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Seasonal Temperature Variations of Lake Vrana on the Island of Cres and Possible Influence of Global Climate Changes

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Abstract: Lake Vrana on the island of Cres is one of the largest fresh water features on Mediterranean islands. The maximum depth of the lake is 72 m and it stores 220 million m^3 of fresh water. The paper provides an overview of lake and groundwater temperature measurements to date and recent activities within the EU project "CC-WaterS (Climate Change and Impacts on Water Supply)". Groundwater temperatures in the lake surrounding are almost constant throughout the year, in the range from 14.6 °C to 13.1 °C, while thermodynamic cycle of the lake conforms to the characteristics of a monomictic, medium depth lake in the moderate climate belt. Present and future climate simulations using three limited area models were analyzed (Aladin, Promes and RegCM3), they pointed out further air temperature increase in range of 0.27 °C/10 yrs to 0.32 °C/10 yrs. The significant changes of precipitation rates were not indicated. Considering increasing water consumption from the lake, already asserted negative trends, indicated climate changes and possible effects on the lake recharge, it is necessary to establish continual monitoring of parameters that describe lake system behaviour and periodically analyze lake conditions, especially with respect to the extraction for the public water supply.

Key words: Lake Vrana, Cres island, karst, climate changes, water temperature.

1. Introduction

Lake Vrana on the island of Cres is a unique hydrogeological and hydrological karst phenomenon and an invaluable water resource as well. It is situated in the north-eastern part of the narrow island of Cres, with 405.7 km^2 the largest island of the Adriatic Sea [1] which extends in the NW-SE direction (Fig. 1). The lake is 5 km long, with the maximum width of 1.45 km. The surface of the lake is about 5.5 km^2 at the average altitude of 12.78 m a.s.l.. The average depth of the lake is around 40 m, with the largest depth of 74.1 m (for mean level). The lake stores 220 million m^3 of fresh water. Since it is situated on an island, the sea is only 3 km to 6 km away. The deepest point in the lake is 61.3 m below the sea level. The land form surrounding the lake and its present hydrogeological function are consequences of exodynamic processes that took place in the past under significant influence of changes in both climate and sea levels.

Due to its exceptionally good water quality, the lake is used for water supply of the islands Cres and Lošinj (average abstraction rate in 2010 was 73.7 L/s) and is the only source of potable water for these tourism intensive islands. The lake's extremely low water level of 9.11 m a.s.l. recorded in 1990 caused great concern among professionals and water users as to the lake's future and was the reason behind a comprehensive research program. As a part of this hydrogeological research, monitoring of groundwater and lake temperature was established in 1995, and continued until 2002. Monitoring results were elaborated in several professional and published papers [2-5]. Almost 10 years later, these activities were resumed within the project "CC-WaterS" funded by

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the South East Europe—Transnational cooperation programme.

2. Geological and Hydrogeological Settings

Cres Island is a part of a wide Dinaric Karst region which makes almost 50% of the Croatian state territory. The island is largely composed of Cretaceous carbonate rocks with limestones and dolomites 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.

According to the latest orogenic evaluation of the External Dinarides [6], the island of Cres is situated on the western part of the Dinaridic SW unit or High Karst. Regardless of the palaeogeographic model of region development, there is no doubt that more than 8,000 m thick succession of predominantly carbonate sediments [7, 8] was exposed to the intense tectonic disturbances in several phases from Triassic period up to present-day. The main deformation episode started in the Late Cretaceous, when synsedimentary tectonics became stronger, and reached its maximum in the Oligocene/Miocene, leading up to the large

