

## THE IMPACT OF CLIMATE CHANGES ON GROUNDWATER UTICAJ KLIMATSKIH PROMENA NA PODZEMNE VODE

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**Abstract.** Groundwater is the source of drinking water for about half of the world's population. Although climate change is an inevitable natural process within the geological timeframe, its intensification caused by the anthropogenic impact raises pressure on many aquifer systems globally. The paper discusses the status of groundwater resources in the past - during the Quaternary period, the current situation, and the prospects for their future sustainable use and protection from pollution. The main emphasis is on the Mediterranean basin, where large differences of the sea level during the Messinian crisis, followed by glaciations, had caused surface and groundwater network redistribution. The forecasted global rise of the sea level could have a negative impact also on many coastal aquifers and could result in salt intrusion and salinisation of the currently tapped fresh water sources. Although Milutin Milanković's theory of climate cyclicity is beyond the scope of this kind of analyses due to time scale, his work has greatly contributed to raising the awareness of the importance of systemic observation of climate elements and forecasting their impact on human population and ecosystems.

**Apstrakt.** Podzemne vode su osnovni resurs vode za piće za polovinu svetske populacije. Iako su klimatske promene neizbežni prirodni proces u geološkim vremenskim okvirima, njihovo intenziviranje pod uticajem čovekovih aktivnosti, uslovalo je rast pritiska na mnoge sisteme izdani širom sveta. Rad razmatra stanje resursa podzemnih voda u prošlosti tokom kvartarne periode, aktuelno stanje i perspektive njihovog daljeg održivog korišćenja i zaštite od zagađivanja. Fokus rada je vezan za prostor Mediterana gde su velike promene nivoa mora tokom Mesinske krize a zatim periodi glacijacija uslovljavali i redistribuciju mreže površinskih i podzemnih voda. Prognozirano povišenje nivoa svetskog mora imaće negativni uticaj na mnoge priobalne izdani i usloviće intruziju morske vode i salinizaciju izvorišta malomineralizovanih voda. Iako je Milankovićeva teorija cikličnosti klimatskih promena izvan okvira ovih analiza s obzirom na vremensku razmeru, ona je veoma doprinela da se poveća svest o značaju sistematskog praćenja klimatskih elemenata i predviđanja njihovog uticaja na stanovništvo i eko sisteme.

**Key words:** groundwater, aquifer systems, climate change, Milutin Milanković, Mediterranean basin

**Ključne reči:** podzemne vode, izdanski sistemi, klimatske promene, Milutin Milanković, Mediteranski basen

### 1. INTRODUCTION

Climate changes (CC) have never been questioned by geologists, and discussions typically revolve around their magnitude and intensity. In more than four and a half billion years since the Earth was born and more than four billion years since first rocks were created on the lithosphere surface, the climate has been changing constantly as a result of numerous factors of cosmic or local Earth's nature. For instance, during the Cretaceous period the sea level was more than 200m higher than it is now, and the climate on most of our planet was tropical [1]. In the long history of Earth there were many exchanges of cold and warm climate, but it is curious that no glaciation took place between late Carboniferous-Permian and Oligocene - a period that lasted more than 200 million years. On the other hand, there were several glaciations during the Quaternary and Anthropogenic period phases.

Pantić and Stefanović [2] have created a list of plausible causes essential to the Earth's climate changes. They are:

1. External causes including orbital variation, insolation, etc.;
2. Internal causes including heat-flow in geological time;
3. Complex movements inside the lithosphere such as continental drifting, volcanism, ice-caps, total water volume, shrinking of the climatic zones;
4. Complex movements inside the hydrosphere and atmosphere: air and water currents,

resulted from interaction of the basic causes included in the first three groups.

The climate of any given interval of a past geological time is determined as a complex interaction of the above causes [2]. Adhémar [3] was the first to indicate that climate variations could be the result of the change of shapes of the Earth's orbit. Agasiz [4] was the first to formulate a hypothesis on Anthropogene glaciations, when most of the Northern hemisphere was under a thick cover of ice. These two components constitute the basis on which Milanković started to build his concept and mathematical expression of a cyclical nature of climate changes some 80 years later [5]. Along with the work of Köppen and Wegener [6], his study "*Theorie mathématique des phénomènes thermiques produits par la radiation solaire*" became one of paleoclimatology's greatest achievements of that time [2], regardless of the fact that it was not accepted, or even understood, by many geographers and geologists. The final result of Milanković's calculations and the *Astronomic theory of climate cycles* based on three variables: eccentricity (the shape of the Earth's orbit), precession (the angle of the Earth's axis in relation to the Earth's orbital plane) and obliquity (the direction of the Earth's axis of rotation) and presented in his famous monograph „*Canon of insolation and the Ice Age problem*“ [7], resulted in further growth of a group of opponents, including some of well-known names in Quaternary and glacial geology (e.g. Albrecht Penck, [8]; Richard Foster Flint, [9]).

