The possible negative consequences of underground dam and reservoir construction and operation in coastal karst areas: an example of the HEPP Ombla near Dubrovnik (Croatia)

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Abstract

The Ombla Spring represents a typical abundant coastal karst spring located in the vicinity of **the town of** Dubrovnik (Croatia). Its outlet is at an altitude of 2.5 m above sea level (m a.s.l.) and the water from it immediately flows into the Adriatic Sea. The minimum and maximum measured discharges are 3.96 m^3 s^{-1} and 117 m^3 s^{-1}, respectively. The Trebišnjica River traverses through its catchment. The mean annual discharge, after the canalization of over 60 km of its watercourse with spray concrete (in the time span 1981-2011), is 24.05 m^3 s^{-1}. Before massive civil engineering work which took place during 1968-1980, the mean annual discharge was 28.35 m^3 s^{-1}. There is a project for construction of the hydro electric power plant (HEPP) Ombla, which will exclusively use groundwater from the Ombla Spring karst aquifer. The underground dam will be constructed about 200 m behind the existing karst spring outflow in the karst massif, by injecting a grout curtain. **The top** of the grout curtain is planned to be at an altitude of 130 m a.s.l. This karst system is complex, sensitive, vulnerable and ecologically extremely valuable. The grout curtain, as well as the HEPP Ombla development, could lead to extremely dangerous technical and environmental consequences. In this paper some probable, negative consequences of the HEPP Ombla construction and development are explained.

1 Introduction

Natural as well as anthropogenic works in karst areas cause strong, sudden, hardly predictable and mostly dangerous processes with immeasurable consequences **for** the environment and social systems (e.g.: Beck, 1984, 1989, 2005; Bonacci and Jelin, 1988; Drew and Hötzl, 1999; Breznik, 1998; Milanović, 2000, 2002; Beck and Herring, 2001; Bonacci, 2004; Waltham et al., 2005; Bonacci et al., 2009, etc.).

Karst is defined as a terrain, generally underlain by limestone or dolomite, in which the topography is chiefly formed by the **dissolution** of rock, and which is characterised by sinkholes, sinking streams, closed depressions, subterranean drainage and caves. A wide range of closed surface depressions, a well-developed underground drainage system, and strong interaction between the circulation of surface water and groundwater typify karst.

Diversity is considered the main feature of karstic systems, which are known to change very fast and in a hardly predictable manner over time and in space so that an investigation of each system on its own is required. In karst terrains groundwater and surface water constitute a single dynamic system. The hydrocomplexity of karst regions is enormous. The determination of catchment boundaries and the catchment area is the starting point in all hydrologic analyses and one of the essential pieces of information which serve as the basis for all hydrologic calculations. In karst terrains this is always a very complex task (Gunn, 2007). Groundwater exchanges with adjacent aquifers through underground piracy routes or via inflows from surface streams and thus accumulations are common in karst. Consequently, only in exceptional cases surface (topographic or orographic) and subsurface (hydrologic or hydrogeologic) catchment boundaries coincide. The problem is additionally complicated by the time-variant hydrologic boundaries which are dependent on fluctuations of groundwater levels (GWL-s) (Bonacci, 1987, 2002; Kresic and Stevanovic, 2010).

Any kind of engineering action in a karst terrain presents numerous challenges to the engineer, including the unpredictable occurrence of cavities and well-developed hydraulic conduits which could lead to sinkhole development. The size and shape of a cavity in limestone depend on the interaction between the characteristics of geological structures, such as internal fractures or discontinuities, and water activity.

Human intervention, especially the construction of dams and reservoirs realized by creating large grout curtains (Bonacci et al., 2009), as well as interbasin water transfers through long tunnels and pipelines, can introduce instantaneous and distinct changes in catchment areas and boundaries, and, in turn, on the hydrological, hydrogeological and ecological regimes (limitation of energy flow, destruction of food cycle, blocking of convections between habitats and species, pollution of groundwater and underground environment etc.) (Bonacci, 2004).

The project for construction of the hydro electric power plant (HEPP) Ombla will exclusively use groundwater from the Ombla Spring karst aquifer. The underground dam will be constructed about 200 m behind the existing karst spring outflow in the karst massif, by injection of a grout curtain.

The main goal of this paper is to encourage further detailed interdisciplinary measurements and analyses in order to understand the possible negative consequences caused by the construction and development of the HEPP Ombla. The intention of the paper is to identify potential problems and to solve them before they occur in complex and **poorly** investigated karst environments. The HEPP Ombla system is internationally shared between Croatia and Bosnia and Herzegovina. Due to this reason one of the goals of the paper is to point out the specific characteristics of the karst aquifer and its water management, which can represent a real trigger for possible conflicts between the two neighbouring states.

The HEPP Ombla example, apart **from** being an interesting case study, can be valuable for many other karst areas worldwide where engineering works and construction are taking place, especially those based on grout curtains. This paper focuses on the critical issues and priorities needed to address karst region risks and governance for disaster prevention.

2 Short description of the natural characteristics of the Ombla Spring and its catchment

Figure 1 represents a map indicating the study area, the site of the Ombla Spring, with its supposed catchment area, the Zaton Spring, the Trebišnjica River, the boundary between Croatia and Bosnia and Herzegovina as well as the position of existing dams, reservoirs and HEPP-s. The photograph presented in Fig. 2 shows the Ombla spring from an areal view.

The catchment area and boundaries shown in Fig. 1 have been determined by using only geological data, without adequate hydrogeological data. The catchment area is estimated to be about 600 km^2 (Milanović, 1996; Sever, 2003). According to the author's investigations which were based on water-budget analyses the catchment area is much larger, and ranges between 900 km^2 and 1000 km^2 (Žugaj and Bonacci, 1994).

The geological setting is mostly composed of highly permeable Jurassic limestone, poorly permeable Triassic dolomite and Eocene flysch, which represent an impermeable hydrogeological barrier (Buljan et al., 2000; Sever, 2003; Paviša, 1998, 2003). The Quaternary sediments cover the bottom of the numerous poljes in the karst. As a consequence of intensive tectonic activity these poljes have been formed as terraces from an altitude of 1000 m above sea level (m a.s.l.) to the sea level. From the hydrological and hydrogeological point of view, the poljes function as part of a wider system. They represent more or less interconnected subsystems within the process of surface and groundwater flow through the Ombla Spring karst catchment. The basic structural and stratigraphic units are elongated in a NW-SE direction, which follows the extension of the Dinarides.

About 90 % of the whole Ombla Spring catchment is covered by limestone. Because of its high **secondary and tertiary** porosity the water infiltration takes place very rapidly. The Trebišnjica River traverses the Ombla Spring catchment (see Fig. 1) and **loses** surface water through numerous sinks located along the bottom of this section which is longer than 60 km, thus recharging the Ombla Spring. In order to reduce loses more than 60 km of the Trebišnjica River watercourse bottom have been covered with spray concrete. The maximum discharge capacity of this canal is about 50 $m^3 s^{-1}$. The average annual discharge of the Trebišnjica River in its natural state was about 68 $m^3 s^{-1}$. It should be noted that the river's natural regime has strongly changed due to the Bileće Reservoir operations and the HEPP Trebinje development.