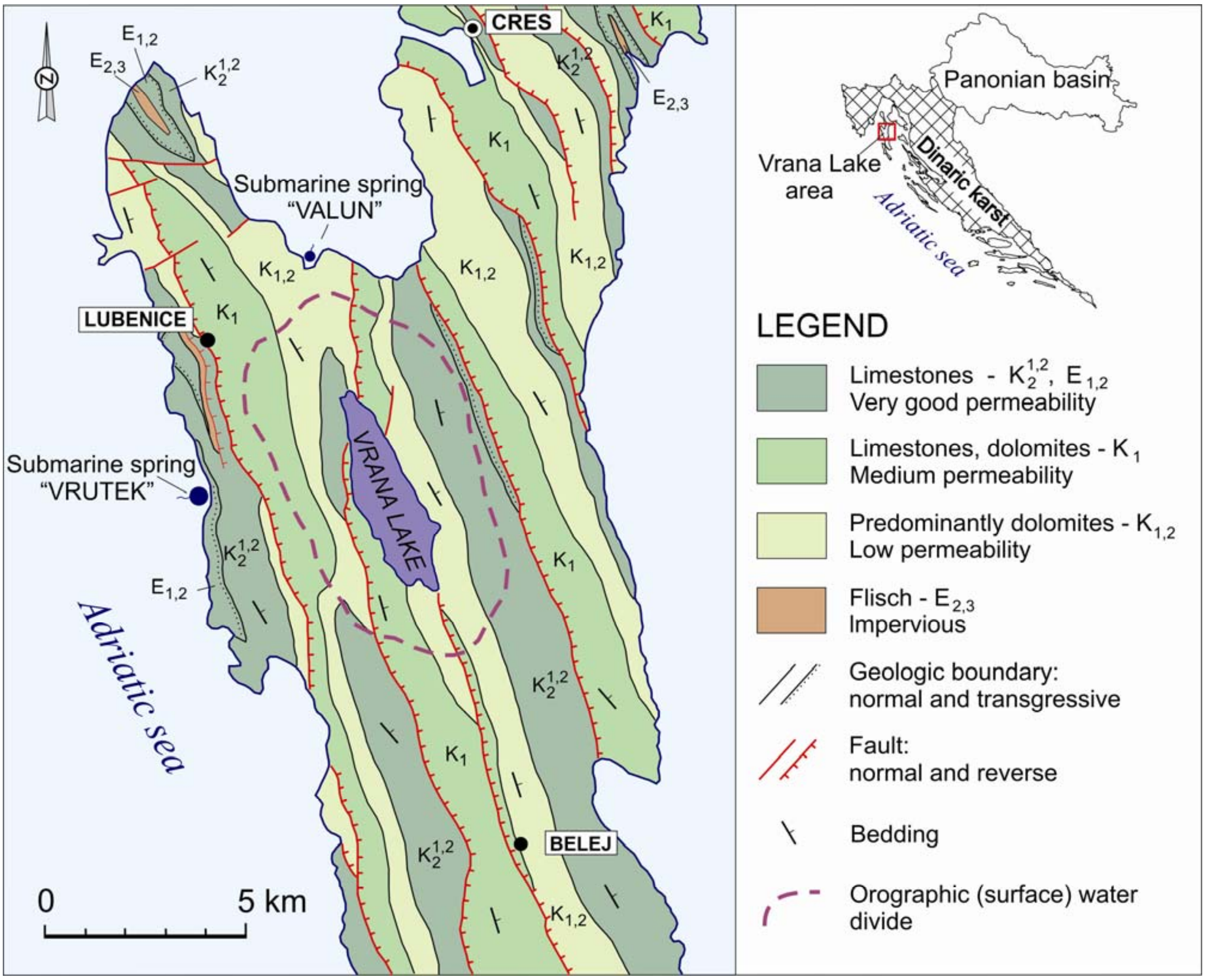

Fig. 1 Hydrogeological map of the Lake Vrana area (geology after Ref. [9]**).**

tangential movements and uplift of the Dinarides [10]. Later orogenic brought shifting of the regional tectonic stress to N-S direction, and wrench tectonic deformations. The comprehensive geological investigations elaborated in the professional report by Biondić et al. [11] pointed out strong tectonic disturbance of the lake area. Major structures and faults are of NNW-SSE strike. The strike-slip tectonics and development of the pull-apart structure along the strong longitudinal fault seems to be a major mechanism that lead to Lake Vrana depression genesis.

Although carbonate rocks dominate in the geological composition of the island, based on their hydrogeological characteristics the rocks can be put into several categories (Fig. 1). 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.

Despite assumptions appeared, regarding it recharging from the mainland [11-13], and so far, the results of all hydrological investigations carried out, both earlier and recent [14-17] pointed out recharging from the local island catchment area is nearly 33 km^2. About 33% of recharge is direct precipitation on the lake surface. Mean monthly recharge in the lake varied between 0.265 (August) and 0.942 (November) m^{3}s^{-1}. It was shown by Hertelendi et al. [18] that a lake water mean residence time of 30-40 years was obtained from the measured tritium values. Based on the content of isotopes ^{2}H and ^{18}O, it was estimated that main origin of lake water was from the atmosphere, with a very small component of water that was longer period accumulated in the underground. To corroborate this, a completely independent hydrological approach led to the same conclusion and estimated the average water residence time in Lake Vrana to 32 years.

3. Present Climate Conditions of the Area

The climate of the island of Cres is determined by the mid-latitude circulation with frequent and intense weather changes in the most part of the year, dominantly modified by the sea. This climate is under the direct influence of the north Adriatic cyclogenetic effect and strongly influenced by high orography of the Gorski kotar region and the Dinaric Alps. In summer it is under the influence of the Azorean high, which prevents cold outbreaks into the Adriatic. The local climate is described for the years 1961-1990, the period recommended by the World Meteorological Organization as the referent period for the present climate conditions.

The analysis by Gajić-Čapka et al. [19] was based on monthly, seasonal and annual averages of air temperature and precipitation data from the meteorological station Cres (10 km north of the lake, H = 5 m), that could be considered as representative for average climate conditions of the lake Vrana catchment (Table 1). The annual cycle of air temperature monthly averages is well defined, with the maximum in June (23.7 ºC) and July (23.2 ºC) and the minimum in January (5.9 ºC). Such annual cycle is characteristic of the maritime type with autumn (September, October, November—SON) warmer than spring (March, April, May—MAM). The average annual air temperature is 14.3 ºC.