Aware of the fact that some other terrestrial factors also influence the effects and intensity of climate changes (see causes 2-4 listed above, by Pantić and Stefanović [2]), in close cooperation with geologists Milutin Milanković looked for evidence and additional facts which would confirm his theory [10]. Eventually, his findings were proven without any doubt by the results of a large international project CLIMAP undertaken in 1971-1976, when drilling of the Indian Ocean floor and sedimentary analyses of obtained cores took place along with extensive paleomagnetic, paleontological and geochemical investigations [11].

Nowadays, the topic of climate changes is actualised and commonly considers anthropogenic impacts on climate as well as, consequently, natural resources and biodiversity at the scale of hundreds or a thousand years [12]. This scale is considerably different than the one Milanković was able to use in his calculations, i.e. 10,000 or 5,000 years. Although, due to time scale, Milanković's theory of climate cyclicity is generally beyond the scope of many current analyses [13] which consider the actual anthropogenic impact (i.e. scale of centuries), his work has greatly contributed to raising the awareness of importance of climate elements' systematic observation and forecasting and their impact on human population and ecosystems.

Groundwater is one of the most important and precise natural resources. It ensures a drinking water supply for almost half the world's population. Climate changes have greatly influenced this resource, and their consequences – such as prolonged droughts with reduced aquifers' recharge, desertification and salt-water intrusion – put great pressure on groundwater and are a risk for its further sustainable use.

## **2. GROUNDWATER – THE PAST**

Our analysis of the status of groundwater does not consider far geological past, but only the last several million years (the period from Late Miocene to Anthropocene). The focus is on the entire Mediterranean basin as a region of a very dynamic geological past and present.

One of the main geologically critical periods was between 6 and 5.3 million years ago (Ma). The Messinian salinity crisis (MSC) was a period when the previously large Tethys Ocean became considerably reduced, decomposed and isolated from the other oceans that functioned as a large salty lake in the Mediterranean depression.

The MSC was an ecological crisis caused by a powerful combination of geodynamic and climatic drivers; it had a great impact on the subsequent geological history of the Mediterranean basin as well as on the salinity of global oceans [14]. This lake used to be significantly smaller, and the connection - via the Gibraltar strait - between the Mediterranean Sea and the Atlantic Ocean was

broken (Fig. 1). The sea level was lowered down by more than 1,500 m in about 100,000 years and thick evaporitic rocks and salt deposits were formed in the basin in the absence of inflow of ocean's water. Since the 1990's, the MCS has been considered by the scientific community a major period of development of a surface waters network, especially of an underground system of karst conduits at great depth and below the present sea level [15].

For instance, during MSC, most of today's islands in the Adriatic basin (Croatia) were connected to the continent, while mountains built dominantly from carbonate rocks were exposed to intensive karstification and deepening of the groundwater table. The lowering of the base level simultaneously caused the lowering of springs and conduit systems. Many deep canyons were incised, transferring river waters to a "new" and much deeper erosional base. One of such submarine canyons, more than 300m deep, can be found in Cassidaigne near Marseille [16]. This was also one of the important phases of the uplifting and creation of the Dinaric mountain range, the area which is often called "classic karst" [17,18,19]. The re-modification of relief and hydrographic/hydrogeological network also took place in other chains of the Alpine orogenic belt (Apennines, Pyrenees, Atlas, Hellenides).

At the beginning of Pliocene, around 5.33 Ma, the opening of the strait of Gibraltar by way of erosion caused a sudden inflow via gigantic waterfall. Bakalowicz [15] states that flood filled up the Mediterranean basin in a few decades, lowering the global ocean by some 15 m. The water level and poorly permeable clay deposits caused many previously open joints and cavities in karst aquifers to be filled; groundwater circulation was disrupted and often redirected to other sub-basins. The rising of the base level resulted in the flooding of at least the lower part of the karst conduit system and the overflow of the aquifer at higher elevation, potentially rejuvenating abandoned karst structures [15]. Deep karstification resulted in the fact that today more than 90% of all the known submarine springs in the world are located in the Mediterranean basin [20].