The climate at the location of the Ombla Spring outlet, measured at the Dubrovnik climatological station is typically Mediterranean. In other parts of the catchment the climate changes as a function of the distance from the Adriatic Sea coast, moving from the Mediterranean to the continental and mountainous areas.

The average annual rainfall exceeds 1500 mm, resulting from intensive convective precipitation of short duration through the entire year but particularly in October and November. About 70 % of the total annual rainfall appears during the cold period of the year, from October to April. During thunderstorms intense precipitations of more than 10 mm h^{-1} occurs on average twice a year (Bonacci, 1995, 2004; Bonacci and Roje-Bonacci, 2000a).

The average annual air temperature measured in Dubrovnik (1961-2012) is 16.5 ºC. During last two decades the annual average air temperature in Dubrovnik was 0.7 ºC higher than in the previous subperiod (1961-1990). This statistically significant trend of an increase in air temperature is found throughout the whole broader region. The average annual air temperature over the whole catchment is assessed to be about 13 ºC.

The average annual water temperature measured at the outlet of the Ombla Spring (1962-2010) is 13.0 ºC. In the case of water temperature no trend of increase or decrease has been found.

The minimum measured discharge **of the Ombla Spring** is 3.96 m^3 s^{-1}. Maximum measured discharges never exceeded a value of 117 m^3 s^{-1}, despite the fact that the spring catchment area has about 1000 km^2, and precipitations are very intensive and abundant. The mean annual discharge after canalization of the Trebišnjica River watercourse with spray concrete is 24.05 m^3 s^{-1}. Before this massive civil engineering work**,** which took place during 1968-1980**,** the mean annual discharge was 28.35 m^3 s^{-1}. The Ombla Spring is **a** typical karst spring with a limited outflow capacity (Bonacci, 2001). Despite frequent and intense precipitation falling over its large catchment, the maximum possible discharge from the Ombla Spring is lower that 120 m^3 s^{-1}. The possible reasons for this limitation on its maximum flow rate can be: (1) limited size of the karst conduit; (2) pressure flow; (3) inter-catchment overflow; (4) overflow from the main spring-flow system to intermittent springs within the same catchment; (5) water storage in the zone above the karst aquifer (Williams, 1983; Bonacci, 2001).

The GWL changes extremely rapidly (up to 100 m in 24 hours), and the total difference between the maximum and the minimum GWL in one piezometer can reach up to 200 m (Paviša, 1998, 2003). The maximum measured GWL rising intensity was 29.2 m per hour. The maximum measured GWL falling intensity does not exceed a value of 2 m per hour (Bonacci, 1995).

The regime of suspended sediment which outflows from the Ombla Spring outlet was measured from 2003 to 2010. The annual quantity of sediment varies between 88×10^3 t yr^{-1} to 474×10^3 t yr^{-1}. Most of the sediment (more than 90 % of whole annual amount) is delivered during the intensive short rainfall, in a few hours (Denić-Jukić et al., 2012).

3 Underground dam and the HEPP Ombla

In karst**,** laminar and turbulent flow exist at the same time, **and** management and development of karst underground dams is very specific and different than in other, more homogeneous media. In the first part of this section some information about underground dams in karst regions will be given. In **the** second part**,** the main characteristic of the HEPP Ombla underground dam will be explained.

An underground dam is a facility that stores groundwater in the pores of strata. Recently, the concept of the underground dam has spread, and many have been constructed (Ishida et al., 2011). Only few of the recently-built underground dams have been realised by using grout curtains. The range of grout curtain height varies from 10 to 40 m.

Most underground karst underground dams were constructed in China. Carbonate rocks cover about 450 000 km^2 of Chinese territory, mostly located in the southern tropical and subtropical region. All underground reservoirs are constructed by clogging large karst conduits and underground cave rivers. Their storage capacity is rather small, therefore water is practically only stored in the conduits and caves (Lin Hua, 1989).

During the 1990s, the Japan Green Resources Agency constructed subsurface dams in a limestone aquifer on Miyakojima Island located in Japan's subtropical climate zone. The project was completed in 2001. The dams are composed of a cut-off wall with a maximum height of 50 m, by which the groundwater flow is dammed and the intrusion of sea water is prevented (Ishida et al., 2003, 2011). The cut-off walls were built using the in-situ Churning method. For irrigation purposes the groundwater is **drown** up by 147 tubes and stored in farm ponds (water tanks) until it is supplied through the **pipeline** systems that serve the entire island. In Miyakojima Island**,** limestone (Ryukyu limestone) only small caves, several cm in diameter, exist.

Gilly and Mangin (1994) described field investigations made in order to create an underground reservoir in French karst **by** closing up the outlet of a small karst spring. This project has not been realised so far.

The HEPP Ombla underground dam will be constructed about 200 m behind the existing karst spring outflow in the karst massif (Fig. 3), by injecting a grout curtain. The projected total area of the curtain is about 300 000 m^2. The total length of the curtain will be about 1470 m, while its maximum depth will be 410 m. Fig. 4 shows a cross-section of the projected grout curtain (underground dam) (modified after Ravnik and Rajver, 1998; Sever, 2003). The top of the grout curtain is projected to be at an altitude of 130 m a.s.l. It is presumed that the grout curtain will be founded on an impervious flysch barrier. The grout curtain is planned to be constructed from three grouting galleries set up at different elevations (Fig. 4).

The installed discharge of the HEPP Ombla is 60 m^3 s^{-1} (Sever, 2003). Four generating units will be located in the power house. Two of them will have Frances turbines with a rated discharge of 24 m^3 s^{-1}, and 30 MVA synchronous generators. The other two generating units will have a rated discharge of 6 m^3 s^{-1}, and 8 MVA synchronous generators. It has been assessed that **the total** HEPP Ombla rated power will be 68 MV, with a mean annual output of about 225 GWh. The bottom outlet has a multipurpose role. Besides functioning as the bottom outlet, it will be used as an emergency spillway and turbine discharge regulator as well as for water evacuation during and after the construction of the HEPP Ombla. Its maximum discharge capacity will be 113 m^3 s^{-1}.

4 Possible negative consequences of the HEPP Ombla development

Milanović (2002) has cited the following negative consequences of human activities and engineering construction in karst regions: (1) severe spring discharge change; (2) groundwater quality deterioration; (3) **endargenment of** endemic fauna; (4) waste disposal failures; (5) induced seismicity; (6) induced sinkholes. Bonacci (2004) has added the following hazardous consequences: (1) occurrence of landslides; (2) intensification of floods and droughts; (3) regional water redistribution; (4) conflict regarding internationally shared karst aquifers; (5) water losses from reservoirs (Bonacci and Rubinić, 2009; Bonacci and Roje-Bonacci, 2012); (6) instability of dams **built** in karst (Dreybrodt et al., 2002). As previously stressed**,** in karst terrains the relationship between surface water and groundwater is very closely connected and interrelated.

The construction and development of the HEPP Ombla can result in many large and hard-to-predict negative consequences. Some of them are specific for this particular HEPP.