The precipitation variations confirm that the annual cycle of the island of Cres is of the maritime type. The lowest precipitation amount occurs during the warm period of the year (April to September), with the

Table 1 Basic statistics for annual and seasonal mean air temperatures and precipitation amounts for Cres, 1961-1990 (source: Ref. [19]).

Statistical	Air temperature (ºC)					Precipitation (mm)				
Parameter	Annual	DJ *	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON
Average	14.3	6.6	12.9	22.6	15.1	1,053.6	290.5	233.5	198.0	338.8
Standard deviation	0.4	1.1	0.9	0.7	0.9	194.2	124.3	61.3	83.4	124.7
Maximum	15.3	8.4	14.6	23.8	16.8	1,366.5	612.2	400.3	429.0	573.3
Minimum	13.5	3.4	11.0	21.4	13.3	732.0	58.6	108.4	60.4	124.8

* DJF—December, January, February, etc..

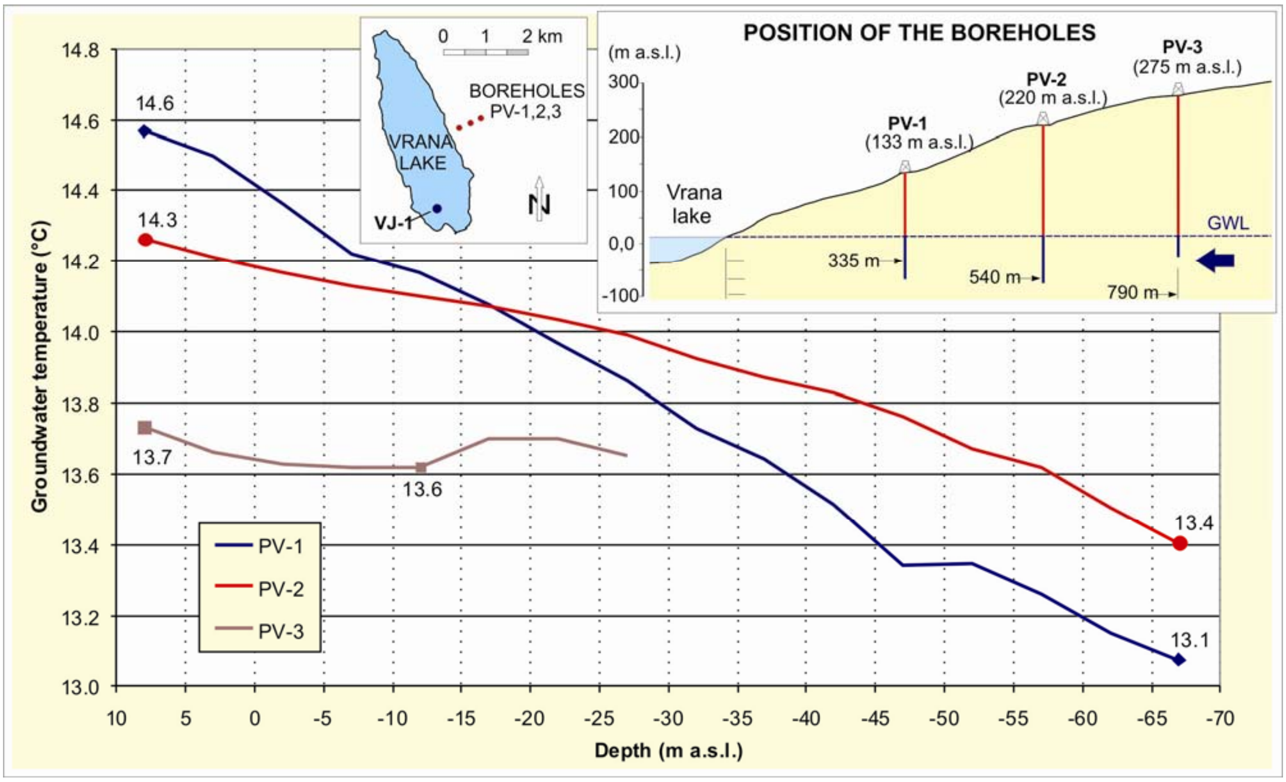

Fig. 2 Distribution of the mean groundwater temperatures in water column of the boreholes PV-1, PV-2 and PV-3.

minimum in July (53 mm). During the cold half-year (October to March), it receives 57% of the annual total, and the maximum occurs in November (136 mm). The average annual precipitation rate for the meteorological station Cres is 1,053.6 mm. In the same time the annual evaporation from free water surface is 1,161 mm [20].

4. Groundwater Temperature Variations

The groundwater temperature was measured in the boreholes on the NE lake bank, situated on distance between 335 m and 790 m from the lake shore (Fig. 2). The measurements lasted for 8 years (1995-2003) with different frequency, and have been elaborated in several professional reports and papers [2-5].