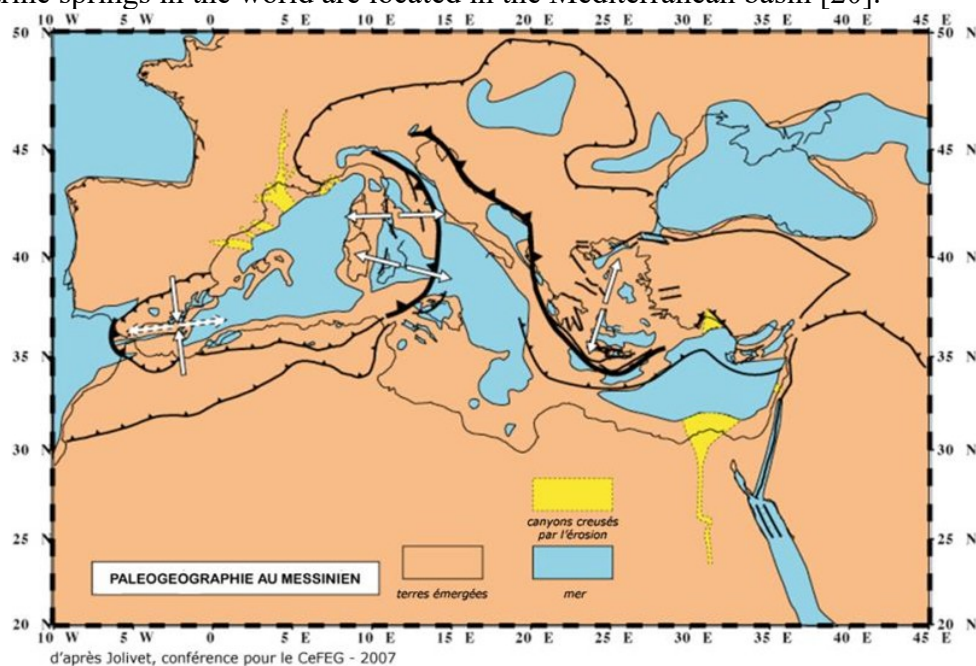


Fig. 1. Sketch map of the Mediterranean basin at the time of the Messinian crisis. The Gibraltar strait between the Mediterranean Sea and the Atlantic Ocean was closed and the sea level was some 1,500m lower, according to Jolivet et al. [21].

Another critical phase for groundwater distribution and circulation took place during the Pleistocene and glacial phases. A very thick ice cover along the entire Europe caused water balance to be completely modified. Reduced inflow of fresh waters into the Mediterranean basin caused another deepening of the sea level and reduction of the volume of the sea water pool. In the last two million years, the mean sea level reached positions as low as 130m below the level which was present during glacial periods, and as high as ~ +6m and possibly +13-15m during interglacial

periods (Fig. 2; Benjamin et al. [22]).

