VRANA LAKE ON CRES ISLAND - GENESIS, CHARACTERISTICS AND PROSPECTS

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Abstract. Vrana Lake on Cres Island in the Croatian part of the Adriatic Sea is one of the largest fresh water features on the Mediterranean islands. The maximum depth is 74 m (61 m below the sea level) and it stores 220 million m^3 of fresh water. Due to exceptionally good water quality the lake is used to supply water to the islands of Cres and Lošinj (up to 150 l/s) and it is the only source of potable water for these islands which have highly developed tourism. The paper provides an overview of the comprehensive hydrogeological investigations of the lake genesis, water origin, hydrodynamic and recharge, as well as the results of long-term monitoring with trend analyses. The investigations have been conducted to improve the sustainable management, and protection of a valuable but the same time extremely sensitive karst water system surrounded by the sea.

Keywords: Vrana Lake, karst, hydrogeology

INTRODUCTION

Vrana Lake on Cres Island is a unique hydrogeological and hydrological karst phenomenon and is at the same time an invaluable water resource. The lake is situated in the north-eastern part of a narrow island of Cres extending in NW-SE direction. The lake is 5 km long, and its maximum width is 1.45 km. The surface of the lake is 5.75 km^2 at the mean level of 13.19 m. The average depth of the lake is around 40 m, while the largest depth is 74.4 m (for the mean level) and it stores 220 million m^3 of fresh water. Since it is situated on the island the sea is only 3 to 6 km away. The deepest point in the lake is 61.3 m below the sea level. The landform surrounding the lake and present hydrogeological function are a consequence of geomorphological processes in the past and which were significantly influenced by changes in the climate and the sea level.

GEOLOGY AND HYDROGEOLOGY SETTINGS

Cres Island is a part of a wide karstic area which makes almost 50 % of the Croatian state territory. The island is largely composed of Cretaceous carbonate rocks with dolomite as the prevalent lithology. There are some occurrences of Eocene limestone and flysch of a relatively small surface spreading (Fig. 1). Quaternary deposits are of a limited extend and are hydrogeologically insignificant except in assisting to the interpretation of Quaternary events and lake genesis. Early Pleistocene and recent lacustrine silty carbonate sediments have been found at the bottom of the lake. Tectonically, the entire Cres Island, together with its lake, belongs to the Adriatic carbonate platform what was shown by Herak (in 1986). Basically it comprises overthrust structures, which are characteristic for the edge of the platform. In order to understand the present structures it is necessary to single out several active tectonic phases. The most important include those of the Tertiary period, when the main tangential structures (overturned folds, reversal faults, imbricate structures) were formed due to an impact of a NE-SW stress.

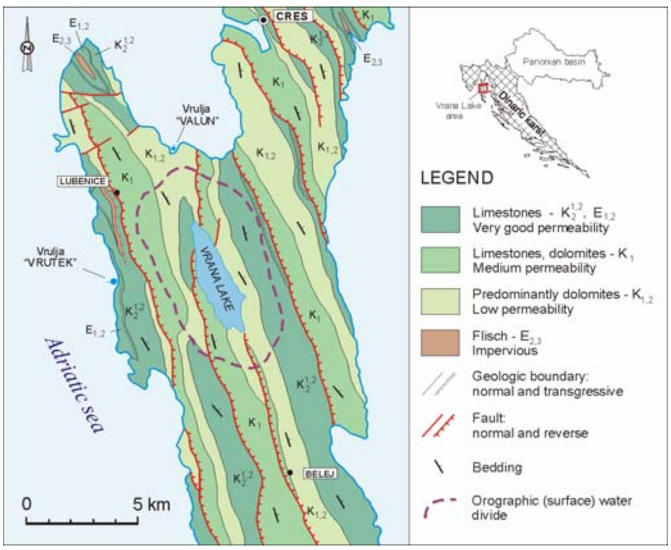

Figure 1: *Hydrogeological map of the Vrana Lake area*

The general orientation of the created structures is in NW-SE direction (Dinaric Strike) and the long axis of the lake follows that line. The comprehensive geological investigations elaborated in the professional report by Biondić *et al.* (1991) pointed out that the younger tectonic phase, characterized by a change of stress direction to N-W, took place between the Late Tertiary and present time. Regardless of that, accompanying structural changes have not been so expressive; the older structures were rotated and moved horizontally.

