HYDROLOGY OF THE GRADOLE KARST SPRING (ISTRIA - CROATIA)

HIDROLOGIJA KRAŠKEGA IZVIRA GRADOLE (ISTRA - HRVAŠKA)

OGNJEN BONACCI

Izvleček

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Ognjen Bonacci: Hidrologija kraškega izvira Gradole (Istra - Hrvaška)

Prispevek predstavlja rezultate hidroloških analiz izvira Gradole. Glavni namen raziskav je bil določiti meje in obseg zbirnega področja, da bi lahko zavarovali kakovost vode. Podzemeljska razvodnica je določena z geološkimi in hidrogeološkimi metodami. Za kontrolo je bila uporabljena analiza vodne bilance. Obseg zbirnega območja je bil določen na 104 km^2. Voda izvira Gradole se uporablja kot vir pitne vode. Pretok izvira je omejen in ne presega 12 m^3/s. Višek vode priteka na površje skozi občasne izvire v soseščini. Minimalni, srednji in maksimalni pretoki 1987-1992 so: 0.28 m^3/s, 1.8 m^3/s, 8.68 m^3/s. Napravljen je bil poizkus, da bi v suši dodatno napolnili kraški podzemeljski vodonosnik.

Ključne besede: kraška hidrologija, kraški izvir, Hrvaška, Istra, Gradole

Abstract

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Ognjen Bonacci: Hydrology of the Gradole karst spring (Istria - Croatia)

The paper discusses the results of a hydrologic analysis of the Gradole karst spring. The main goal of the investigations was the determination of the catchment boundaries and area in order to protect the spring water quality. The underground watershed has been determined by geologic and hydrogeologic methods. The control used was the hydrologic water budget analysis. The catchment of Gradole spring is defined as 104 km^2. The Gradole spring water is used as a drinking water supply. The capacity of the spring is limited and does not exceed 12 m^3/s. All discharges which exceed this amount flow to the surface through other intermittent springs in the vicinity. Minimum, average and maximum discharges in the 1987-1992 period are: 0.28 m^3/s, 1.8 m^3/s, 8.68 m^3/s respectively. In dry period an attempt to recharge the karst underground aquifer was made.

Key words: karst hydrology, karst spring, Croatia, Istria, Gradole

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INTRODUCTION

The Gradole karst spring is located in the northern part of the Istria peninsula (Fig. 1) in Croatia. It is an ascending or vauclusian karst spring (Flandrin and Paloc, 1969; Bögli, 1980; Bonacci, 1987; Bonacci and Magdalenić, 1993). Since 1973, the water from the main Gradole spring has been used as a water supply. The water demand in this area is increasing due to the intensive development of tourism. Human activities in the catchment area have increased which has resulted in serious pollution threats to the present high quality of the groundwater. Consequently it has been necessary to carry out investigation to define the catchment area and its boundaries.

The Gradole spring belongs to a group of karst springs with limited outflow capacity (Bonacci and Magdalenić, 1993). These springs have a maximum discharge limited by the dimensions of karst conduits, especially their exits. Therefore, a few temporary karst springs generally appear immediately after heavy rainfall which causes a sudden increase in the groundwater levels in the catchment. At least two of these springs have been found in the vicinity of the Gradole spring. Their hydrologic hydrogeologic function is to accept the excess discharge of the main Gradole spring during a short period with high and sharp flood hydrographs. It has been stated that these temporary karst springs appear when the outflow discharge exceeds 6 m^3/s, which occurs once in five years.

There are no permanent open streamflows in the Gradole spring catchment. Intensive rainfall is followed by the short-lasting flows whose water quickly sinks underground through the large karst fissures. The average elevation of the catchment is 330 m a. s. l., and the opening of the Gradole spring is at 4.6 m a. s. l. The inflow to the spring is formed exclusively by underground water circulation through a karst aquifer.

The whole hydrological analysis performed in this paper is based upon data on the discharge measurements carried out during a six-year period from 1987-1992. The available data refer to the rainfall measurements carried out in the immediate vicinity of the catchment from 1949-1992, the water temperature measurements from 1957 to 1962, and the air temperature measurements from 1950-1992. The study also includes data on pumping and quality of drinking water from 1980-1992.