It is not possible to determine the volume and **extent** of the underground reservoir, as well as its functioning. The crucial question, until now unsolved, is to what extent it will be possible to manage the water from a completely underground karst reservoir in which more than 95 % of the groundwater is stored in small karst fissures and joints where diffuse laminar flow prevails (Bögli, 1980; Milanović, 1981; Bonacci, 1987; Ford and Williams, 2007) . The natural behaviour of the karst aquifer through the Ombla Spring will be drastically changed by operation of the HEPP Ombla, but is not easy to predict in **what** manner.

4.1 Changes in water regime

The Ombla Spring mean annual discharges will be diminished because of increases in the GWL over the whole karst aquifer. It will cause more water overflow from the Ombla Spring catchment to other surrounding permanent and temporary karst spring catchments. Due to increasing of the GWL caused by grout curtain construction**,** some temporary karst springs in the local Ombla Spring catchment area **could** become permanent. In some cases these intermittent springs **might** remain intermittent but their mean discharges **could** be higher. **For the** same reason, minimum spring discharges **may** be magnified. The maximum discharges **may** be magnified.

Figure 5 represents the relationship between the hourly values of the GWL in piezometer P8 (Fig. 3), GWL P8, in m a.s.l., and the respective discharges of the Ombla Spring, Q_{OMBLA} in $m^3\ s^{-1}$ **(Bonacci, 1995)**. It is of crucial importance to notice that the GWL stagnates in the period when the hydrograph increases from 9.32 $m^3\ s^{-1}$ to 54.9 $m^3\ s^{-1}$ (over 11 hours). The intensive rainfall which caused this hydrograph started 2 h earlier. This phenomenon can be explained by the fact that during 11 h**,** large karst conduits were filled and flow which was under pressure was formed only in the large karst conduits and caves where turbulent flow is present. At this time the small karst fissures in which diffuse laminar flow prevails were not filled by water (Bonacci, 1995). If this assumption is correct, it is possible to determine the volume of the large caverns to be about $1.5\times10^6\ m^3$. The relationship between GWL P8 and Q_{OMBLA} differs during the rising and descending parts of the hydrograph. The formation of this loop can be explained by the different influence of turbulent and laminar flow.

Because of the much higher GWL caused by the grout curtain, increase **in the number** and duration of karst flash floods in the area of Mokošica (Fig. 3) can be expected. It should be stressed that Mokošica represents **a** densely populated suburb of Dubrovnik. High water, due to **emptying** of **the** underground reservoir will cause higher flood levels, a likely cause of destruction. At the same time it is realistic to expect the occurrence of landslides along the Mokošica flysch slopes. **The calculation of the Mokošica area slope stability had been performed with GWL at an altitude of 100 m a.s.l. The expectation of landslide occurrence is based on comparison with the Vajont landslide (Paronuzzi and Bolla, 2012). Their geological settings are similar. Eocene flysch layers build the Mokošica low permeable slope, which spread over the limestone and dolomite. The flysch layers can be influenced by high uplift caused by fast GWL rising. The siltstone layers in the flysch are very soft rocks, and sensitive to water content. In combination with low effective stresses and changes of its water content they can lose its shear resistance.**

It is very difficult to work out a reliable hydrological-hydrogeological-hydraulic model of the functioning of the underground karst reservoir. In many cases, such as it the operation of the HEPP Ombla, this task is not possible because the exact boundaries of the catchment are not known. It is obvious that they change over time, being dependent on the fast and unknown changes of the GWL in this large, dynamic and inadequately investigated complex karst aquifer. The problem is that only a few active caves and conduits in the vicinity of the spring outflow are partly known. Another large underground karst space has not been investigated well enough.

One good example of the fast and unexpected changes of the GWL in natural conditions in the Ombla Spring karst aquifer can be seen in the graph provided in Fig. 6, where two time data series of hourly GWL, measured by piezometers P8 and P14 (Fig. 3) during high water, are represented. At the same time, this representation can be used to explain the influences of the GWL changes on catchment boundary movement and the overflowing of groundwater from the Ombla Spring to other neighbouring karst springs shown in Fig. 3. Two piezometers which are not very far from each other react very differently to the same precipitation. The GWL in P14 is generally (more than 97 % of the time during one year) higher than the GWL in P8. This means that during this period groundwater from P14 flows to the Ombla Spring aquifer. In the case when the GWL in P8 is higher than the GWL in P14, the overflow of groundwater from the Ombla Spring to the Zaton Spring (Figs. 1 and 3) appears. This overflow started when the GWL in both piezometers reaches an altitude of 74 m a.s.l. and finished when both were at an altitude of 71 m a.s.l.

Figure 7 shows the relationship of the simultaneous hourly discharge of the Ombla and Zaton Springs. It can be seen that the discharge of the Zaton Spring suddenly increased when that of the Ombla Spring exceeded values from 60 m^3 s^{-1} to 70 m^3 s^{-1}. The Zaton Spring has a maximum capacity between 5 m^3 s^{-1} and 6 m^3 s^{-1} of the water discharging from its own catchment. Discharges above these values result from the overflow of water from the Ombla Spring catchment. It is necessary to notice the different behaviour in the relationship analysed in Fig 7 during the raising and descending section of the GWL hydrograph. Bonacci (2004) showed that the overflow from the Ombla Spring catchment to the Zaton Spring catchment started when the GWL-s at P9, P6 and P18 reach altitudes of 75 m a.s.l., 135 m a.s.l. and 165 m a.s.l., respectively. Piezometer P9 is only 1.4 km away from the projected grout curtain. This means that when the GWL in the underground reservoir will be higher of about 70 m a.s.l., overflow from the Ombla Spring catchment to the Zaton Spring catchment (and maybe in some other neighbouring karst springs) will occur.

4.2 Influence of the grout curtain

In this subsection, only the possible negative technical aspects of the grout curtain will be discussed. Grouting in karst terrains represents the injection of appropriate materials under pressure into rock through drilled holes to change the physical characteristics of the karst formation. Its consequences should be the sealing of all kinds of karst voids in order to make the injected part of the karst massif less permeable and stronger. From the engineering point of view**,** grouting essentially consists of the waterproofing of a rock mass where there is a network of karst conduits, cracks, joints, fissures and excessive fragmentation (Nonveiller, 1989).

Injection pressure should not exceed the overburden stress because lifting on the horizontal planes could occur. In practice, the injection pressures used often exceed the maximum recommended values.

Figure 8 shows a cross-section through the system of explored karst caves and large conduits in the vicinity of the Ombla Spring, indicating the location of some key parts of the projected HEPP Ombla, the grout curtains and the concrete blocks (modified after Ravnik and Rajver, 1998; Sever, 2003). Attention should be drawn to the fact that three known large active karst conduits will be clogged by concrete packers. The designer **aware** that it is not possible to plug such large karst cavities **by injection**. The main problem is that there may be **additional** active or large fossil cavities in this space. Milanović (2002) pointed to the problem that high non-homogeneity in the permeability of karst makes it a most difficult target for grouting. Particular problems which can arise during grouting are zones of concentrated underground flow.

In the case of the grout curtain constructed at the Đale Reservoir (Cetina River in Dinaric karst of Croatia) Bonacci and Roje-Bonacci (2012) showed how quick and serious its impact was on the groundwater regime in karst.

