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Spatio-temporal distribution of discharges in the Radovna River valley at low water conditions

Prostorsko-časovna porazdelitev pretokov v dolini reke Radovne v obdobju nizkih vod

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Abstract

The Radovna River is a 19.4 km long river located in the north-western part of Slovenia, which runs almost entirely over the area of Triglav National Park. The bottom of the valley is filled with fluvioglacial sediments, which represent an unconfined aquifer with karst aquifers in the recharge area consisting of carbonate rocks of the Triassic age. The Radovna River has only few short stream tributaries, which are recharged from the karstic springs. Therefore, the Radovna River is groundwater dominated river. Within this study, simultaneous measurements of discharge were performed. Discharge and electrical conductivity (EC) were shown to increase downstream. In low water conditions, the average increase in discharge was from 88 $l/s\ km^{-1}$ to 287 $l/s\ km^{-1}$.

Izvleček

Reka Radovna je 19,4 km dolga reka v severozahodni Sloveniji, ki skoraj v celoti teče po območju Triglavskega narodnega parka. Njeno dolino tvorijo fluvioglacialni sedimenti, ki predstavljajo odprt vodonosnik, zaledje pa tvorijo kraški vodonosniki v triasnih karbonatnih kamninah. Reka ima le nekaj kratkih pritokov, ki jih napajajo kraški izviri, zaradi tega je pretežno pod vplivom podzemne vode. V okviru raziskav so bile izvedene večkratne simultane meritve pretokov, s katerimi je bilo ugotovljeno, da pretok in elektroprevodnost naraščata vzdolž toka. V obdobju nizkih vod znaša povprečni prirastek pretoka od 88 $l/s\ km^{-1}$ do 287 $l/s\ km^{-1}$.

Introduction

In Slovenia, most of the drinking water comes from groundwater resources. Although the Radovna River is not a large river, groundwater from its alluvium already supplies three large communities in NW Slovenia: Bled, Gorje and Radovljica. It is important to understand the hydrogeological conditions in the Radovna River valley and its recharge area. Firstly, because potential water reserves are much greater than used today (Marinko, 1978; Internet 2), and secondly, because the valley is positioned in the Triglav National Park, representing an important natural treasure.

The purpose of the present study is to describe hydrogeological phenomena and conditions in the Radovna River. In parallel, the spatial distribution of discharges in low water conditions along the river course. It is hypothesised that, in low water conditions, only groundwater outflow is presented in the Radovna riverbed, and with the methods applied, possible spatial relations between various contributions to the river flow can be interpreted. During 2006, 2008 and 2009, discharge and electrical conductivity (EC) were measured at several locations along the river.

General settings

The Radovna River is, in large part, an Alpine river positioned in a narrow glacial valley with steep slopes. The bottom of the valley is filled with alluvial and glacial material. The river flows between the karstified mountainous plateaus of Pokljuka in the south and Mežakla in the north, both of which are covered by forests (Fig. 1). Pokljuka is a 20 km long plateau with an altitude of between 1000 and 1400 m a.s.l., with the highest point at 1630 m a.s.l. The Mežakla plateau is surrounded by two rivers: the Sava Dolinka River in the north and the Radovna River in the south. The altitude of the plateau is approximately 1200 m a.s.l., with the highest point at 1593 metres. The total width of the Radovna River valley is between 300 and 350 metres. The narrowest part is the Vintgar gorge, which is located in the lower part of the valley and is surrounded by two hills: Hom (834 m) and Boršt (931 m). The river's terminal springs are positioned in Zgornja Radovna. In the village of Moste, near Žirovnica, the river, after 19.4 km, converges with the Sava Dolinka River. In the valley, only a few stream tributaries are present; all of which are short, and nearly all are supplied by karstic springs. From south of village Zgornje Gorje, small stream Buden is coming from the dolomite aquifer and in the watershed of Rečica part of water is coming from the Obranca area where also dolomite aquifer is present. North of Rečica is the Poljane valley, which does not have significant surface water flow. All water sinks into the sediments on the valley floor; even after a heavy rain, water does not reach Rečica. Between Spodnja Radovna and the Grabče gorge, Ribščica is also present, where water only flows after heavy rain. It has been estimated that the balance contribution of these creeks during periods of low water is negligible.

