring (refer to Fig. 2)

out of the rock along the grout curtain. After filling the empty cavern space by inert material, the seepage was reduced to 4 m^3/s.

Leakage from Great Falls Reservoir (Tennessee, USA) increased from 0.47 m^3/s in 1926 up to 12.47 m^3/s in 1954. A first registered leakage of 1.4 m^3/s in 1965 from the Gorica Reservoir in Herzegovina increased to 4.4 m^3/s in 2003. Increasing seepage is also reported at the Slano Reservoir (Montenegro), El Cajon (Honduras, Guifarro et al. 1996), Mosul (Iraq),Seymareh (Iran) and many others. Abrupt leakage started through new ponors created in the bottom of Hammam Grouz Reservoir in Algeria after 17 years of operation (Milanović P., Stevanović Z., Beličević V. Hamam Grouz, Saf-Saf and Ourkis Dams. Rapport de Expert Mission, Agence Nationale des Barrages et Transfert. Republique Algerienne Democratique at Populaire (not published, 2007). At the upstream end of the Mavrovo Reservoir (North Macedonia) there were a number of sudden collapses after 25 years of operation.

The efficiency of remedial works

By increasing our understanding of the nature of karst and experience in dam geology, plus the development of new techniques of investigation and sealing, the construction of dams has become less risky. Over time the number of failures has decreased substantially. Nevertheless, karst itself, as a distinctive geo-phenomenon, is still not a friendly environment for dam and reservoir construction.

It is well known that reservoirs in karst may fail to fill despite extensive investigation programs and sealing treatments. The risk of constructing in karst cannot be eliminated completely due to its hydrogeological and geotechnical complexity, even when best engineering practices are followed. Due to the complex and varying patterns of the porosity the probability that each and every karst channel or solution-widened crack can be plugged by applying current sealing technology is very low. Because of this, the efficiency of each dam and reservoir constructed in karst cannot be established before the first reservoir filling. If selection of the dam site and reservoir area is based on detailed geological information and well-designed measures of prevention are applied, there is a good chance that there may be only negligible or acceptable leakage; remedial works will not be necessary. However, in many instances, leakage has started at the very beginning of reservoir impoundment and increased proportionally with the rise of the reservoir water level. In such cases, remedial works must be applied immediately after the first seepages are observed. Any postponement may provoke increasing leakage, shifting of the erosion to greater depths, and increasing pressure, i.e.

worsening the technical possibilities of efficient sealing in the future.

In some instances the leakage during first filling was more than 10 m^3/s: Hales Bar, USA(50 m^3/s, Tennessee Valley Authority Projects 1949), Keban, Turkey (26 m^3/s), Vrtac, Montenegro (>25 m^3/s), Camarassa, Spain (11.2 m^3/s, Therond 1972), Ataturk, Turkey (>11m^3/s, Riemer et al. 1997), Lar Dam, Iran (10.8 m^3/s), Salakovac, BiH (>10 m^3/s), Freemen Dam, Kentucky, USA (~10 m^3/s), Great Falls, USA (9.5 m^3/s), and many others are recorded with losses between 2 and 10 m^3/s (BuškoBlato, Croatia; Dokan, Iraq (Perrott and Lancaster-Jones 1963); Slano and Krupac, Montenegro; Montejques, Spain (Therond 1972); Seymareh, Iran; Kowsar, Iran; Hutovo, Herzegovina; (Milanović 2004, 2018).

In many such cases the results of the remedial works justified the additional expense invested: Canelles, Spain (Weyermann 1977); Dokan, Iraq; Krupac, Montenegro; Great Falls, USA; Camarasa, Spain; Marun, Iran; Mavrovo, North Macedonia; Kama, Russia (Maximovich and Meshcheryakova 2009); Hutovo, Bosnia and Herzegovina, and a number of others. However, in some cases, problems cannot be eliminated completely due to the hydrogeological and geotechnical complexity of karst, even when best engineering practices are followed (Lar, Iran; Salakovac, Bosnia and Herzegovina; Seymareh, Iran; Samanalawewa, Sri Lanka; Keban, Turkey).