It is not possible to prevent water leakage from grout curtains, especially over long periods. This is especially important in the case of the HEPP Ombla grout curtain with its maximum height of 410 m. When the grout curtain is finished the upgradient of the curtain is increased to levels which have never been previously realized. This increased pressure eventually results in "clay plugs" being **expelled** from some of the cavities adjacent to where the grout penetrates, opening up new cavities which gradually enlarge themselves as effective underflow conduits. The general conclusion is that the large hydraulic gradient imposed by the reservoir accelerates leakage. These high hydraulic gradients accelerate the dissolutional widening of fractures and bedding planes by orders of magnitudes (Dreybrodt et al., 2002; Romanov et al. 2003; Turkmen, 2003; Karimi et al., 2007; Rogers, 2007; Unal et al., 2007; Kaufmann and Romanov, 2008; Bonacci and Rubinić, 2009; Hiller et al., 2011; Bonacci and Roje-Bonacci, 2012; Zubac and Bošković, 2012).

Under the pressure of the underground reservoir head, internal erosion of the cavity infilling material creates a piping phenomenon. Water rinses filling **under** the karst features and **widens** openings, which results in an increasing volume of lost water, an increase in its velocity and higher erosive potential. Ultimately, this can result in the formation of collapse sinkholes. In Fig. 4**,** two large karst conduits are shown. Ravnik and Rajver (1998) discovered them by measuring groundwater temperatures in 30 deep piezometers drilled from an investigation gallery (gallery 1 in Fig. 4). These two karst conduits are active. Nobody knows how many fossil and inactive karst conduits there are in this space. Some of these could be reactivated due to the influence of high hydrostatic pressure which will be formed by the grout curtain. Regarding the functioning of the HEPP grout curtain Ravnik and Rajver (1998) have stressed that: "The positions and dimensions of all the basic structural elements of this power plant have now, after 20 years of interrupted investigations, been outlined. However, one very important problem remained unsolved, concerning the degree of impenetrability of the planned underground dam and especially of its lower part, which is located inside the rock massif below sea level."

As the Ombla Spring is a coastal karst spring there is a further likely problem. About 25 000 yr ago the Adriatic Sea level was 96.4 m lower than at present (Šegota, 1968), thus representing the karst base level. Due to this reason, there are many submarine springs along the Croatian Adriatic Sea coast. In the case of the currently active Ombla Spring, the possibility of inactive and blocked fossil conduits which are expected to open under the influence of the new and much higher (than in its natural state) hydrostatic pressure caused by the grout curtain (underground dam) construction cannot be excluded.

Regarding the operation of the HEPP Ombla grout curtain, it is of special importance to point to the case of the grout curtain of the Gorica Reservoir on the Trebišnjica River (see Fig. 1), which is constructed in the same catchment and geological setting as the HEPP Ombla, at a distance of about 20 km. The loss of water from the Gorica Reservoir has a tendency toward constant growth which creates a huge problem for water management in Trebišnjica HEPP's system. Zubac and Bošković (2012) propose to build a new grout curtain, which should restore the existing degraded one which was built in 1981, only 33 years ago. This case indicates a **probable fate** of the HEPP Ombla grout curtain, which is at least five times higher.

The construction of the HEPP Ombla underground dam will definitely destroy the natural equilibrium between salt sea water and fresh water. The grout curtain will prevent fresh groundwater flow from the Ombla Spring aquifer to the downstream coastal area. Because of this sea water will penetrate all of the local area downstream of the grout curtain. The consequences of this process should be investigated.

4.3 Some other possible negative consequences and problems

The questions are: (1) what will be the spread of the underground reservoir under different GWL conditions?; (2) what will be the maximum GWL altitudes in new conditions? Problems can be expected **when** intensive and abundant precipitation **falls** on the catchment, when the underground reservoir will be full. In this case the GWL can quickly rise more than 100 m. It will cause not only the overflow of groundwater into neighbouring permanent and temporary karst spring catchments but the overflow of groundwater downstream and upstream of the underground dam, where all the installation of the HEPP Ombla are planned. The rising of the

GWL is a very rapid process which will not be possible to control efficiently by the HEPP Ombla operation (controlled releasing of water from the reservoir) as is possible in the case of a classic HEPP with surface reservoirs.

The photograph in Fig. 9 shows three torrential streams which occurred on 22 November 2010 as a consequence of heavy intense rainfall. They outflowed from three fossil caves, **where** temporary karst springs were produced by a rapid rise in the GWL. These torrential streams, as well as many other smaller GWL break-throughs **from the karst massif** in the broader area around the Ombla Spring, flooded the suburb of Dubrovnik Mokošica, causing serious damages.

At the same time it is realistic to expect the occurrence of landslides along the Mokošica steep and unstable flysch slopes, part of which are urbanized.

A higher than the natural state GWL caused by the grout curtain, will diminish the vadose zone and increase the phreatic zone. The regime of suspended sediment will be definitely altered, but it is hard to assess **to** what extent. Most of the sediment will be separated through sedimentation in the karst matrix upstream of the grout curtain. The suspended sediment (mostly clay - terra rossa), will close the karst **fractures, fissures and joints** of the limestone and dolomite in the former vadose zone. Hydraulic conductivity in most of the karst matrix will decrease, and the capacity of the underground reservoir diminishes and the groundwater circulation change.

It is still a challenge to develop underground constructions in limestone areas, where the possibility of sinkholes and subsidence events always exists. Identifying and predicting karst cavity networks which could cause sinkholes and subsidence on the ground surface would help engineers overcome this challenge (Waltham et al. 2005).

Dynamic interplay between sea water and flow discharging from the Ombla Spring in the Rijeka Dubrovačka has not been investigated sufficiently so far. It is known that during low discharges (until about 10 $m^3 s^{-1}$) fresh water flows over sea water without mixing. For higher discharges fresh spring water displace sea water along different long sections of the Rijeka Dubrovačka (see Fig. 3). For greater discharges these sections are longer, but for what extent has not been yet investigated. It should be stressed that in the natural state, during high water severe floods appear regularly once to twice yearly. The operation of the HEPP Ombla may aggravate this dangerous situation.

One of the greatest problems for conducting reliable analyses or modelling hydrological-hydrogeological processes in the analyzed catchment is that the exact catchment boundary and area are not defined. The heterogeneity and anisotropy of the study area **are** extreme and not well understood. **For** this reason modelling the groundwater behaviour represents a great challenge. Modelling water circulation in the Ombla Spring catchment requires a **mixture** of surface water concepts and groundwater concepts. Karst hydrology and hydrogeology need all kinds of models and modelling, as well as the new scientific approaches, methods and technologies. At the same time one should be profoundly aware that they are only a useful tool but not a panacea. For complex karst systems, no single model can be all-embracing, so different models may be needed for different purposes, including explanation, prediction and control (Bonacci and Roje-Bonacci, 2012). This is especially true when prediction of the behaviour of a karst system due to HEPP development is attempted.

Jović (2003) made a numerical model of flows in the underground storage reservoir of the HEPP Ombla. The greatest and until now unsolved obstacles for flow modelling the vadose and phreatic zones of the large Ombla Spring underground karst massif are the geological setting and hydrogeological characteristics as well as the dimensions and positions of the main karst conduits. The local area around the Ombla Spring has until now been only partly investigated.