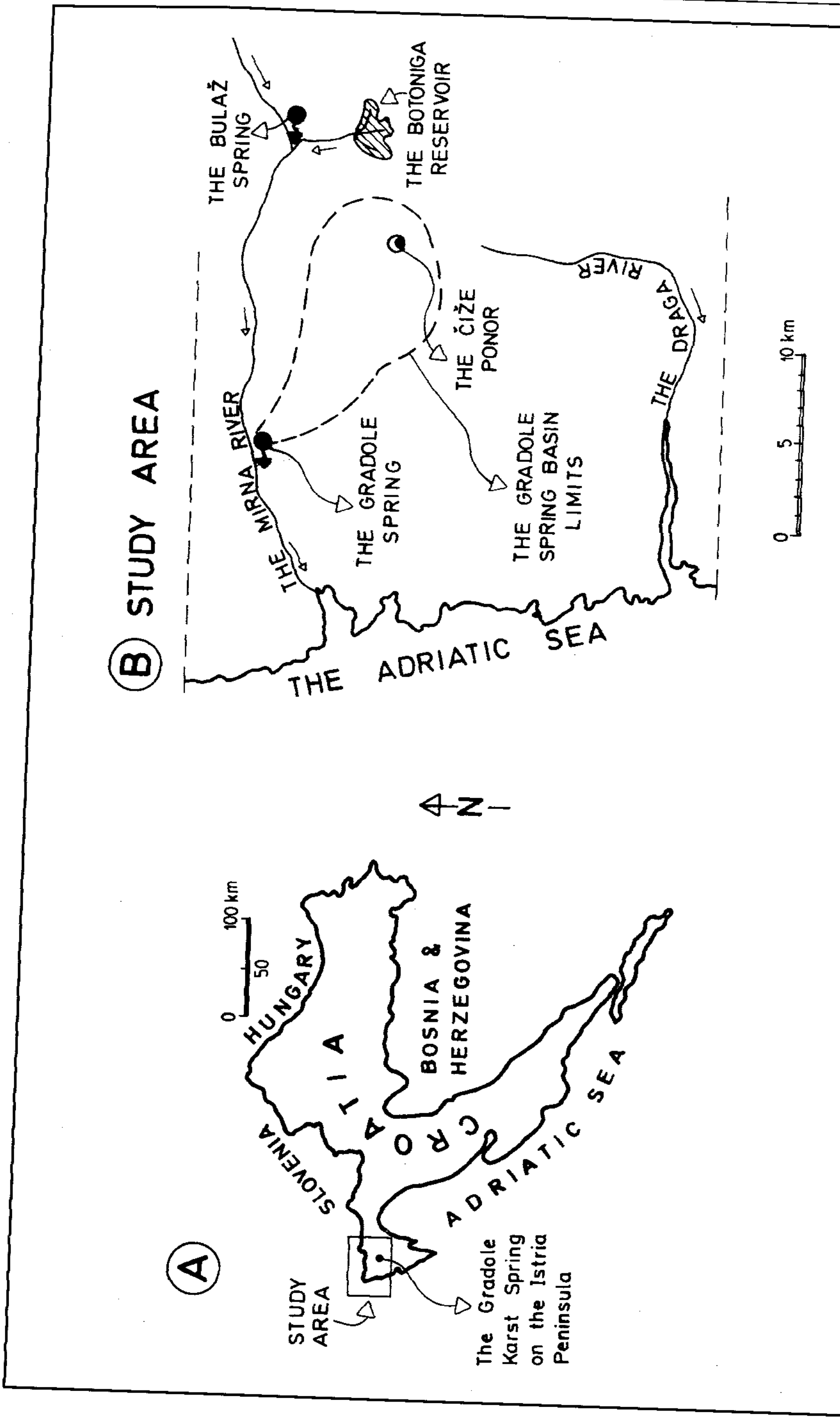

Figure 1 LOCATIONS MAPS

GEOLOGY, HYDROGEOLOGY, CLIMATOLOGY AND WATER TEMPERATURE

The Gradole spring catchment is mainly formed of carbonate rocks and partly of impermeable flysch (Magdalenić and Bonacci, 1993). The carbonate layers differ in age, lithological composition, bedding and in their structural-tectonic position. A great number of the faults, fissures, sinkholes and shafts exist in the carbonate layers which are very permeable to water. The main direction of circulation is SE-NW, towards the Mirna river (Fig. 1b) which corresponds to the direction of the structures and main fault systems.