Results reveal almost constant groundwater temperature throughout the year. During the observation period, the temperature oscillations in each observation point (in 5 m intervals) are very low and ranged within 0.2 °C to 0.4 °C. The total mean temperature ranged from 14.6 °C to 13.1 °C, with an average value of 13.8 °C, i.e., about 0.5 °C lower than the average annual air temperature in the area (14.3 °C, Table 1). The groundwater temperatures in the first 20 m below the water table decreased with the distance from the lake and the thickness of the unsaturated zone. A significant negative geothermal gradient was determined in the boreholes PV-1 (0.02 °C/m) and PV-2 (0.012 °C/m), while PV-3 was too shallow (Fig. 2). This phenomenon could be a consequence of thermal convection from permanently colder lake hypolimnetic area. It can be observed that the impact is stronger on closer borehole PV-1.

5. Temperature Characteristics of the Lake

Based on the measurements to date, it can be stated that Lake Vrana is a typical example of a medium depth lake in the moderate climate belt (which does not freeze in winter). The established development of thermal stratification during the year and isothermal conditions at the end of winter confirm that the lake's environment is of monomictic nature, i.e., entire water mass of the lake mixes once a year.

The annual thermal cycle of the lake is presented by the characteristic curves of changes in water temperature according to the depth (Fig. 3), measured at the measurement profile VJ-1 located in the deepest part of the lake, at its southern bank. Since the differences registered at other measurement profiles were within the margins of accuracy for the used instruments (±0.15 °C), it can be stated that the data measured at the profile VJ-1 are adequately representative of the conditions prevalent for the entire lake. The general overview is based on monthly measurements conducted in the period from October 2001 to November 2002.

The heating of the lake's upper layer (epilimnium) begins at the end of winter or beginning of spring (March-April). A gradual increase in temperature of the surface water layer leads to an increasingly more marked, larger temperature difference from the lake's deeper layers (hypolimnium). The separation area, i.e., the thermocline is characterized by a significant temperature gradient (recorded changes of up to 5 °C/m). The position of the thermocline changes and is most frequently at the depths between 10 m and 20 m. The highest temperatures in the epilimnic area occur during June, July and August, when the first 10 m of the water are heated to an average of 25 °C (Fig. 3a). The hypolimnetic area is also exposed to gradual heating, but here the changes are much slower and of lesser scope, so that in the observed period during the heating cycle the temperature at the bottom of the measurement profile VJ-1 increased from 6.7 °C in February to 7.9 °C in September 2002, i.e., by only 1.2 °C.

The first signs of cooling of the lake may occur already in September and intensify during October and November (Fig. 3b). In December, conditions are usually met for complete isothermy of the lake water, which lasts for about 3 months. During the observation period, the homogenous temperature of the lake water according to the entire depth of the water column ranged from 8.9 °C in December 2001 to over 6.8 °C in January and to 6.7 °C in mid-February 2002.

The presented thermal cycle, as well as the summer maximums and the temperatures of winter isothermy strongly depend on climate characteristics of a particular year. The impact of seasonal air temperature variations on lake water temperature and stratification is clearly evident from data of continuous measurements on different depths of the lake water column, conducted from November 2010 to April 2012 (Fig. 4).

In the autumn of 2011 the heat flux into the lake becomes negative and the lake begins to cool. Due to unusually hot weather during November and December, even January 2012, isothermal conditions were established about one month later than usually, i.e., at the beginning of February. The end of January and first part of February were extremely cold (for the island of Cres) and windy. That caused lake cooling to the very low 5.13 °C. When the weather conditions become normal, the positive heat flux started water thermal stratification. It can be observed that isothermal conditions in 2012 lasted very short, i.e., for less than one month.