In the worst cases, some of the already constructed dams are abandoned (Montejaques). Some dam projects are frozen (Bogovina, Serbia) (Stevanović 2010). Some dam sites are displaced at the new location: Cedar Ridge Dam, Texas (Johnson and Wilkerson 2013). The location of Havasan Dam, Iran, after detail investigations, was moved a few kilometres upstream.

The need for remediation depends on possible consequences of the leakage, principally, its effects on the stability of the dam and economic impacts caused by increasing losses of water. A common question is 'What is the *minimal acceptable leakage?*' This will depend on the volume of the reservoir and the average flow into it. For reservoirs with volume less than 10 million m^3, acceptable leakage is usually less than 40 L/s, while for large reservoirs with a few hundred million m^3, it can be 0.5 m^3/s or more. Very often, however, 'acceptable leakage' is decided for other technical, economic or political reasons. For instance, the acceptable leakage from the Polifiton Reservoir in Greece (volume = 1,900 million m^3) is 6 m^3/s, which is 10% of the mean annual river flow there.

Risk increases attributable to bureaucratic misunderstanding of the nature of karst

A large proportion of the carbonate regions are rich in water resources, partly because of the exceptional groundwater storage in their evolving karsts. As they also experience surface fluvial erosion (at least in the early stages of a cycle) deep and narrow river gorges are created, the most favourable topography for building a dam and thus the most inviting for dam designers. However, in many cases the engineering geological and hydrogeological properties of selected sites were not properly investigated and analysed, sometimes being totally overlooked! At the end of the nineteenth and beginning of the twentieth centuries, the typical budget provided for engineering geological and hydrogeological investigations at a site was negligible. In many cases, geological engineers were not part of design teams. It was a time when the processes and features of karst were analysed mostly at a qualitative level. A number of problems and failures, some of them disastrous, occurred due to dam and reservoir sites being selected with gravely inadequate geological understanding. One of the largest disasters was the collapse of the St. Francis Dam in California (USA) in 1928, killing 450 people downstream. It was one of the most important "triggers" of change in approach. "The St. Francis tragedy also drew attention to the importance of engineering geologic input in site selection, which became standard practice, as did engineering geology in the civil engineering curriculum" (Rogers 2006). After 1930, a number of companies dealing with dams hired their first geological engineers. "The California Division of Waters in 1934 hired a staff of 5 geological engineers which grew to 134 by 1968" (Rogers 2007).

After geologists became important members of dam design teams, the risks decreased. Detailed analysis of the structural integrity of karstified rock in the foundations of a dam and the impounding capability of the reservoir area proposed behind it require more complex and time-consuming investigations than are usually applied in sites on insoluble rocks. Any restriction of the budget and time allocated for investigations and later during construction may lead to erroneous conclusions and failure.

The prevention measures at a majority of dams will need modifications and adaptations on the basis of geological findings beneath the surface. Underground karst features are excessively expensive to treat because they need careful assessment of their feasibility, practical engineering, funds and time. The final design of the prevention measures—mostly, the parameters for a grout curtain(s)—can only be finally decided during the actual construction phase.

For example, for the Salman Farsi Dam (Iran) the total length of grouting galleries proposed in the tender documents was 2,290 m. Due to remediation of caverns discovered during the construction, a large part of the grout curtain needed modification. The redesigned curtain required the extension of existing grouting galleries and construction of new ones (including a by-pass curtain to isolate the largest cavern) and a few additional investigation shafts and galleries for further possible cavern infilling. The total length of galleries now exceeds 5,800 m and the grouting section is 3,700 m. The budget and time for the construction have increased considerably. Similar situations are reported during construction of many other dams in karst.