Although carbonate rocks dominate in the geological composition of the island, based on their hydrogeological characteristics the rocks can be put into several categories. Upper Cretaceous limestones and Foraminiferal limestones of Eocene are karstified and well permeable. Lower Cretaceous sediments composed of limestones with lenses of breccia, dolomite and thinly bedded limestones are somewhat less permeable. The sediments settled on the transition point from Lower to Upper Cretaceous are mostly composed of dolomites and are of low permeability. Actually, only locally present flysch sediments are impermeable. It is believed that forming of the lake and the fresh water karstic aquifer, from which the lake is fed with water, is conditioned by the structural position of poorly permeable dolomites and flysch which prevent or significantly slow down the discharge towards the sea. The lake

LAKE GENESIS

The genesis of Vrana Lake is predisposed by the Neotectonic movements which, as a result of the change in the regional stress direction, have rotation and horizontal moving of structural blocks generated in the prior tectonic phase as a consequence. The lake depression is formed in the extension zone along a reactivated longitudinal relaxation fault. Besides that, there are indications that the youngest horizontal movements had as a consequence the forming of a local "pull-apart" structure in the area of today's lake, which contributed to the further extension of the rocks. Since these tectonic preconditions happened in the last tectonic phase, we can assume that the development of the lake depression started at the end of the Tertiary.

When we consider the lake genesis, we must certainly take into account the regional palaeographic conditions. In that aspect, it is necessary to point out that during the Pleistocene, the north Adriatic area was actually land in which low-land flow of the River Po was dominant (this area is today under the sea). During the sub-aquatic explorations of the deepest parts of the lake, about twenty metres thick lake sediments of Pleistocene age were discovered. These sediments prove that the lake was mainly formed already in Lower Pleistocene, i.e. in the period when the sea level was significantly lower than today. At that time the lake and land phases exchanged, during which the depression functioned as a karstic polje. Appearance of paleosoil intercalations within the lake sediments directs us to this conclusion. Waters from the local catchment area sunk in today's deepest part of the lake and were flowing away in the underground towards the lower parts of the terrain outside today's island.

The final phase of the forming of Vrana Lake happened at the end of Pleistocene, i.e. when the Würm glacial period ended after which the level of the sea rose by 100 meters. The rising of the sea level is a cause of rising and pushing the fresh water in the direction of the remaining land area. The lowering of the hydraulic gradient between the lake and the newly formed, elevated erosion base had as a consequence the slowing down of the underground runoff and closing of the previously developed drainage system. This enabled the filling of the depression with water and the forming of the recent Vrana Lake. The lake is a nice example how important stratigraphic, structural and lithologic controls on groundwater flow can be even in generally rapid-flow environments like the Dinaric karst.

HYDROLOGY

Its dimensions and island position, as well as for the circumstances that there are no visible inflows, the problem of the origin of the lake water has for a long time been attracting scientists' attention. As early as in the 19th century, contrary theories on its feeding arose. According to one group of authors, the lake is fed by deep underground inflow from the land, which is over 30 km away. The second theory, according to which the lake is fed solely from its local island catchment area, is advocated by hydrologists.

The matter of the functioning of the Vrana Lake regime as well as its viability in the conditions of pumping for the public water supply was especially present at the end of 1980s, when the minimum water level of only 9.11 m was registered. As a consequence of this, comprehensive hydrologic researches started which resulted in new cognitions on the functioning of Vrana Lake. This was shown by Ožanić & Rubinić (1994). According to the mentioned authors the lake is fed from its own catchment area of 24 km^2 (the lake surface not included). The average yearly recharge into the lake have been calculated to 588 L/s (18.5 x 10^6 m^3), out of which 33 % is a direct inflow to the surface of the lake, and the rest is inflow from the flow of the underground aquifer. With the medium yearly evaporation of 1150 mm, the evaporation losses from the free water surface amount to 6.7 x 10^6 m^3 (at the medium lake level). Mean annual precipitation rate is 1073 mm.