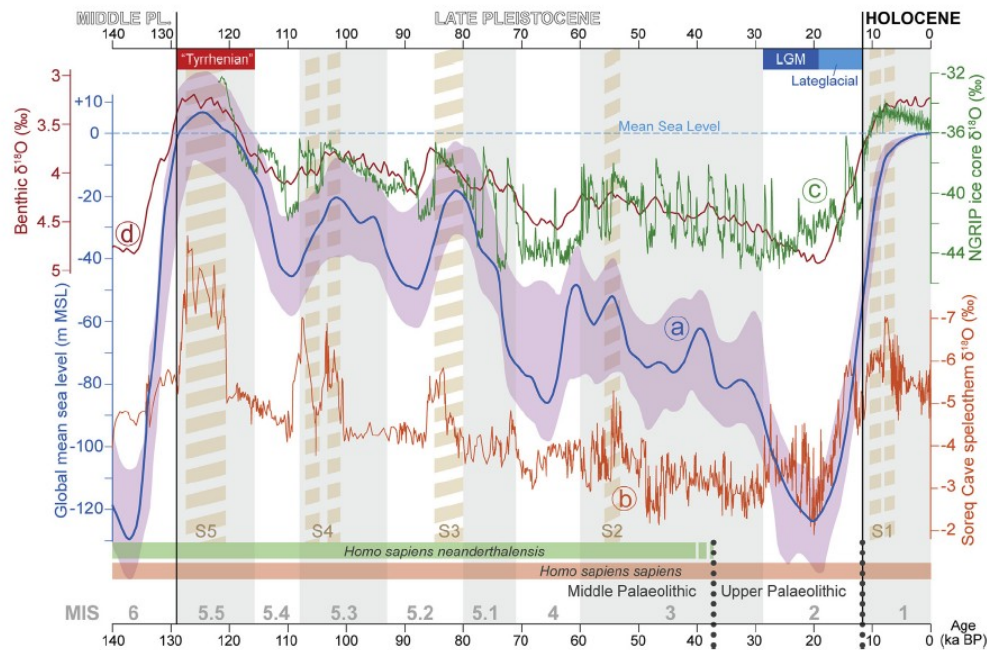
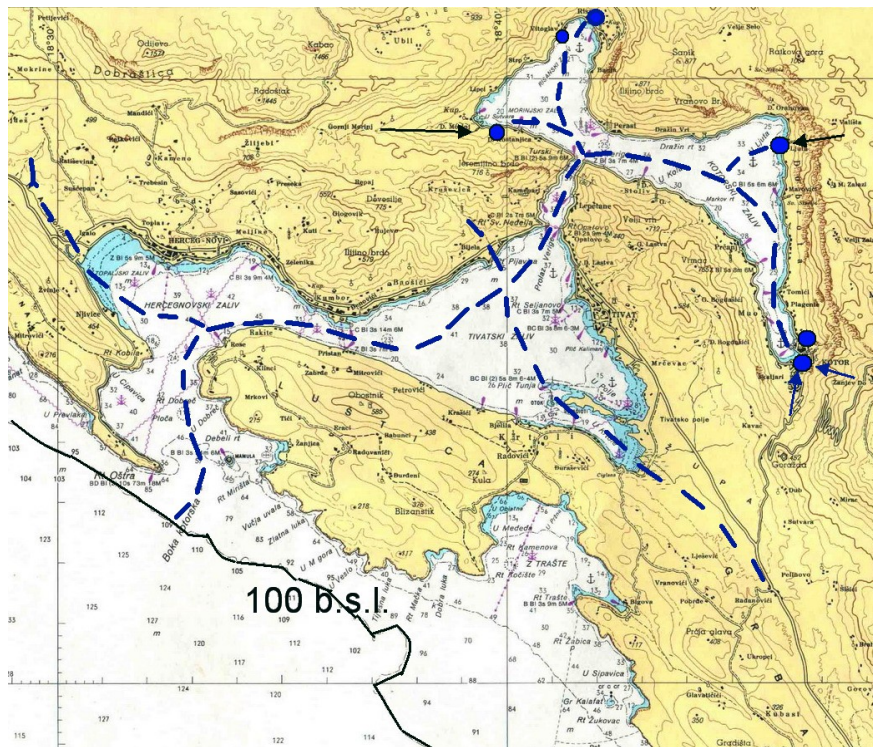


Fig. 2. Comparison between the past global mean sea level and paleoclimatic, paleoenvironmental and archaeological data for the Mediterranean basin based on multidisciplinary research. Period from the Middle Pleistocene to present (source: Benjamin et al. [22])

In the Adriatic basin, during the period of maximal glaciations the seashore line was moved by one to tens of kilometres to the west. Figure 3 shows a topographic-nautical map of the exemplary area of the Bay of Boka Kotorska. The isobath line of 100m and measured depths of the seafloor indicate that Boka Bay was in fact a dry depression without any sea water during all four main glacial periods (Günz, Mindel, Riss, Würm). The tracers of glaciers transported the material, and moraines are evidenced at Orjen Mt. high above the Bay. The direction of groundwater flow was similar or keeping the general course of these glaciers or paleo streams. The springs, where most of the karst aquifers had drained during the interglacial stadiums (Fig. 3), are now at the sea level or just a few metres above it (Gurdić, Škurda, Tabačina near Kotor, Ljuta orahovačka, Risanska spila, Morinj), or are functioning as submarine springs (Sopot).

The confirmation of such morphological and hydrological development came as a result of multibeam bathymetry combined with seismic reflection images [23]. They showed a maximum depth of 67m in the narrowest part of the Verige passage (Fig.3) while the observed morphologies showed steep upper slopes and flat sub-basin central sectors lying at depths ranging from 35 to 45m. Seafloor morphology is the result of interaction at different timescales of climate, water circulation, sea level changes, erosion, sedimentation and tectonics constrained by the geological and structural setting of the area [23]. The deeply incised valleys are related to past seafloor falls triggered by strong earthquakes, while delta fans have resulted from sedimentation of strong bottom streams. These pathways were reconstructed by the author of this paper and shown in Figure 3. Some streams just followed the path of the valleys that were incised in the pre-Quaternary period (pre-glacial), while others originated from karstic springs.

The sea level was progressively raised to the present position during the post-glacial period of the last 10,000 years, and the surface waters network and incised valleys inside the Boka depression were fully submerged. Surface water network in the surrounding hilly-mountain area (Lovćen, Orjen) was degraded, while recharge of aquifer systems from heavy rainfall intensified. The processes of weathering of epikarst, the creation of sedimentary cover, and intensive karstification with fast deepening of the water table led to the development of thick and highly karstified rocks and rich aquifer systems.