Bonacci (1995, 2000b) has shown how fast, unpredictable and over what a large range the values of hydraulic conductivity, K, change in time and space upstream **of** the Ombla Spring underground aquifer. This means that conditions for the reliable modelling of the functioning of this system are not fulfilled, and the real question is: **is it** possible at all to fulfil such conditions in this large, deep and complex karst area? This is especially true in the case where modelling should include the anthropogenic influence of HEPP development on the regime of groundwater circulation. The previously explained phenomenon of the limited maximum discharge capacity of the Ombla Spring should be included in a rainfall-runoff model. Probably one of the reasons for the present poor quality of hydrological modelling in karst is that this phenomenon has not been taken into consideration.

It is becoming increasingly critical for scientists and decision makers to become aware of the ways in which their work is influenced by legal and policy aspects. This is especially true for the case of the HEPP Ombla, which uses water from a transboundary karst aquifer divided by Croatia and Bosnia and Herzegovina. The large majority of this aquifer, as well as the Ombla Spring catchment, is in Bosnia and Herzegovina. The operation of the HEPP Ombla can cause trouble within the territory of Bosnia and Herzegovina, which could provoke international disputes. It can be expected that any problem in the part of the Ombla Spring catchment which belongs to Bosnia and Herzegovina will be explained as a consequence of the HEPP Ombla operation.

4.4 Induced seismicity

Large-scale fluid injections induce both seismic and aseismic motion (Cornet, 2012). The injection of fluid into a rock mass results in the variation of effective stresses that sometimes generate induced seismicity. An increase in pore pressure may induce some microseismic activity. Roje-Bonacci (1995) analysed the interdependence between the change in rock mass stress conditions caused by changes in piezometric pressures due to the impoundment of large reservoirs and induced seismicity observed in such structures. There are many studies of earthquakes triggered by artificial water reservoirs (e. g. Talwani and Acree, 1984; Stojić and Lalić, 1994; Gupta, 2002; Fan Xiao, 2012).

The oscillations of the GWL in the Ombla Spring aquifer are sudden and on a large scale. The changes they cause within the rock mass are so strong that they can lead to a redistribution of stress states and as such can cause sinkhole collapses (Roje-Bonacci, 1997).

Occurrences of a series of minor earthquakes and roars in the coastal karst Adriatic Sea area are quite frequent; those which occurred in the area of Dubrovnik were particularly intense (Cvijanović, 1971; Garašić and Cvijanović, 1991; Stojić and Lalić, 1994). The seasonal character leads to the assessment that they are caused by abundant, intensive precipitation and the large karst caves and conduits in the area. Garašić and Cvijanović (1986) hold that earthquakes and speleological phenomena are connected with fault zones and with the tectonic processes, which have taken place.

Milanović (2002) believes that the abrupt rise of the GWL in the analysed Dinaric karst area compresses air trapped in karst conduits, caves and siphons. A trapped “air pillow” may thus escape, creating strong explosions felt by the inhabitants and recorded by the nearby seismological stations.

In regard to the HEPP Ombla, it is of crucial importance to take into consideration that induced seismicity has been triggered during the operation of large dams in the neighbouring Dinaric karst area of Grančarevo and Piva/Mratinje (Milanović, 2002).

Undoubtedly, the massive injections which should be done for the HEPP Ombla grout curtain construction will induce many small seismic motions followed by unpleasant acoustic effects.

5 Influence on the ecosystem

The local area of the Ombla Spring is a nature park with protected flora and fauna, since this particular locality was recognized as an especially valuable and vulnerable coastal karst environment.

In regard to the ecological issues in karst terrains, Bonacci et al. (2009) stated: “The karst environment has very different characteristics than all other environments. The biological importance and particularities of karst are enormous. The evolution of entire karst landscapes is thought to be biologically controlled through the interrelationships of vegetative cover, erosion, and dissolution rates. Subterranean karst ecosystems are sensitive to environmental changes that occur on the surface. The importance of maintaining biological diversity goes far beyond mere protection of endangered species and beautiful landscape.”

Injection will definitely lead to many negative consequences **for** the underground ecosystem. The construction of the grout curtains will rashly, strongly and dangerously disrupt the **existing** vulnerable ecological equilibrium of the karst underground system. The natural food chain and the contact between species and their habitats will be lost in this very large but unknown underground space.

The main ingredients of a grout curtain (Portland cement, clay, bentonite, sand, asphalt and some chemicals) may be toxic, neurotoxic or **carcirogenic**, irritant to the skin or corrosive. Their use is dangerous for human beings and the environment. Such toxic components can pollute the karst aquifer and cause long-lasting hazardous consequences on karst underground species (Bonacci et al., 2009).

The penetration of salt sea water into the local area between the sea coast and the grout curtain will destroy the vulnerable ecological equilibrium of this narrow but important ecotone.

In the valuable and vulnerable environment of the Ombla Spring, the hot spot is represented by Vilina Cave (see its position in Fig. 8). In this cave**,** seven sorts of bat have their habitats. The guano which they produce plays a crucial role for sustaining the life of all the other terrestrial as well as aquatic species in the Vilina Cave-Ombla Spring ecosystem. The construction of this extremely high grout curtain can have a strong and negative influence on the natural food chain in the Vilina Cave-Ombla Spring ecosystem, where eight cave species, five terrestrial and three aquatic (endemic and endangered) are found (Sket, 1997; Schütt, 2000; Bedek et al., 2006). The vadose zone will be decreased, and all terrestrial species which have habitats in this zone will be destroyed.

Despite the fact that the grout curtain will be constructed below the bottom of the Vilina Cave, the cave will be temporarily flooded. After heavy rainfall, a rapid and uncontrolled rise in GWL will occur. It is realistic to expect that the Vilina Cave will function as temporary spring for the fast water evacuation from the karst aquifer to the surface. In this case all habitats and species from the Vilina Cave will be washed away and destroyed.

5 Concluding remarks

Problems discussed in **this** paper are extremely complex. In accordance **with** existing literature and authors' experience all **(or at least most) of the** risks previously discussed **belong** to the so called "shallow uncertainties hazards", which arise when the probabilities of outcomes are reasonably well known. Deep uncertainties arises when the probabilities of outcomes are poorly known, unknown, or unknowable (Stein and Geller, 2012; Stein, 2013; Stein and Stein, 2013).

This is the first underground dam and reservoir of such size and height to be constructed in this deep, weakly investigated and extremely heterogeneous coastal area of Dinaric karst. The available data and information are not ample enough to make definite and reliable conclusions and offer technical solutions. On the basis of the analyses developed in this paper, it is very probable that the negative consequences of the construction and development of the HEPP Ombla will be very serious.

Generally speaking, each grout curtain acts individually. To understand its role and its influence on the environment, it is absolutely necessary to have long-lasting, continuous monitoring (before and after construction), at least for GWL, groundwater temperature, and the chemical composition of the water itself (Bonacci and Roje-Bonacci, 2012).

The present-day ecological and environmental aspects of grouting, i.e. its influence on this wonderful, valuable and vulnerable karst underground environment has not drown much attention, if any. This problem could be very serious, and due to this reason grouting in karst should be treated with much great caution (Bonacci et al., 2009).