During the calculation of the water balance of the lake, the defining of the groundwater loss turned out to be a separate problem. This was due to the fact that no discharge areas, for which we could confirm with certainty that it is being fed by the underground inflows from the lake. Vruljas Vrutek and Valun are potential discharge places. Vrulja Vrutek is the most significant place of the discharge of groundwater in the Cres area, and it is situated next to the sea coast, 3.3 km westwards from the lake. Its abundance depends on the hydrological conditions and according to some estimates it ranges from 50 to 250 L/s which was shown in the professional report by Kuhta (2002). Groundwater tracings performed on the west coast of the lake did not confirm its connection to the vrulja. Vrulja Valun is located 3.2 km northern from the lake, and its abundance ranges from 4 to 15 L/s. The connection to the lake has not been tested, but temperature measurements show that the vrulja is largely being fed from its own catchment area. In that situation underground discharge from the Vrana Lake aquifer was determined by a mathematic analysis which was performed based on the changes of the lake water level and other familiar elements of the water balance. According to those calculations, the discharge (loss) from the catchment area has been estimated to 370 L/s.

RELATION LAKE-UNDERGROUND AQUIFER

Vrana Lake has characteristics of medium deep lakes of the moderate zone which is being supplied with the precipitations and inflows from the surrounding karst aquifer. The lake does not freeze in the winter, and it has oligotrophic and monomictic character. The entire lake mass is well aired. The development of thermal stratification during the year and isothermal situation at the end of winter, when the change of the entire lake water mass happens, was established. It was shown by Hertelendi *et al.* (1995) that a mean residence time of 30-40 years was obtained from the measured tritium values.

The comparison between the lake and groundwater was made based on the measuring in the very lake and on boreholes performed on its eastern side. Monitoring data of the lake and groundwater level are highly correlated, r^2=0,99 for a piesometer 210 m away from the lake to r^2=0,98 for piesometer 485 m away. Hydraulic gradient is extremely low; it is directed towards the lake and range from 0.0048 in low water conditions to 0.1345 immediately after heavy precipitation. The measurements lasted for 8 years and have been elaborated in several professional reports by Biondić *et al*. (1998), Kuhta & Mesić (2001) and Kuhta (2002).

As opposed to the levels, the temperature measurements show extremely large differences. The temperature of the lake water changes throughout the year. At the end of the summer, there is a extreme thermal stratification. Thermocline is most frequently formed at 15 to 20 m below the surface. In the area above the thermocline the water temperature in the surface layer can reach up to 26 °C. At the same time, the temperature is extremely low in the hypolimnic area and which, depending on the climate characteristics of a year, ranges from 7.1 to 9.1 °C. In the isothermal period, which lasts for 2 to 3 months, the whole water mass has a homogenous temperature ranges from 6.7 to 8.7 °C. As opposed to the lake, the groundwater in the boreholes has almost constant temperature throughout the year, mildly falling with depth. Groundwater temperature ranges from 13.1 to 14.5 °C what is close to the average yearly air temperature which ranges from 14.1 to 15.5 °C. Besides the difference in the temperature, the groundwater differentiates in the chemical composition also which is shown through elevated mineralization, conductivity, alkalinity, SiO_2 and nitrates content, and lower oxygen level as it was shown by Biondić *et al.* (1995).

PROSPECTS

Vrana Lake is the only resource of potable water for the islands of Cres and Lošinj. Protection measures undertaken fifty years ago, whose basic elements are the urbanization restriction in the most part of the catchment area and a ban to any activities on lake, proved to be rather efficient. The bacterial analyses show pure water which could be used without any treatment. The chemical results also provide a similar good quality picture. Thus lake water meets the drinking water standards, although for safety reasons it is lightly chlorinated, particularly to avoid possible quality deterioration in the water-supply network.