*Fig. 3. Topographic-nautical map of Boka Kotorska. Blue dots show locations of today's main active springs and vruljas (submarine springs); arrows show groundwater flow directions; black line is the isobath line of 100m below sea level (b.s.l.); dash lines show the reconstructed riverbed of paleoriver Boka and its tributaries based on actual deepest depths to the seafloor (Map source - Website: Best of Boka, modified [24])*

### 3. GROUNDWATER – THE PRESENT

Groundwater is our planet's essential resource. Currently, between 1.5 billion and 2.5 billion people depend solely on groundwater to satisfy their daily need for potable water [25,26]. Approximately 38% of the crops in the world are irrigated by use of groundwater [27]. Irrigation is the main consumer of groundwater and in many arid parts of the world no crops can be grown without pumping groundwater [28]. Therefore, 70% of the total amount of extracted groundwater is utilised for irrigation, 21% for drinking water supply, while the remaining 9% is abstracted for industrial or mining purposes [29,30].

Groundwater is used the most in Asia (70%) and North America (15%). Global population growth and climate change are the main threats to freshwater resources (Fig. 4). These two factors provide a negative synergy and many countries or regions are already facing water shortage and significant depletion of their water reserves (China, India, parts of USA, Arabian Peninsula, northern Africa). Currently, 18 countries that host half of the world's population are over-pumping their aquifers [31]. Such a situation is likely to continue and forecasts are even worse concerning the arid part of our planet [32,28].

A series of reports issued by the Intergovernmental Panel on Climate Change (IPCC) concluded that the climate of our planet is changing [13]. The most important impacts of climate change on the world's fresh water supplies will be those caused by increased temperatures, changed precipitation and shifts in the historic hydrologic cycle. Increased air temperatures changed the regime of precipitation and humidity, strongly impacting the world's fresh water supply [33]. The fourth IPCC report [13] estimated a global pattern of contrasting changes in rainfall to occur between the present and the end of the 21<sup>st</sup> century, with a decrease in rainfall, compared to the 1980-2000 averages, that could exceed 20% in arid and semi-arid zones which are already vulnerable to reduced recharge of water resources. This change will have an impact on land use

activities, which in turn will exert pressure on water resources.

CC can also alter water consumption, with demand increasing during dry, warm periods and decreasing during periods that are cool and wet [34]. Depletion of groundwater resources is likely to continue, and the impact of CC and reduced recharge during extended droughts will not affect only the quantity but also the quality of groundwater [35]. The sea level increase will further stimulate salt-water intrusion and reduce the quality of many coastal aquifers.

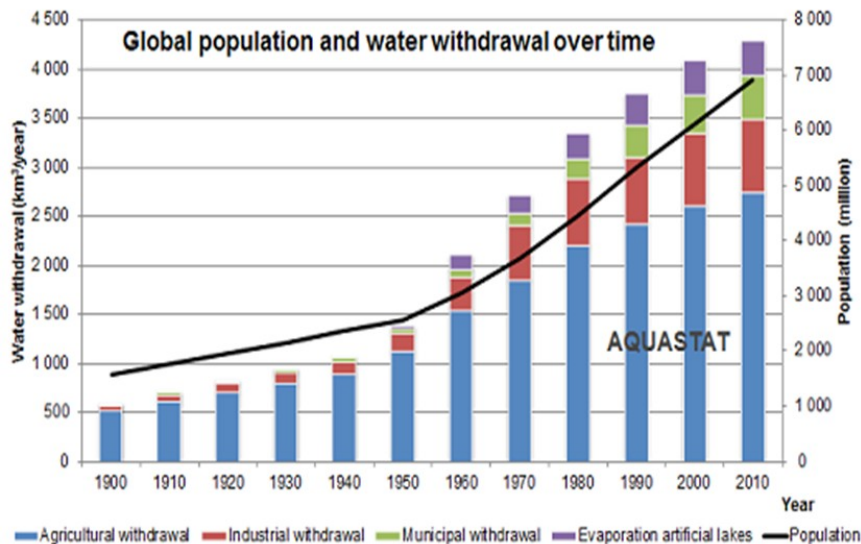


Fig. 4. Simultaneous growth of the global population and water withdrawal in the period 1900-2010 (according to FAO Aquastat [36])

Due to the presence of rich karst aquifers, moderate climate with well-balanced rainfalls, and intensive water balance, the Mediterranean basin is not that affected [37]. However, there is a big contrast in water resources availability between the northern parts of Europe and southern parts of North Africa and the Near East.