To obtain a harmonious, reliable and sustainable development in this very complex, valuable and vulnerable eco- and social-system, it is necessary to take the complex, interactive, technical, social, economic, environmental and cultural aspects of water resources management into account in decision-making.

In the analysed case, issues of the transboundary karst water resources management represent an especially difficult and dubious task. Water policy is becoming progressively more relevant across different sectors (including energy, land use, natural resource management, health and the environment) and effective implementation is crucial for the sustainable development of all of these aspects.

The possibilities for overcoming karst system complexity can be found in close co-operation between hydrology and hydrogeology, as well as between different branches of the geosciences, and in implementation of detailed monitoring. The need for a better understanding of the deep and long-lasting mutual relationship between human activities and natural processes in karst terrains is of crucial importance. In order to achieve their real sustainable development, it is necessary to fill in the gaps which remain in the understanding of hydrological and ecological behaviour.

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Figure captions

Figure 1 Location map indicating the study area, the site of the Ombla Spring with its supposed catchment area, the Zaton Spring, the Trebišnjica River, the boundary limit between Croatia and Bosnia and Herzegovina, as well as the position of **existing** dams, reservoirs and HEPP-s

Figure 2 Areal photograph of the Ombla Spring **and surrounding area** (taken by Antun Maškarić)

Figure 3 Location map indicating the position of the projected grout curtain, **five** piezometers (P6, P8, P9, P14 and P18), the data of which **are** used in this article, and the adjacent karst springs (Zaton, Ombla, Slavljan and Zavrelje)

Figure 4 Cross-section through the projected grout curtain (underground dam) (modified after Ravnik and Rajver, 1998; Sever, 2003)

Figure 5 Relationship between hourly Ombla Spring discharges and the GWL measured in piezometer P8 (modified according Bonacci, 1995)

Figure 6 Time data series of hourly GWL measured by piezometers P8 and P14 during high water caused by intensive precipitation

Figure 7 Relationship between hourly discharges of the Ombla and Zaton Springs (modified according Bonacci, 1995)

Figure 8 Cross-section through the system of explored karst caves and large conduits in the vicinity of the Ombla Spring indicating the location of some key parts of the projected HEPP Ombla, grout curtains and concrete blocks (modified after Ravnik and Rajver, 1998; Sever, 2003)

Fig**ure 9** Photograph of GWL overflow through three fossil karst conduits on 22 Oct. 2010


0
5
10km
N
Supposed Ombla
Spring basin limit
Bileća
Reservoir
Trebišnjica River
Bosnia & Herzegovina
Grančarevo
Dam
Gorica
Dam
Zaton Spring
Ombla Spring
HEPP
Trebinje
tunnel
Croatia
Adriatic Sea
State bounday
HEPP
Dubrovnik

Figure 1

Figure 2

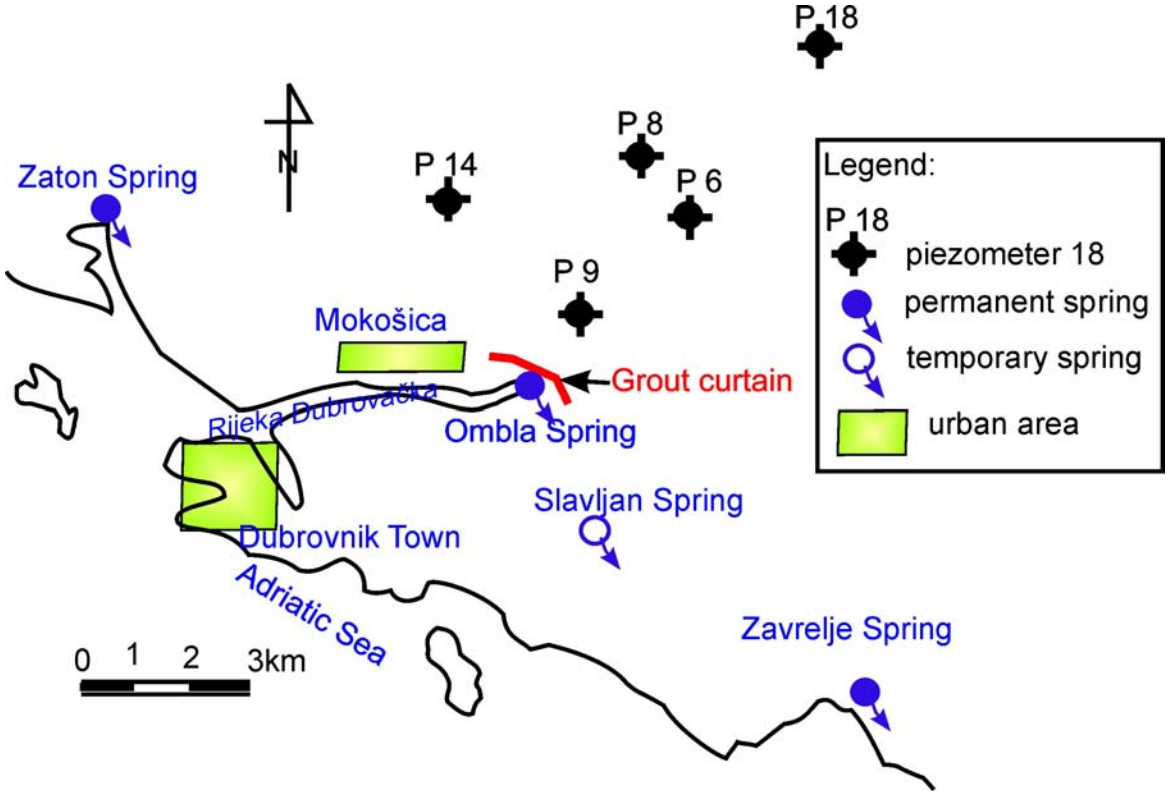

P 18
P 8
P 14
P 6
N
Zaton Spring
Legend:
P 18
piezometer 18
permanent spring
temporary spring
urban area
P 9
Mokošica
Grout curtain
Rijeka Dubrovačka
Ombla Spring
Slavljan Spring
Dubrovnik Town
Adriatic Sea
Zavrelje Spring
0 1 2 3km