In these and other less drastic situations, strict requirements to finalize a structure *strictly on-time* and *on-budget* tend to be in direct contradiction of the much important requirement to *decrease risk of failure as much as possible.*

The importance of site investigation works

To select a safe dam site and watertight reservoir the most important starting point in risk-reduction strategy is preparation of a good geological map of the site, beginning with a regional geological and hydrogeological analysis. The crucial features that make karst an unfriendly environment for dam construction are the caverns and lesser (smaller but usually lengthy) solution channels. Many of the commonly applied methods of investigation are imperfect. None of them alone is sufficiently reliable to solve the problems. Detection of the precise position and form (shape) of a cavern from the surface is still very problematic at depths of more than 20 m. Karst features detected at the surface such as shafts, caves, ponors and sinkholes, are confirmation that there are karst channels and caves underground; however, the absence of karst features on the surface does not mean their absence underground. A well-defined prevention approach to minimise or eliminate risk of leakage will require application of a number of different methods: geological mapping, geomorphological analysis, investigation boreholes, investigation adits, hydrological measurements, groundwater level monitoring, geophysical investigations, tracer tests, engineering-geological tests, speleological explorations and some other specific methods. One possible engineering karstology approach to dam site selection and sealing treatments during construction in karstified rocks is presented in flow-chart form in Fig. 7.

The borehole is a crucial component in the investigation of dam geology; however, in karstified rocks, boreholes have limitations. More than 80% of the problems created by caverns and karst channels are likely to be deep beneath the dam foundations and the reservoir banks. As emphasized in the preceding, detection of caverns and solution channels are not truly predictable from the surface, even by the best methods of investigation available today. Whereas dam site is investigated by a large number of boreholes, it probably will be not enough for valid estimation of intensity and depth of karstification. A well-known example is the investigation borehole that was drilled inside a large Eastern Herzegovina swallow-hole that has a sink capacity >>25 m^3/s: the derived permeability was 0.00 Lugeondown the entire hole!

Determining the three-dimensional (3D) location of karst voids underground is a major problem—for instance, in spite of the 27 boreholes that were drilled along the 500 m of investigation adit behind the large Ombla Spring (Croatia), the principal karst channel, with a flow capacity of more than 100 m^3/s, was not detected. Or, at the Salman Farsi dam site (Iran) a large cavern (150,000 m^3) was not discovered by 3,500 m of boreholes. In the left bank of the Sklope dam site (Croatia, Božičević 1969), a cavern with a volume of 25,000 m^3 remained undiscovered in spite of many investigation boreholes. At the Keban Dam (Turkey) a giant cavern of 600,000 m^3 stayed undiscovered despite 30,000 m of boreholes and the application of many other methods of detection.

Investigation adits are the most effective means of exploration in karstified rocks. Adits make direct observation and investigation possible deep inside the rock mass. Detection of significant karst channels and caverns by adits is much more likely than by any other method, including boreholes.

Conclusions

These case histories have shown some of the problems of constructing dams and reservoirs in karstified rocks. Karst areas are extremely complex and exhibit a great variety of geomorphological, hydrogeological, hydrological, and engineering geological conditions. When a major period of dam building began at the very beginning of the twentieth century, the amount of geological expertise involved in the planning process was either negligible or neglected entirely. Dam failures were frequent and, in many other cases, the reservoirs never filled to the designed water level despite extensive investigations and remedial works, resulting in their abandonment. A dilemma arose—keep away from karst terrains or accept the special challenges. With increasing demands on water resources in many karst regions, the only way for socio-economic development has been and remains to be the construction of storage reservoirs. In spite of the term *karst* frightening engineers, the lessons learned from failures during more than one century have confirmed the possibility of successful water management where the dam is the key installation. After the infant stage of modern dam construction, the input of engineering karstology has become crucial in selection of dam sites and reservoir locations. The efficiency of the methods of investigation and the effectiveness of watertight sealing technology has increased tremendously. The number of large failures has decreased considerably. The *keep away from karst* position has been replaced with *be familiar with karst,* in order to construct safe large structures. However, due to the nature of karst, risk cannot be absolutely eliminated even where the best engineering practice is followed. The chief targets in engineering karstology are to minimize the risk at technically and economically acceptable levels. An approach based on flexibility and resilience is needed to prevent or mitigate leakage and its consequences. Remedial works