In the Mediterranean region, the main aquifer systems are located in thick alluvial fans that follow major rivers and highly karstified carbonate rocks. The percentage of participation of groundwater in the public supply varies from one country to the next but is generally over 50%. A large portion thereof represents consumption of groundwater from karst aquifers, the highest being in Montenegro, where it exceeds 80%. Many large settlements, including six European capital cities of this region (Vienna, Rome, Sarajevo, Podgorica, Tirana, Skopje) base their water supply on tapped karst springs. Most cities along the shores of the Adriatic and Ionian seas, as well as many settlements on the islands, were founded near large springs and their development is the result of the presence of these springs. For instance, cities such as Rijeka, Split, Dubrovnik and Kotor became important naval and (later) tourist centres thanks to these large water sources.

Data showing water availability per capita are more illustrative. In an average hydrological year, each inhabitant of Montenegro has 21,395 m<sup>3</sup> of water available, but utilises just 1.18 % of it. In Bosnia and Herzegovina the utilisation rate is even lower, below 1%. Citizens of Croatia and Albania use less than 5% of water that is available to them per capita [36].

However, the situation with water availability is not favourable everywhere, and over-extraction is present in Lebanon, Morocco and Syria.

Although some springs of Boka Kotorska, Montenegro belong to the group of the world's most powerful, due to their maximal discharge during the recession periods in summer and early autumn months they tend to dry out or drain small amounts of water below the sea level. As such, the Sopot spring near Risan (Fig. 5) can discharge more than 100 m<sup>3</sup>/s during maximal floods, but for most of the year it functions as a submarine spring. The highest discharge is a result of fast prolongation and short residence time for the rainfall water infiltrated at the Orjen Mountain and "Stone Sea" area, where more than 300 vertical shafts were registered within the area covering only 8 km<sup>2</sup>, with depth of 200-350 m [38].

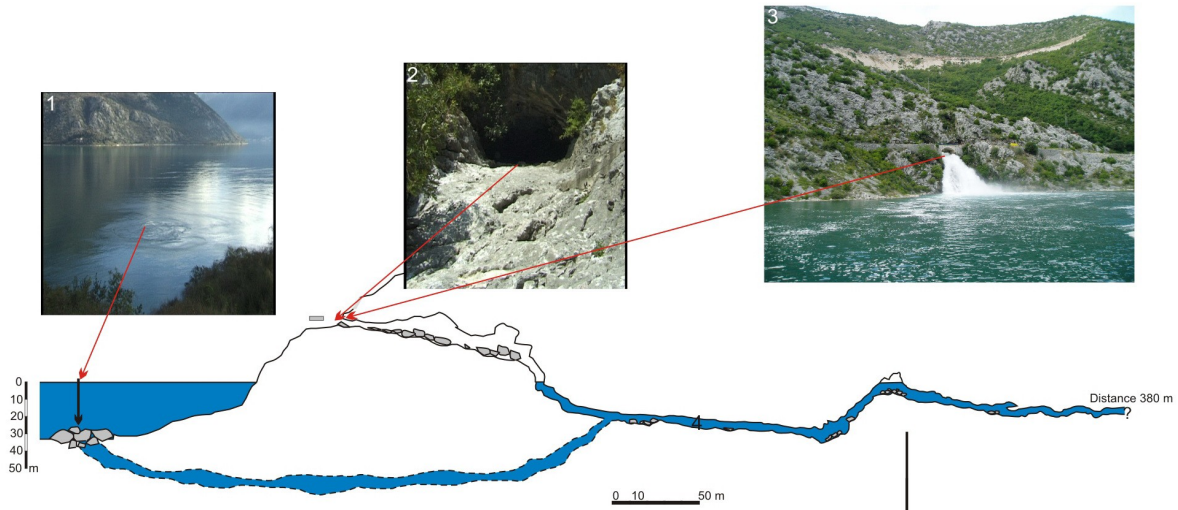


Fig. 5. Photos and section of the Sopot spring near Risan in Boka Kotorska, Montenegro. During maximal floods it is one of the world's largest (3), but with a dry orifice (2) and submarine discharge (1) during summer. (According to Milanović S., [39]; reprinted from Stevanović, 2010, Elsevier copyright [40])

Engineers and water managers are thus facing many problems in their attempts to ensure water provision: due to the unstable regime of karstic springs, the main challenge for most of the waterworks is to overcome water shortage during recession periods, which coincide with summer and early autumn months when consumption is at its highest [32]. Several successfully completed projects based on utilisation of groundwater from considerable storage in the deeper parts of aquifers provide a new prospect for the development of aquifer systems in many locations, as was done with the sources of Lez (Montpellier, France) and Bolje Sestre (the Montenegrin coast [40]).