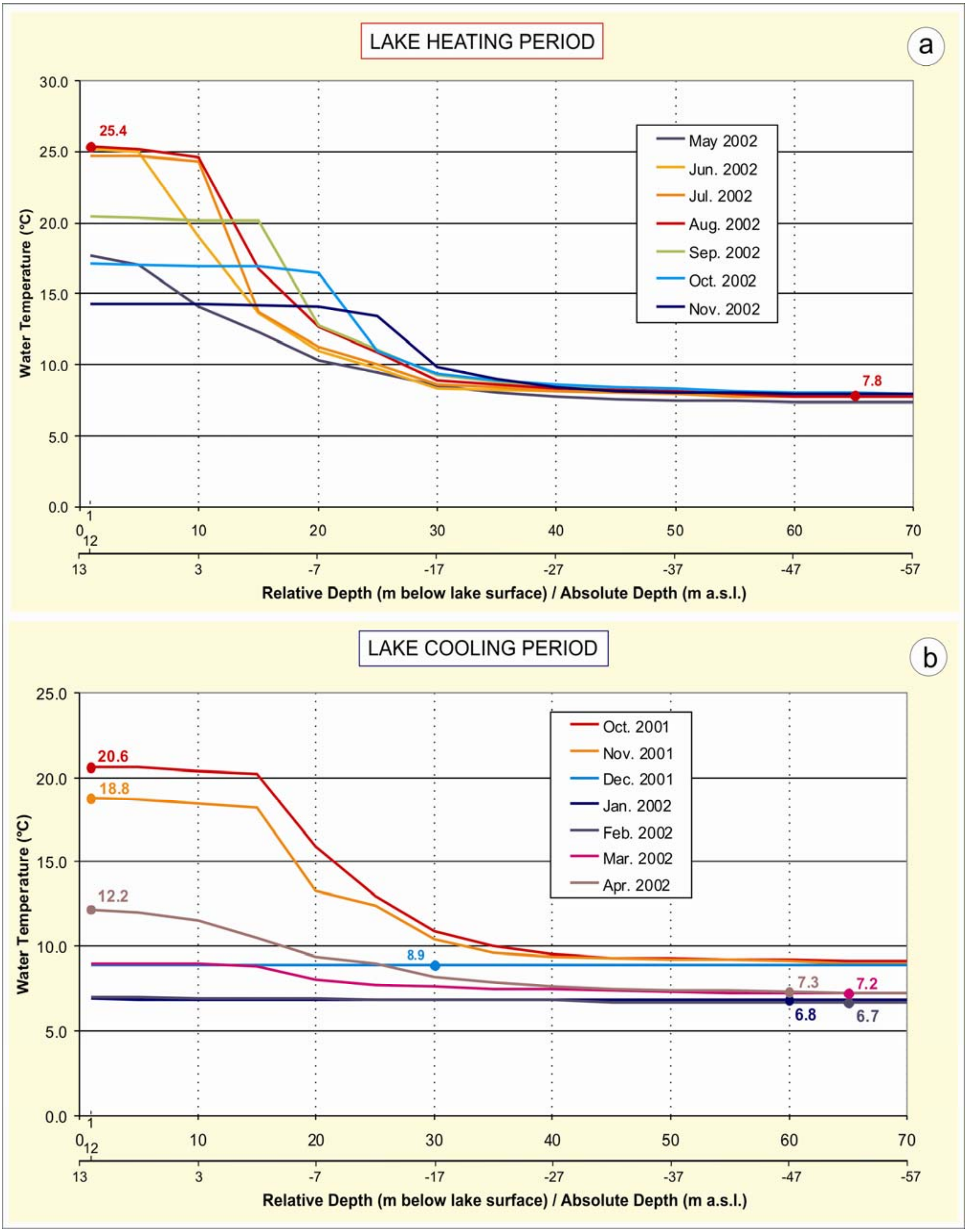

Fig. 3 Characteristic curves of the lake water temperature for the observation period October 2001-November 2002. (a) lake heating period; (b) lake cooling period.

Fig. 4 Mean daily water temperature fluctuations on different depths of the lake in comparison with temperatures of air and groundwater.

6. Historical Lake Temperature Data

The global increase in temperature caused by pollution of the earth's atmosphere and the related greenhouse effect are becoming a widely accepted fact. Since these are gradual changes, their recording requires multi-annual series of systematically collected data, which, as should be noted, do not exist for Lake Vrana. What is available are the results of sporadic measurements conducted in the period from the early to mid-20th century, the results of occasional measurements in the period from 1995 to 2002 and the recent data collected within the EU project "CC-WaterS". Since water temperatures in the hypolimnic area, particularly if measured in the isothermal period, reflect to some extent the climate characteristics of the entire annual cycle, a comparison of available data was carried out in an attempt to arrive at some indications as to the impact of global temperature changes.

The first data on water temperatures in Lake Vrana were published by Gavazzi [21] and relate to measurements conducted in 1900 and 1901. Since these measurements were only conducted in the upper thermal unstable layer of the lake's water, down to the depth of 16 m, these data are not used in our analysis. Measurements according to the entire depth of the water column were conducted by Morton [22], Nümann [23] and Petrik [24]. The collected archive data and the results of more recent measurements are presented in Table 2 and are related to water temperatures in the hypolimnetic area, i.e., at depths below 40 m. Based on the presented results, it can be seen that the temperatures of lake water after the winter cooling period are in all three earlier measurement sets lower than those recorded in the period from 1996 to 2002. The minimum difference is between the measurements by Nümann [23] in March 1941 and our measurements in February 2002, in the range from 0.3-0.5 ºC. When the measurements by Petrik [24] in March 1956 (lowest recorded values) are compared with our data from March 1997 (highest recorded values), the maximum temperature difference is as large as 3.45 ºC.

Table 2 Overview of the water temperatures in Lake Vrana measured in the hypolimnetic area, i.e., at depths below 40 m.