The number of sinkholes varies within the boundaries of the catchment. It is estimated there are on average 20 sinkholes per square kilometer. Tracings of the Čiže ponor (Fig. 1b), on several occasion during low and high ground water levels, have proved that this ponor is directly connected to the Gradole spring. The ponor is 14.5 km from the spring. Various types of tracers thrown into the Čiže ponor appeared at the Gradole spring with 92 % to 100 % of the initial quantity. The velocity of the tracer ranged from 0.33 cm/s is the dry period to 3 cm/s in the wet period (Magdalenić, 1988). The time necessary for the tracer to reach the spring in the wet period, when the aquifer was saturated, was from 10 to 18 days, and in the dry period through the unsaturated aquifer it took the tracer about 90 days to travel to the spring. By geologic and hydrogeologic analyses it was possible to determine that the catchment area of the Gradole spring covers 104 km^2. About 85 km^2 is covered by carbonate rocks and 19 km^2 by flysch layers (18 % of the entire area).

The climate of the catchment is North Mediterranean. The average annual temperature is 11.1°C with a minimum daily average temperature in December-February period of -2°C and a maximum average temperature in July and August of 30°C. There are six pluviographs in the vicinity of the catchment. The annual rainfall in the period from 1949-1992 ranged from a minimum of 769 mm in 1956 to a maximum of 1569 mm in 1960. The average annual rainfall is 1132 mm. The maximum rainfall occurs in November and the minimum in July.

The water temperature of the main Gradole spring varies from 11.6 to 15.2°C. The extreme air temperature range in this region is 40°C. Since the water temperature in the spring varies around 3.6°C it is evident that air temperature affects the water temperature very little or only indirectly. This is consistent with the idea that the groundwater in karst underground conduits is retained for a long period of time.

At the Gradole spring it is possible to monitor the quality of the untreated and treated water (Buttignoni, 1990). The water turbidity ranges from 10 to 2000 NTU. The pH value varies from 7.2 to 7.3 and in the rainy period is reaches 8. The total hardness ranges from 17.4 to 19.6 dH. Chlorides vary from 10 to 28 mg/l Cl and sulphates from 8 to 43 mg/l SO_3. The water is transparent during the great part of the year and it is very turbid only during short periods after abundant and intensive rainfall.

HYDROLOGIC ANALYSIS

Table 1 presents the characteristic discharges measured at the Gradole spring. The ratio between the minimum and maximum annual discharges ranges from 1 : 9.9 to 1 : 22.3, which confirms that it is a karst spring with a balanced hydrologic regime. This balance can be explained by the fact that the volume of the underground karst aquifer is large in comparison to the catchment area.

Ord. numb.	Year	Q [m^3/s]	Q_{min} [m^3/s]	Q_{max} [m^3/s]	Q_{min} : Q : Q_{max}
1.	1987	1.87	0.45	5.92	1 : 4.16 : 13.2
2.	1988	2.15	0.45	5.61	1 : 4.78 : 12.5
3.	1989	1.21	0.28	4.50	1 : 4.32 : 16.1
4.	1990	1.45	0.51	5.05	1 : 2.84 : 9.90
5.	1991	1.93	0.39	8.68	1 : 4.95 : 22.3
6.	1992	2.18	0.43	6.15	1 : 5.07 : 14.3
7.	Average	1.80	0.42	5.99	1 : 4.29 : 14.3

Table 1: Characteristic Discharges of the Gradole Spring.

Further analysis includes the study of the increase in the discharge hydrographs (ΔQ) caused by rainfall (P) in the spring Gradole catchment. Figure 2 gives a graphical presentation of this relationship for the 1987-1992 period. It can be seen that the intersection of the line $\Delta Q = a + b \times P$ with the x axis is $P_0 = 12$ mm which suggests that rainfall below this quantity does not lead to an increase in the spring discharges. Generally a rainfall quantity below 12 mm (up to 50 mm in dry period) is evidently retained underground in the karst. Assuming that the catchment is 104 km^2 the total volume which can be retained in the karst aquifer, in average conditions, is estimated to range from 1.3 x 10 m^3 to 5.2 x 10 m^3.