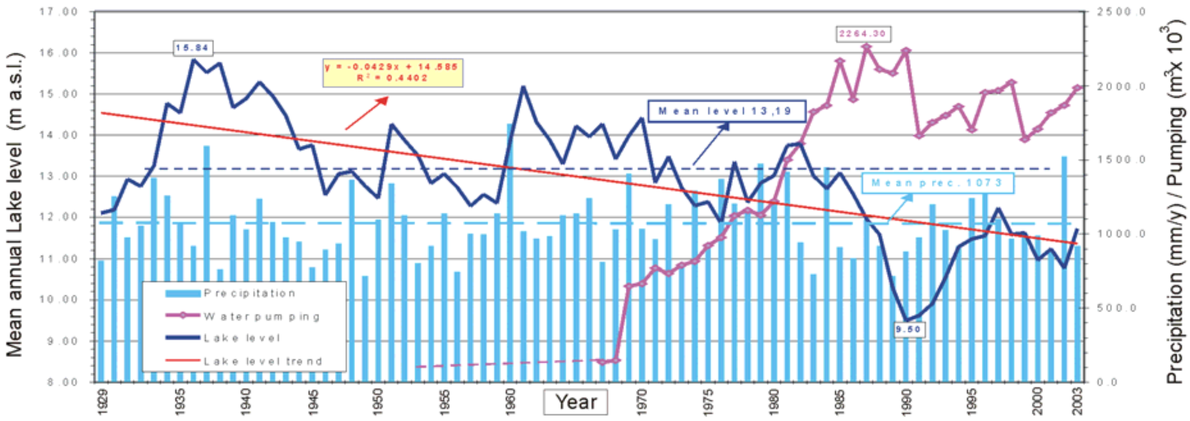

Figure 2: *Mean annual Lake level, annual precipitation and water pumping for the period from 1929 to 2003*

The water supply system from Vrana Lake started working in 1952. In the last twenty years approximately 1.92 x 10^6 m^3, i.e. about 62 L/s, are being extracted from it every year. The largest consummation was registered in 1987 when 2.26 10^6 m^3 of water (max. 150, averagely 72 L/s) were pumped from the lake. Although the total extraction quantity is the smallest element of the water balance, hydrological analyses show that it has a certain influence, so a trend of the decline of the lake level is being related to this element as well as to the quantity of precipitation. This trend was especially stressed in the period from 1983 to 1991 (Fig. 2). Analyses have shown that the decline of the lake level is partially being compensated by a smaller underground runoff and by the addition of recharge probably related on the catchment area enlargement. Through a math analytical model a consumption of 100 L/s was simulated and the results show that in this case the average lake level would at the end of simulation be at 9.80 m, and the lowest at 7.86 m what was shown by Ožanić (1994). Although these data point to the fact that in the future, the pumping capacity can amount to 100 L/s, the available quantities are significantly lower than 250 to 350 L/s which have been predicted up to now. Furthermore, a constant trend of the lake level decline (see Fig.2) points to a need of a gradual increase of the pumped quantity and monitoring of all changes in the lake system.

REFERENCES

Biondić B, Ivičić D, Kapelj S and Mesić S 1995. Hydrogeology of Vrana Lake on Cres Island. **In**: Proc. First Croatian Geological Congress, 95-100.

Herak M 1986. A Concept of Geotectonics of the Dinarides. *Acta Geologica*, 16/1, 1-42.

Hertelendi E, Svingor E, Rank D and Futo I 1995. Isotope Investigation of Lake Vrana and Springs of Kvarner Area. **In**: Proc. First Croatian Geological Congress, 201-205.

Ožanić N 1996. Hydrological model of Vrana Lake on Cres Island. PhD dissert., University of Split, Croatia.

Ožanić N and Rubinić J 1994. Analises of the Hydrological regime of the Lake Vransko Jezero on the Island of Cres. *Hrvatske vode*, 8, 535-543.