Measurements	Morton [22]	Nümann [23]		Petrik [24]	
Date	April 1931	March 1941	August 1941	March 1956	July 1956
Temperature（°C）	6.08	6.2-6.4	8.2-9.3	4.45-4.6	6.5-6.9

HGI—Croatian Geological Survey (Kuhta)									
Mar. 1996	Aug. 1996	Mar. 1997	Sep. 1997	Mar. 2000	Aug. 2000	Feb. 2002	Aug. 2002	Feb. 2011	Feb. 2012
7.1	7.6-7.8	7.9	8.5-8.9	7.4-7.5	8.5-8.8	6.7	7.8-8.5	7.7	5.1

Table 3 Decadal trends of seasonal and annual means of temperature, and seasonal and annual precipitation amounts. Statistically significant trends at the 5% confidence level according to Mann-Kendall test are in bold. Trends are based on 150-year time series except for Promes where 100 years are available.

	Trend in *t* (°C/10 yr)					Trend in *P* (mm/10 yr)				
	DJF*	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
RegCM3	**0.26**	**0.25**	**0.33**	**0.25**	**0.27**	**5.1**	0.1	-2.5	-0.8	2.3
Aladin	**0.20**	**0.24**	**0.44**	**0.28**	**0.29**	**-5.1**	-2.4	**-3.6**	-3.7	**-14.7**
Promes	**0.36**	**0.32**	**0.36**	**0.25**	**0.32**	6.4	**7.2**	-0.5	2.9	**16.2**

* DJF—December, January, February, etc..

Looking at the above data, it can be stated that today's minimum temperatures of the lake's water are generally higher than those recorded 50 or more years ago. This, however, is by no means an indicator of the impact of global climate changes, since data are insufficient and temporally far apart, and since the recorded conditions primarily reflect climate conditions in the year when the research was carried out. For instance, very low temperatures of the lake's water measured in March 1956 were a consequence of an extremely severe and cold winter. According to Petrik [24], in the first 20 days of February of that year the temperature was constantly below zero, and minimum values dropped to as low as -7.6 °C. A similar situation was observed during our last measurement cycle in 2011-2012 (Fig. 4). An unusually cold period during February 2012 resulted in a temperature drop of the lake's water to 5.1 °C. This is the lowest temperature recorded in the most recent measurement period, i.e., from 1995.

The hypolimnetic area temperatures are highest on the end of summer or during early autumn. The highest values measured from 1995 are up to 8.9 °C (September. 1997, Table 2). It should be mentioned that the highest temperature in the hypolimnetic area of 9.3 °C was recorded by Nümann [23] at the beginning of August 1941, i.e., much before the global warming.

7. Regional Climate Models Simulations

Present and future climate simulations using three limited models were analyzed by Gajić-Čapka et al. [19]. The models are Aladin [25], Promes [26] and RegCM3 [27]. For 2 m temperature and precipitation, time series for each model were considered and for present climate they are compared with local observations and with the EOBS (European Observation) data [28]. Climate change using RCMcorr_adj were analysed for two 30 year periods, the period P1, 2021-2050, and the period P2, 2071-2100, with respect to the reference period P0 (1961-1990) which represents the present or the near past.

Time series of mean annual temperature and precipitation amounts are shown in Figs. 5 and 6. Table 3 shows decadal trends in seasonal means of temperature and seasonal precipitation amounts. Trends for RegCM3 and Aladin data are calculated from 150 years and for Promes from 100 years. This does not allow a direct inter-model comparison of trends, but they indicate the likely trends as simulations continue as far as possible.

Changes in temperature means are always positive and all three models perform similarly on monthly,