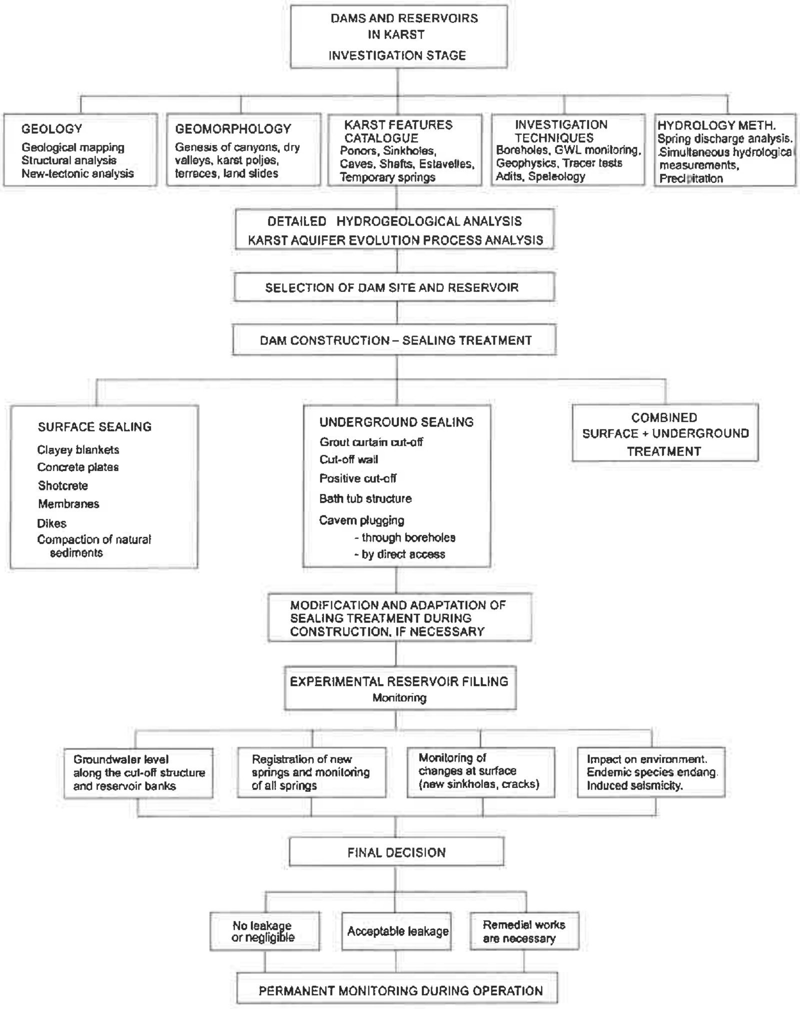

Fig. 7 Flow chart of the engineering karstology approach in dam and reservoir construction

after the first filling are the destiny of a majority of dams and reservoirs built in karst areas.

For a dam project to be successful, a crucial requirement is good understanding of the *evolution of the karst aquifer* at and around the site. This complex process, known as *karstification,* depends on many parameters that are likely to differ from site to site and from reservoir to reservoir. Important parameters and processes include: the lithostratigraphic properties (mechanical strength, porosity, etc.), precise location and nature of geological structures (joints, faults, bedding planes, folds, etc.), geomorphological characteristics (surface landforms, conduits, caverns, the karst base), neo-tectonic movements, presence of evaporites, occurrence of upward flows from depth, relationships between fluvial erosion, corrosion and the groundwater regimes. The decision to accept a given site for dam construction needs to be based upon a detailed analysis of these parameters and processes. The groundwater regime, presence of evaporites and any deep upward water flows are of key importance for estimating the feasibility of a project from both the technical and the economic view points.

Reclamation projects, particularly the construction of large dams and reservoirs, can have many different impacts on the sensitive karst environment, often including detrimental effects. Keeping a balance between the need for regional socio-economic development and the preservation of the naturally rich and complex environment in karstlands should be mandatory in any reclamation project.

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