The lowest measured discharge was 0.28 m^3/s. It occurred on February 26-27/1989, after an eight-month drought with only 30 % of the average rainfall. It should be noted that there was no rain during eighty days in the period

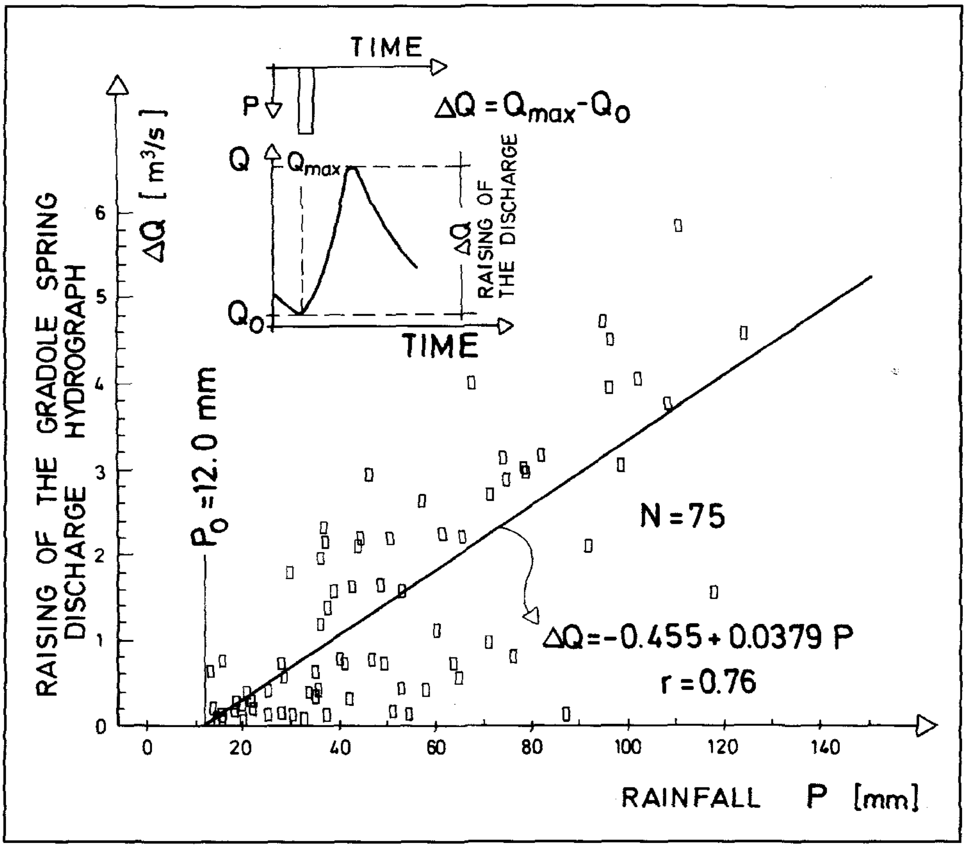

Fig. 2: Raising of the Gradole spring discharge hydrograph ΔQ versus rainfall P in 1987-1992 period

from December 1988 to February 1989. Considering the drought intensity and that these low water discharges appeared in the winter period, which is otherwise wet, the discharge of 0.28 m^3/s can be regarded as close to the absolute minimum. It is probable that the low water levels of the Gradole spring hardly can go below 0.25 m^3/s.

In order to satisfy the water supply demand it is necessary to ensure a quantity of 1.00 m^3/s, particularly in the dry summer period during the tourist season. Table 2 presents the values of the minimum discharges Q_{min} for each month from 1987-1992 and the average number of days N with discharges lower than 1.00 m^3/s.

It can be concluded that the greatest problem in the water supply occurs in August at the peak of the tourist season. Therefore a pipeline 17 km long has been built which delivers untreated water from the Bulaž spring to the Gradole spring where it is pumped and chemically treated. In addition, water was delivered twice to the Čiže ponor from the Butoniga reservoir through the component pipeline about 3 km long. Figure 1 shows all these springs, ponors and reservoirs. Bonacci (1992) described the effects of recharging the karst aquifer of the Gradole spring by delivering water to the Čiže ponor.

Month	Q_{min} [m³/s]	N [day/month]
Jan.	0.33	10.0
Feb.	0.28	6.7
Mar.	0.77	4.8
Apr.	0.97	0.16
May	0.72	2.2
Jun.	0.67	7.0
Jul.	0.72	12.8
Aug.	0.52	20.5
Sep.	0.46	20.0
Oct.	0.43	17.5
Nov.	0.39	9.2
Dec.	0.45	5.16
Year	0.28	116.0 day/year

Table 2: Minimum Discharges of the Gradole Spring per Month Q and the Average Number of Days N per Month with a Discharge Lower than 1000 l/s. Measured from 1987 to 1992.