#### 4. GROUNDWATER – THE FUTURE

“The past is the key to the future”. This well-known sentence can be accordingly applied to many current attempts of the scientists to forecast impacts of climate changes on the environment and natural resources. And this is also why many of them have Milanković's theory and its findings as their starting points.

Many projects conducted in the past two decades aimed to forecast the magnitude and effects of climate changes on groundwater in different types of aquifers [41,42,43]. The forecasting period usually extends up to the end of the 21<sup>st</sup> century. These projects often use greenhouse gas emission scenarios developed by the IPCC [13] and create climate projections by manipulating Global Climate Models (GCM). By correlating GCM downscaled climate data to the basin scale of a specific grid, and coupling them with observed historical data of a spring's discharge or water table fluctuations, it is possible to establish a cross-correlation between climate elements and the groundwater regime. The outputs of these coupled models are numerical and include the aquifer's response to predicted climate conditions [44,45]. Hartmann *et al.* [46] developed a large-scale simulation model to assess karstic groundwater recharge over Europe and the Mediterranean, which can also be used to forecast further climate and hydrology situations. Some recent studies are also aiming to assess aquifers' behaviour and their intrinsic vulnerability or resilience to variable climate elements and primary rainfall, which happens to be the main recharge component [47].

Climate simulations suggest that, in the next 90 years, Mediterranean regions will be exposed to higher temperatures and lower amounts of precipitation [13]. Further inland, the predicted changed climate elements include an additional reduction of days with snow and intensive rainfall in winter, and extended droughts in summer-autumn months.

The example of forecasted average discharges for low-water seasons (summer months) until the end of 21<sup>st</sup> century is presented in Figure 6. The tested Mlava spring in the Carpathian karst of

Eastern Serbia is the largest in the entire region and its discharge has been continually observed the longest (since 1969). The diagram shows real measured data up to 2010 and data forecasted by use of bias corrected GCM and a stochastic model created for the rest of the concerned period. Significant depletion trend is evidenced [42].

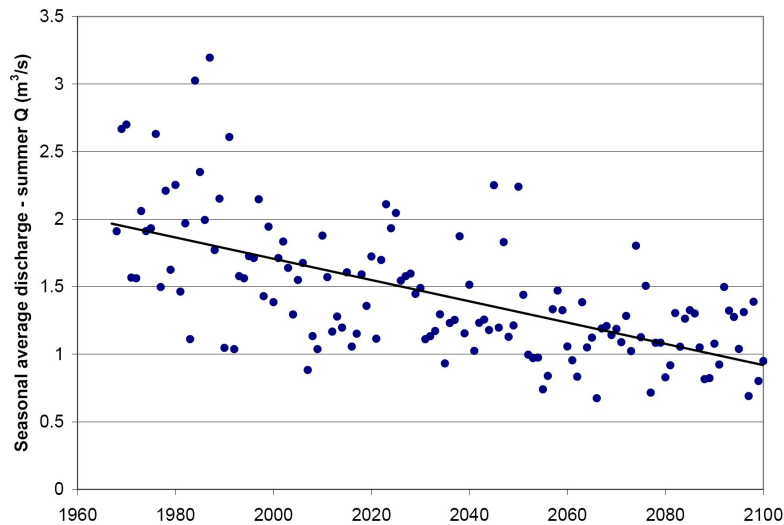


Fig. 6. Seasonal (summer period) average discharges of Mlava spring and the trend line until the end of 21<sup>st</sup> century (Stevanović et al. [42])

Many coastal springs in the Mediterranean basin are in danger from further sea level rise as a consequence of climate changes. The situation is the same with Almyros, the largest spring on the island of Crete in Greece, which had supplied Heraklion with potable water for many centuries. The spring issues at the elevation of 5m asl (Fig. 7), but the deeper part of the aquifer is under a strong influence of salt intrusion. The spring discharge varies from 3.3 to 30m<sup>3</sup>/s and the problem with salinity starts with the discharge lower than app. 15m<sup>3</sup>/s (during minimal yields, concentration of the Cl ion reaches 6 g/l). The concrete dam, constructed at the discharge point to increase the freshwater level, only partly mitigates the problematic brackish flux [48].