Along the valley, several factors indicate that the Radovna River is a groundwater dominated river; in all cases, the groundwater level on the banks is higher than the water level in the river. In the upper part of the valley, Kreda, an artificial lake representing a former chalk pit, is present. During exploitation, two separate layers of gravel were open from where groundwater flowed into the pit: the water level in the lake was higher than in Radovna. In Srednja Radovna, in two artesian boreholes (downstream from RMP-4), the hydraulic head is higher than the water level in the Radovna River. The last indicator is the drainage gallery in Ovčja jama, in which the water level is again higher than in the Radovna. Streams dominated by groundwater can be indicated by other factors, including a stable flow regime and stable water temperature (Sear et al, 1999).

The upper part of the Radovna River valley continues further to two Alpine glacial valleys, Kot and Krma, with occasional streams Kotarica and Krmarica. Both valleys are filled with highly permeable gravel. Precipitation in this area infiltrates and recharges groundwater; therefore, no surface springs and streams are present. Springs and torrential water in the streambeds occur only after prolonged periods of rain.

In various parts of the valley, several geological and hydrogeological investigations were conducted. However, almost no results were published, but all data are available in the archive of the Geological Survey of Slovenia. In 1961, the first geological mapping was conducted for chalk exploitation in Srednja Radovna (Jamšek, 1969). In 1977 and 1987, geological mapping was performed in the same region for the preparation