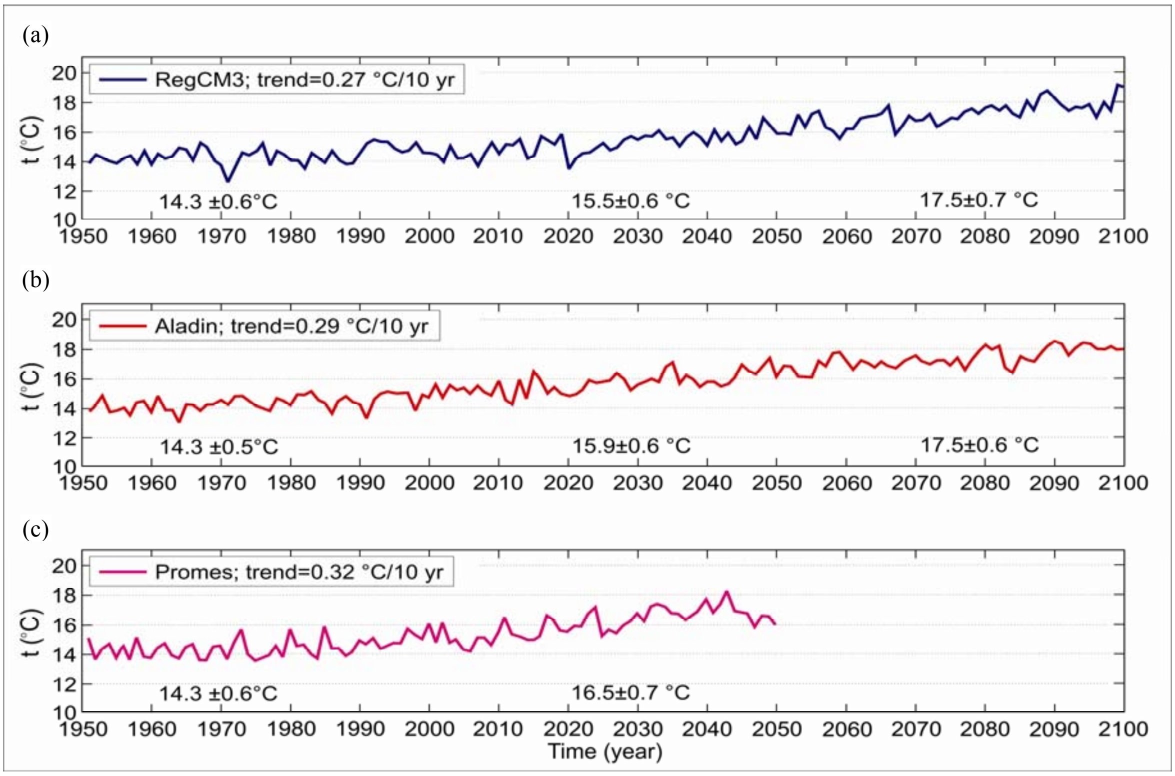

Fig. 5 The Lake Vrana catchment: annual mean temperatures. (a) RegCM3; (b) Aladin; (c) Promes. In each panel decadal trend based on entire available time series is shown. Additional numbers at the bottom of each panel are mean values and standard deviations during P0, P1 and P2 (after: Gajić-Čapka et al. [19], 2010).

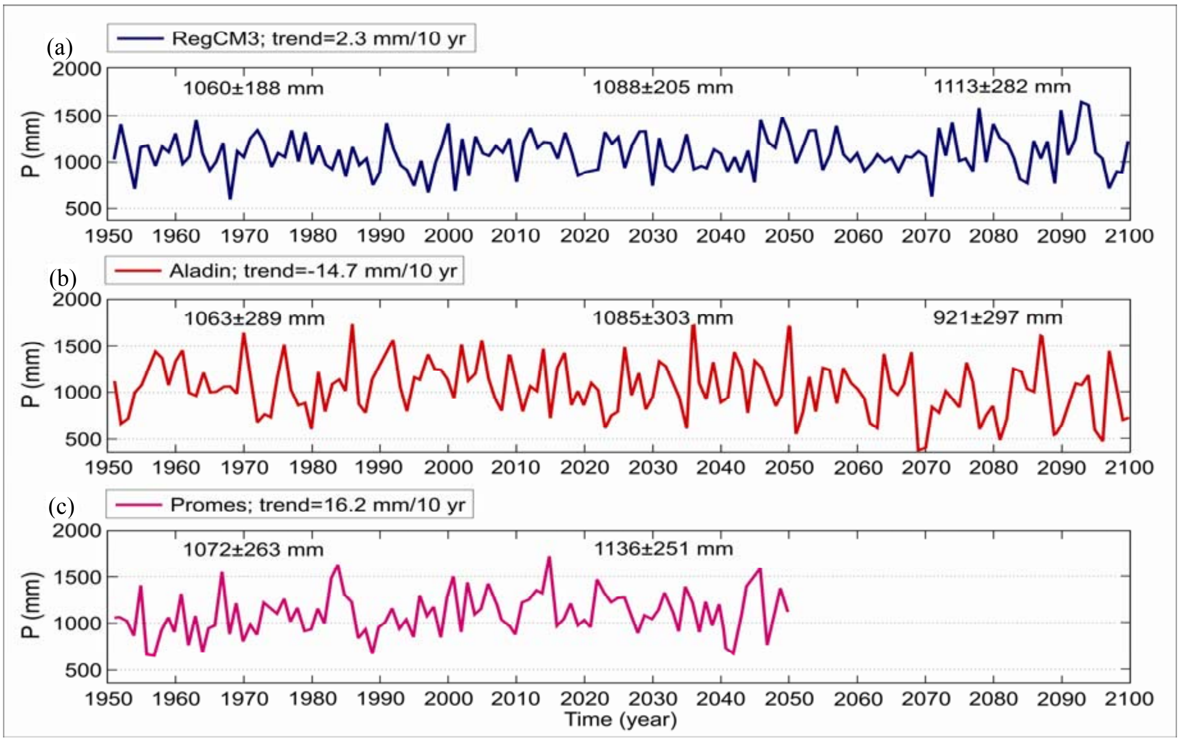

Fig. 6 The Lake Vrana catchment: annual precipitation amounts. (a) RegCM3; (b) Aladin; (c) Promes. In each panel decadal trend based on entire available time series is shown. Additional numbers at the top of each panel are mean values and standard deviations during P0, P1 and P2 (after: Gajić-Čapka et al. [19], 2010).

seasonal and annual time scales. For the period P1, 2021-2050, Promes shows the highest increase in temperature and RegCM3 shows the lowest increase (Fig. 5). For the P2 (2071-2100), RegCM3 and Aladin have almost the same temperature increase of monthly averages. Changes in temperature climate means between different periods (P1-P0 and P2-P0) and trends for all time series are statistically significant.