Figure 3

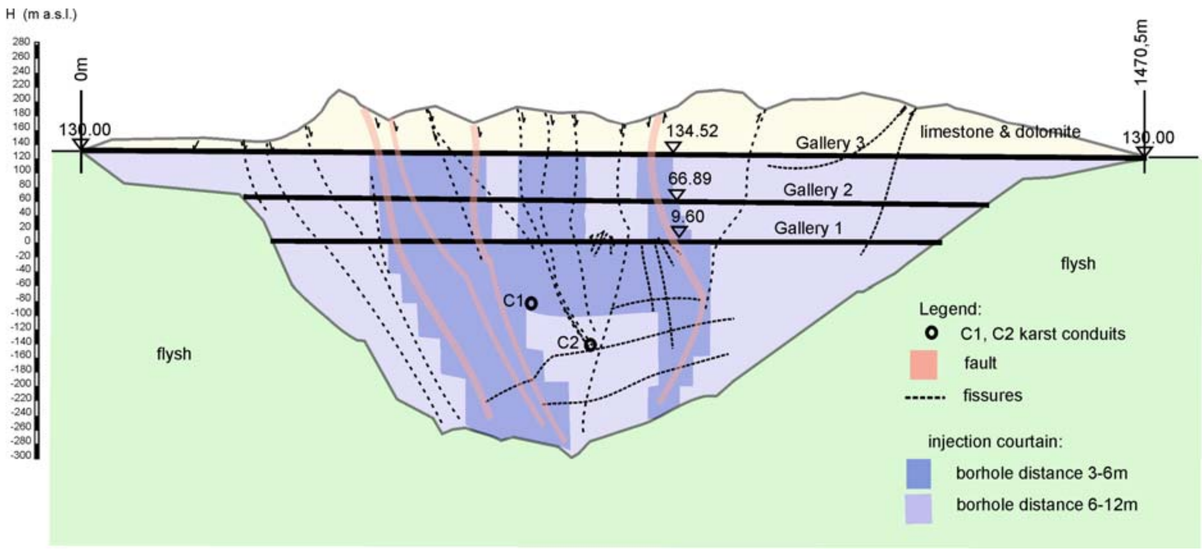
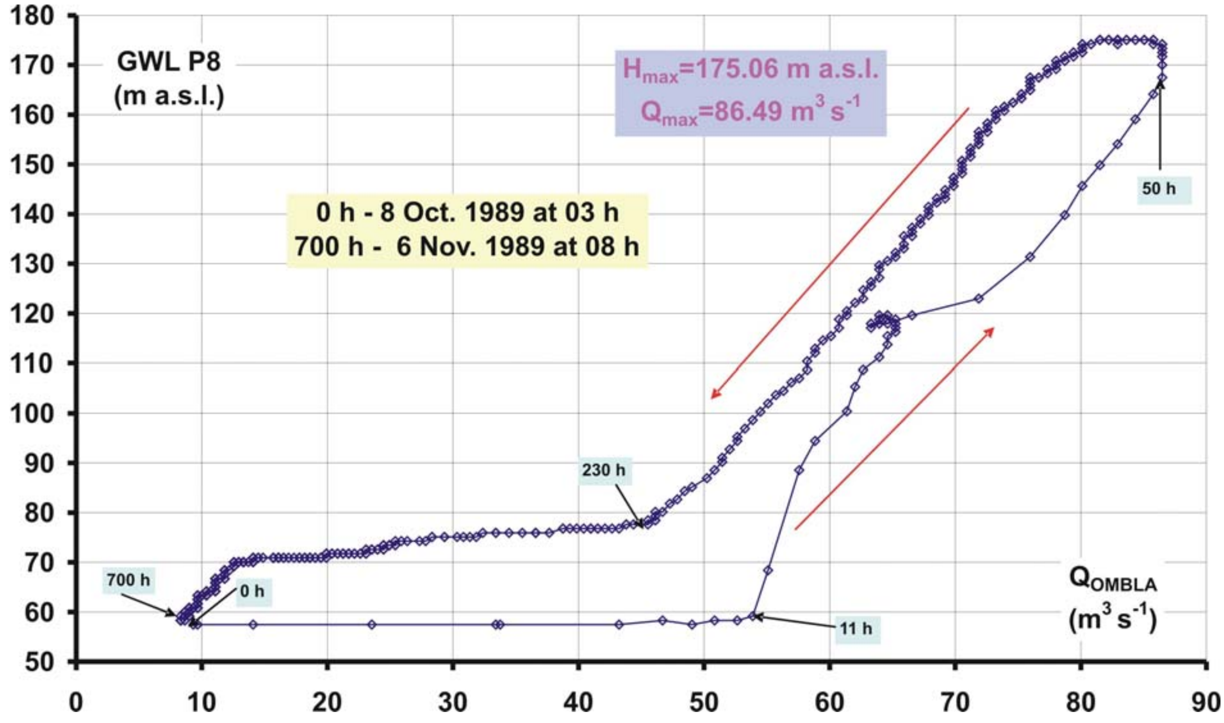
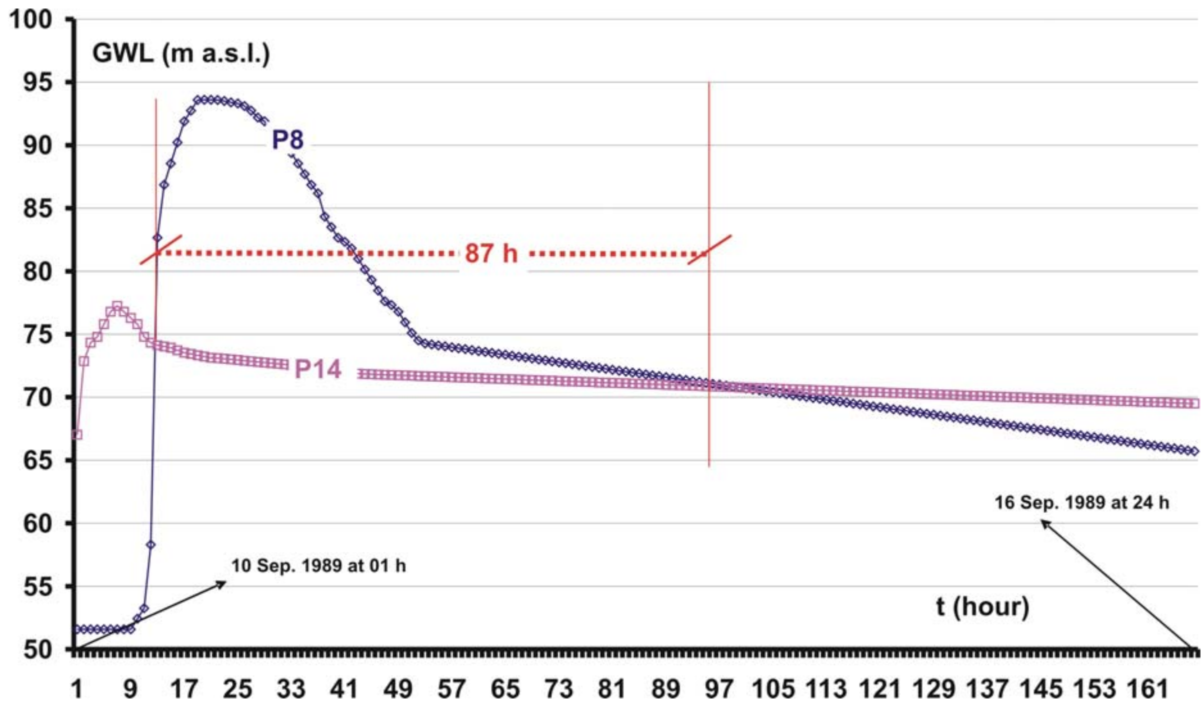

H (m a.s.l.)
0m
1470,5m
130.00
134.52
66.89
9.60
Gallery 3
Gallery 2
Gallery 1
limestone & dolomite
130.00
flysh
flysh
C1
C2
Legend:
C1, C2 karst conduits
fault
fissures
injection courtain:
borhole distance 3-6m
borhole distance 6-12m