The available hydrometric data measured during a six year period did not make it possible to draw detailed and reliable conclusions related to the high water levels of the Gradole spring. It was mentioned in the introduction that this spring belongs to a group of karst springs with a limited maximum outflow capacity. Such springs are frequent in the Dinaric karst. The maximum annual discharges ranged from 4.5 m^3/s in 1989 to 8.68 m^3/s in 1991. These maximum discharges are too low for a catchment covering an area of 104 km^2 and for the rainfall in that area. For example the maximum discharge at the Bulaž spring, with an area of 105 km^2, reaches 40 m^3/s. The catchment of the Bulaž spring is only 15 km from the Gradole spring so that their climatic and geologic characteristic are almost identical. The only significant difference is that the Bulaž spring does not belong to springs with limited outflow capacity. The dimensions of its outflow opening (exit) do not represent an obstacle for releasing the greatest discharges caused by heavy rainfall in the catchment. Consequently, there are no temporary springs in the vicinity of the Bulaž spring, whereas there are at least two of these springs located near the Gradole spring. Their discharges cannot be measured at high water levels since the entire area is flooded during that period 1987-1990. In 1991 they appeared only briefly and the water volume discharged through them is estimated to be about 1 % of the total annual volume of the Gradole spring. In 1992 the water volume released from the temporary springs did not exceed 5 % of the total annual volume of the Gradole spring.

A simple and approximate hydrological approach was used in an attempt to determine the catchment area of the Gradole spring since a lot of necessary hydrologic data were not sufficient. A catchment area defined in this way must either confirm or question a catchment area defined by geologic and hydrogeologic analyses. Srebrenović (1970) and Bonacci (1988) used regional analyses, proving that the average annual runoff coefficient for flysch is 0.35 and for carbonate rocks 0.6. Considering the previously mentioned sections of the Gradole catchment area, it can be stated that its average runoff coefficient is:

$$\bar{\alpha} = 0.35 \times 0.18 + 0.60 \times 0.82 = 0.555$$

The average annual rainfall in the Gradole spring catchment in the 1987-1992 period was P = 941 mm and the average annual discharge in the same period was Q = 1.8 m^3/s. Using the expression for the runoff coefficient which is:

$$\bar{\alpha} = \frac{\bar{Q}}{(\bar{P}xA/t)}$$

where A expresses the catchment area and t the time of one year duration. When the expression is derived in the function of the catchment area A expressed in km^2, and after all units have been brought into accordance, by introducing the previously stated values for rainfall P and measured discharge Q, the following catchment area can be defined:

$$A = \frac{1.8x(86400x365)}{0.941x0.555x1000^2} = 108.7km^2$$

This value confirms the value defined by geologic and hydrogeologic analyses. It can be stated that hydrologic analysis confirmed the results obtained by geologic and hydrogeologic investigations.

CONCLUSIONS

The Gradole spring is a karst spring with a limited outflow capacity. Springs with similar discharge characteristics are frequently found in the Dinaric karst. The limited capacity results from the dimension of the outflow karst conduit. Consequently, intensive rainfall in the vicinity of the Gradole spring is followed by the appearance of several temporary springs. Hydrologic analyses have been performed over a relatively short (six-year) period between 1987-1992. Due to the short measurement period certain data, particularly those related to extremely dry or wet conditions are not sufficiently reliable. This refers in particular to the maximum discharges of the Gradole spring. The highest measured discharge was 8.68 m^3/s. It is assumed that in the most extreme conditions the discharges can reach 12 m^3/s and that this value can hardly be exceeded. The minimum discharge which occurred in February 1989, i. e. 0.28 m^3/s, is probably close to the absolute minimum.

The ratio between the minimum, average and maximum discharges ranges from 1 : 2.84 : 9.9 to 1 : 5.07 : 22.3 which confirms the large capacity of the karst aquifer of the Gradole spring.

The catchment area determined using geologic and hydrogeologic investigations (A = 104 km^2) was confirmed by simple and approximate hydrologic computation (A = 108.7 km^2).