Climate change in precipitation amounts and trends is more variable (Fig. 6). All three models have the same sign of the annual mean differences between P0 and P1, although these values are not statistically significant. For the P2 minus P0 differences, the amplitude of change is larger than for the P1 minus P0 differences (but still not significant) and the sign of differences varies. For example, for winter precipitation RegCM3 and Aladin have significant positive and negative trends of the same magnitude (Table 3), and for annual precipitation Aladin and Promes have significant negative and positive trends, again of similar magnitude. The differences in the sign of climate change for precipitation amounts makes projection of these changes quite uncertain. However, the raw (uncorrected) Aladin data are in particularly good correspondence with local observations; thus, this might give more weight to this model in studying projections of future climate and related recharge changes.

As the next step, on the basis of the results of the applied models (predicted temperatures and precipitations), estimations of climate changes impact on the lake recharge (water balance) were done by Langbein's approach [29] for the chosen 30-years long periods by Rubinić et al. [30] and validated with more complex "Vrana" mathematical model [20, 31]. The recharge of the lake was estimated on the annual time discretization. For the evaluation of critically dry periods, the parameter of minimum mean monthly recharge was chosen.

Achieved results pointed out that different climate models indicate different water balance changes. For the 2021-2050 period (P1) significant changes of average annual recharge are not expected. There is even notable slight increase of recharge, with respect to the referent climatic dataset 1961-1990. Still, there will be certain negative consequences manifested. The variations and range of values of the annual recharges will be higher. There will also be appearance of single years with much lower values of annual recharges than are those noted in historical data (1961-1990). The minimum values of annual recharges for P1 are between 15.2% (RegCM3) and 48.3% (Aladin) lower than in P0. There are even bigger differences in minimum mean monthly recharges, and during the extremely dry periods there will be situations with practically no recharge into the lake.

According to the Aladin model data, during the 2071-2100 period (P2) some further deteriorations of water balance can be expected. There will be significant decrease in recharges to the Lake Vrana. On the level of the average annual recharge decrease expected is about 28.2%, while for the minimum mean annual recharges it can reach 67.2%. The differences in minimum mean monthly recharge will be even bigger, and situations with no recharge will happen much often.

According to the data from model RegCM3 situation in the P2 should be more favorable. The average annual recharge practically will be the same as for relevant climate set P0, but the variations and range of values will be still very high. The minimum mean annual recharges could decrease up to 44% and there will be situations with practically no recharge into the lake.

8. Conclusions

The measurements to date of water temperatures in Lake Vrana on the island of Cres show that the thermodynamic cycle of the lake conforms to the characteristics of a medium depth lake in the moderate climate belt. The determined thermal stratification during the year as well as isothermal conditions at the end of winter confirm that the lake's environment is of monomictic nature. A marked thermal stratification of the water takes place in the period from June to August, while conditions of complete isothermy usually last from December to February. Thermal conditions in the lake are under a significant influence of local climate characteristics at both seasonal and annual levels. The epilimnic area in the warm part of the year heats up to approximately 25 ºC. At the same time, deeper water layers (hypolimnium) retain very low water temperatures in the range from 6.5 ºC to 9.3 ºC. Temperatures of the lake's water in the isothermal period directly depend on the winter period characteristics. The minimum values measured to date range from 4.65 ºC to 7.9 ºC.

The measurements conducted in boreholes at the eastern bank of the lake showed that it is surrounded by a karst aquifer in which groundwater temperatures range from 14.6 ºC to 13.1 ºC, and which has a clearly evident reverse geothermal gradient. The occurrence of a drop in groundwater temperatures according to the depth can be explained by the impact of constantly cold deep lake water.

The available data from past measurements, although they are a good illustration of the influence of seasonal climate on the state of lake water, are by no means an indicator of the impact of global climate changes, since data are insufficient and temporally far apart.

According to the measurement data from the period 1951-2009 an increase in the mean annual air temperature of 0.1 °C per decade is present since 1951 and it is amplified within the recent shorter periods (up to 0.4 °C/10 yrs in period 1981-2009). Present and future climate simulations using three limited area models were analyzed (Aladin, Promes and RegCM3), and they pointed out further air temperature increase in range of 0.27 °C/10 yrs to 0.32 °C/10 yrs. The changes of precipitation rates are more variable and quite uncertain.

Based on the results of applied climate models, the impact of possible climate changes on the lake recharge was analyzed. The strongest impact of climate changes can be expected based on Aladin model input data, especially for the period 2071-2100 when the average annual recharge decrease will be about 28.2%, while for the minimum mean annual recharges it can reach 67.2%.

Considering increasing water consumption from the lake, already asserted negative trends, indicated climate changes and possible effects on the lake recharge, it is necessary to establish continual monitoring of parameters that describe lake system behaviour, and periodically analyze lake conditions, especially with respect to the extraction for the public water supply.

Acknowledgments

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