Figure 4



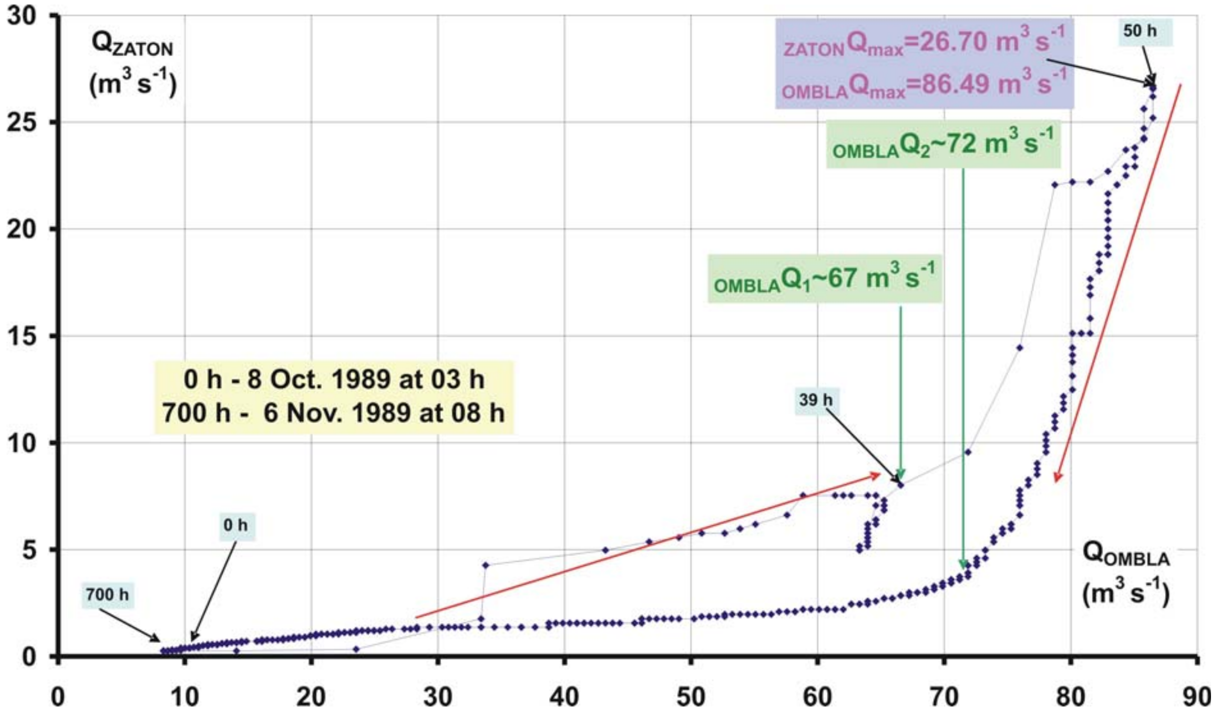
GWL P8
(m a.s.l.)
Hmax=175.06 m a.s.l.
Qmax=86.49 m3 s-1
0 h - 8 Oct. 1989 at 03 h
700 h - 6 Nov. 1989 at 08 h
50 h
230 h
700 h
0 h
11 h
QOMBLA
(m3 s-1)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
0
10
20
30
40
50
60
70
80
90

Figure 5



GWL (m a.s.l.)
100
95
90
85
80
75
70
65
60
55
50
P8
87 h
P14
16 Sep. 1989 at 24 h
10 Sep. 1989 at 01 h
t (hour)
1
9
17
25
33
41
49
57
65
73
81
89
97
105
113
121
129
137
145
153
161

Figure 6



Q_ZATON (m^3 s^-1)
ZATON Qmax=26.70 m^3 s^-1
OMBLA Qmax=86.49 m^3 s^-1
50 h
OMBLA Q2~72 m^3 s^-1
OMBLA Q1~67 m^3 s^-1
0 h - 8 Oct. 1989 at 03 h
700 h - 6 Nov. 1989 at 08 h
39 h
0 h
700 h
Q_OMBLA (m^3 s^-1)
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
90

Figure 7

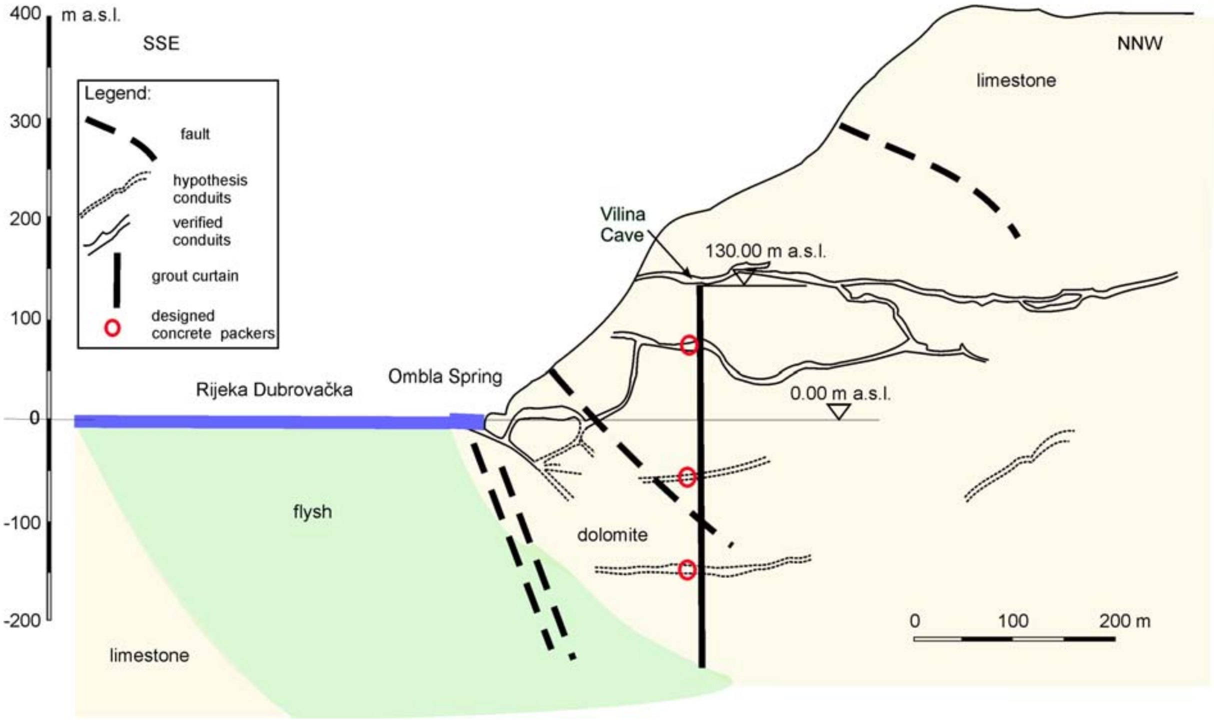

400
m a.s.l.
SSE
NNW
Legend:
fault
hypothesis conduits
verified conduits
grout curtain
designed concrete packers
300
200
100
0
-100
-200
limestone
Vilina Cave
130.00 m a.s.l.
0.00 m a.s.l.
Rijeka Dubrovačka
Ombla Spring
flysh
dolomite
limestone
0
100
200 m

Figure 8

Figure 9