The water supply demand during the tourist season amounts to 1000 l/s. In the warm period of the year, i. e. in the tourist season from July to September, the number of days with discharges smaller than 1000 l/s is greater than in any other time of the year, and it ranges from 12.8 to 20.5 days per month. The water shortage during those periods is solved by delivering water from the Bulaž spring to the Gradole spring and from the Butoniga reservoir to the Čiže ponor.

REFERENCES

Bögli, A., 1980: Karst Hydrology and Physical Speleology.- Springer Verlag. 284 pp.

Bonacci, O., 1987: Karst Hydrology.- Springer Verlag. 184 pp.

Bonacci, O., 1988: Determination of the catchment areas in karst.- In: Karst hydrogeology and Karst Environmental Protection (Proc. IAHS 21 st. Congress, Guillin, China, October 1988) V. 2, IAHS Publ. no 176, 606-611.

Bonacci, O., 1992: Relation between karst hydrology and water tracing.- In: H. Hötzl and A. Werner (eds.) Tracer Hydrology. A. A. Balkema, 227-232.

Bonacci, O. and Magdalenić, A., 1993: The catchment area of the Sv. Ivan karst spring in Istria (Croatia).- Ground Water 31 (5), 767-773.

Buttignoni, V., 1990: Kvaliteta vode izvora i bunara Istre u razdoblju 1981-

1990 (Water quality of springs and wells in Istria in period 1981-1990).- Pula, Croatia, Case Study, unpublished.

Flandrin, J. and Paloc, H., 1969: Etude d'une source de karst: la fontaine de Vaucluse (France).- 5 Int. Kongr. Speläol. Stuttgart. Abh. 5, Hy 13, 1-15.

Magdalenić, A., 1988: Hidrogeološka istraživanja trasiranja ponora Čiže u Istri (Hydrogeological interpretation of tracing Čiže ponor in Istria).- Zagreb, Croatia, Case Study, unpublished.

Magdalenić, A. and Bonacci, O., 1993: Sliv izvora Gradole u Istri - zone sanitarne zaštite (Catchment area of spring Gradole in Istria - zone of sanitary protection).- Zagreb, Croatia, Case Study, unpublished.

Srebrenović, D., 1970: Problemi Velikih Voda (Analysis of Flood Events).- Školska knjiga, Zagreb, 320 pp.

HIDROLOGIJA KRAŠKEGA IZVIRA GRADOLE (ISTRA - HRVAŠKA)

Povzetek

Gradole je kraški izvir z omejenim pretokom. Izviri s podobnimi pretočnimi značilnostmi so v dinarskem krasu pogosti. Zaradi dimenzij kraškega prevodnika so količine pretoka omejene. Zato se po intenzivnih padavinah v okolici Gradol pojavi več občasnih izvirov. Hidrološka opazovanja so potekala razmeroma kratek čas (6 let), 1987 - 1992. Zaradi kratkega časa opazovanj so nekateri podatki, predvsem tisti, vezani na izredno sušo ali izredno namočeno leto, nezanesljivi. To se nanaša predvsem na maksimalne pretoke Gradol. Največji izmerjeni pretok je bil 8.68 m^3/s. Domnevamo, da se v izjemnih razmerah ta količina lahko poveča na 12 m^3/s, ta vrednost pa najbrž ne more biti presežena. Minimalni pretok je bil februarja 1989, 0.28 m^3/s, kar je najbrž blizu absolutnega minimuma.

Razmerje med minimalnimi, srednjimi in maksimalnimi pretoki je med 1 : 2.84 : 9.9 in 1 : 5.07 : 22.3, kar potrjuje velike kapacitete kraškega vodonosnika, ki napaja izvir Gradole.

Z geološkimi in hidrogeološkimi raziskavami določeno zaledje (A = 104 km^2) je bilo potrjeno s približnim hidrološkim izračunom (A = 108.7 km^2).

Med turistično sezono je potreba po vodi okoli 1000 l/s. V toplem letnem času, to je v turistični sezoni od julija do septembra, je število dni s pretokom pod 1000 l/s večje, kot v drugem delu leta in sicer med 12.8 do 20.5 dni na mesec. Pomanjkanje vode v tem času rešujejo tako, da v Gradole dovajajo vodo iz izvira Bulaž, iz rezervoarja Butoniga v ponor Čiže.