Fig. 7. Almyros spring (Heraklion, Crete, Greece) during a period of low water when concentration of Cl ion rises

The GEF/UN Environment project MedPartnership completed in 2015 produced amongst others an assessment of coastal aquifers and related coastal ecosystems in all Southern and Eastern Mediterranean and Adriatic countries [49]. The project provided conclusive evidence that:

- Climate change and variability will increasingly affect Mediterranean coasts and the livelihoods of ever-growing coastal populations, compounding all other issues of transboundary concern, with particularly severe impacts in identified hot spots;
- The critical role played by coastal aquifers within the context of the coastal zone including the shallowmarine environment is fully confirmed.

From the time immemorial the city of Kotor in Boka Kotorska Bay, Montenegro has been

using groundwater from Gurđić and Škurda, two springs located just outside the city fortress walls. The former is currently issuing at 0.0 +/- few cm. asl. Consequently, fresh water can be tapped during periods of flood, while during the summer spring water becomes brackish and then more and more salty. With further rising of the sea level in the coming centuries, this spring will no longer be usable. However, the recently completed project of tapping the spring Bolje sestre in the Skadar basin and distributing its water to the entire Montenegrin Coast has provided an adequate alternative [50].

Millenia will be needed for some other springs along the Mediterranean coast to be submerged by sea water, as they are located a few metres above the sea level. With this sort of time-scale, we are approaching the scale from Milanković's theory of climate cyclicity, or change of climate under the influence of a combination of natural and cosmogenic factors on one side, and anthropogenic impact on another. However, if the anthropogenic impact remains dominant, most climatologists agree that the sea level raise could reach a magnitude of 1m/1000 years. For example, with such a time scale, the main water source for the city of Dubrovnik – Ombla – will be under sea water in less than 2,500 years.

Some other coastal aquifers will also gradually become more brackish. The Bojana/Buna River issues from Skadar Lake at the elevation of 6m a.s.l. With a very small gradient, this river flows towards the Adriatic Sea, receiving also a certain amount of water from its large tributary Drin (Drim) River. With the above indicated magnitude of the sea level raise, the large alluvial delta of Bojana will be transformed into a salty marsh in about 6,000 years (Fig. 8). In this case, the current groundwater source Lisna-Bori near Fraskanjel, used to supply the city of Ulcinj, will be abandoned, while many vruljas (sublacustrine springs) along the banks of the Skadar Lake will also be affected by salty and brackish water inflow.



*Fig. 8. Skadar Lake and Bojana River valley and confluence to the Adriatic Sea. The shaded area has altitudes 0-6m and is under threat of being submerged (source: Google Earth copyright)*

## 5. CONCLUSIONS

This paper took the reader through a time-tunnel which started about 6 million years ago, crossed the present environment and ended somewhere in the very probable future. From the geological point of view, this future is very close. The Mediterranean basin and the Montenegrin coast, in particular, have been chosen as test areas. The entire region has a very dynamic geological history and is still exposed, in certain parts, to active and dramatic geological events such as volcanic eruptions, earthquakes and floods.

The focus of this analysis is on groundwater and its evolution. During the 20th century, air

temperature in the Mediterranean basin was observed to have risen by 1.4 °C to 4 °C depending on the sub-region. As such, the countries of the Mediterranean are already witnessing the impacts of climate variability. Most of the cities of the region use groundwater for potable water supply, but many of them are facing shortage of water during summer months due to very unstable and dynamic regime of karst aquifers, which are the principal utilised resource. According to IPCC report, by the end of the century the rise in temperatures is expected to be between 2°C and 4°C for the medium-low emissions scenario (RCP 4.5). At the same time, overall rainfall is also likely to decrease as high as 20% less than the current mean precipitation.

Other important water management problems are high aquifer vulnerability to pollution and salinisation - especially along the coast and on the islands. However, due to intensive water balance, sufficient rainfall and good absorption capacity of karst aquifers when receiving the rain, it is still possible in many places to intervene and artificially adapt the groundwater regime. Several such successful projects, including the most recent one which included tapping the Bolje sestre spring to supply the entire Montenegrin coast with water, may mitigate the water situation in decades and even centuries to come. Therefore, sustainability in water exploitation and environment protection should remain primary goals of water managers and decision makers in the entire Mediterranean region.

Milanković's theory of climate cyclicity has a much larger time scale than those that applied to centuries, and does not include terrestrial (geological) factors or the anthropogenic impact which is currently highly influencing our planet's climate. However, most of our analyses of the impact of climate change on water resources are stemming from his findings, and they must be taken in consideration when forecasting for extended periods of thousands of years. Anticipating climate changes and assessing their impact on water resources is essential for safeguarding the future water supply and designing a sustainable water management system which would also enable protection of dependant eco-systems.

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