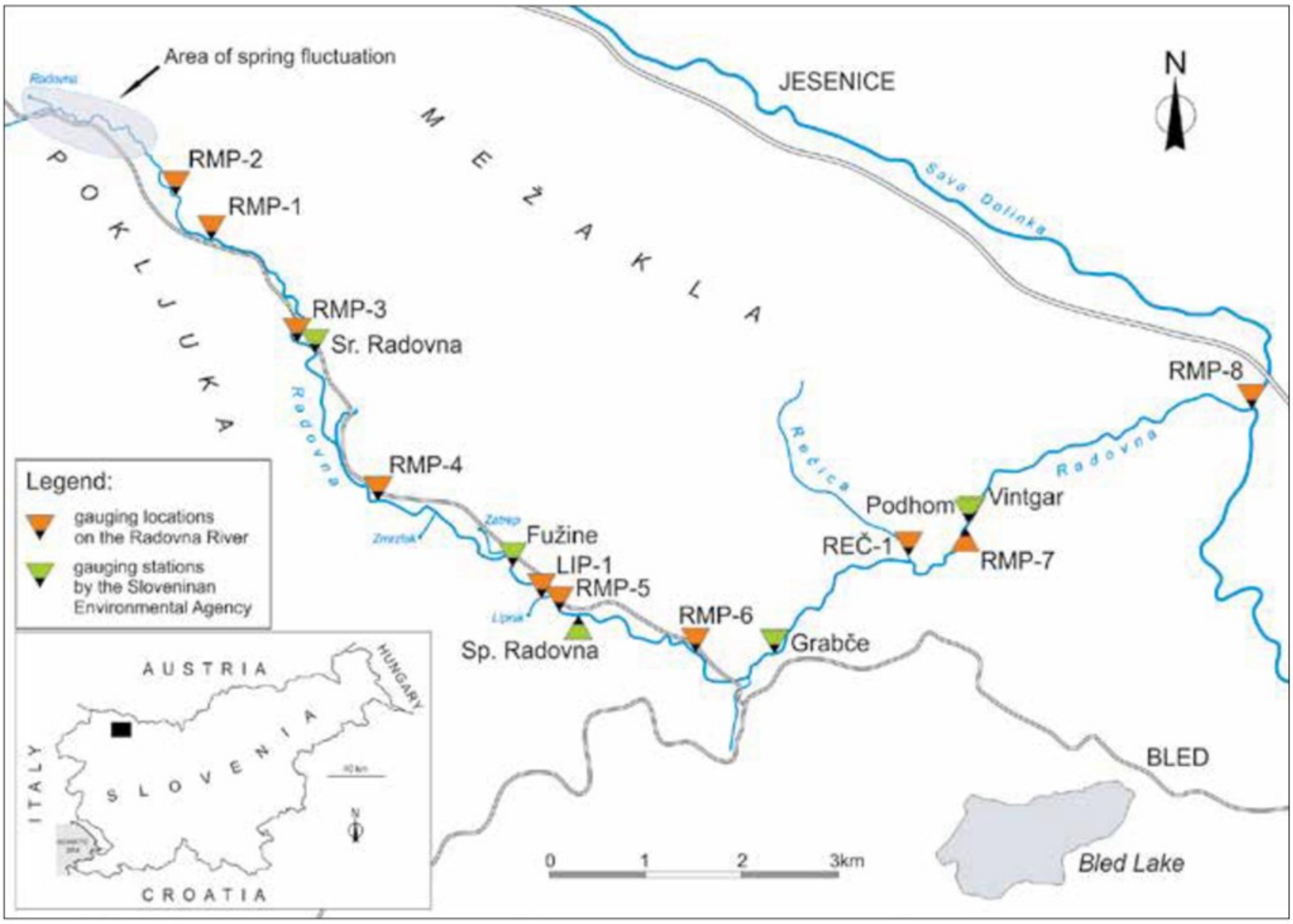

Fig. 1. Geographical map of the area with gauging locations.
Sl. 1. Geografska karta območja z lokacijami merskih točk.

of state geological maps: sheets Celovec and Beljak - Ponteba (Buser, 1980; Jurkovšek, 1987). In 1975, hydrogeological and geomechanical investigations were carried out in the region between Zgornja Radovna and Gabrje for a high-dam construction waterstorage reservoir (Drobne, 1975); however, construction never began. In 1978, hydrogeological investigations were performed south-east of Srednja Radovna (Ovčja jama) for planning and designing a deep-drainage for water supply (Marinko, 1978). In parallel, engineering geology was performed along the pipeline route (Marinko & Andrič, 1978). After the capture zone, the Ovčja jama was constructed and in 1984, detailed hydrogeological mapping was done for the design of groundwater protection zones (Rogelj, 1984). Recent studies in the Radovna River valley refer to the stable isotope composition of three karstic springs (Kanduč et al, 2012) and to the impact of iron ore processing activity in Srednja Radovna (Ferjan Stanič et al, 2013). In addition, the hydrogeology of spring Zmrzlek was investigated (Serianz, 2013).

Geological settings

Wider area of the Radovna River valley is comprised of Triassic, Tertiary and Quaternary rocks and sediments. Lower Triassic marl, marlstone, oolite, grained limestone, mica dolomite and silt are positioned in the eastern part of the Mežakla plateau. Anisian strata located in the north-eastern part of the Mežakla plateau are represented as light grey and thick stratified massive reef limestone, which is deposited on stratified dolomite. There exists an Anisian-Ladinian rock outcrop on the southern slope of Mežakla near the village of Srednja Radovna, in which dolomite prevails; the rocks are different colours and vary from dark and olive grey to brown and slightly pink. Ladinian rocks are positioned in the eastern part of Pokljuka and Mežakla, represented as light and brownish grey platy and stratified micritic limestone with chert. Numerous patches of volcanic rock are present on the Pokljuka plateau; however, their frequency is higher in the east than in the west. A large portion of the Carnian rock in both plateaus is represented as granular massive dolomites; among them, stratification is subordinate. Locally, dolomite, limestone and dolomitised limestone can also occur. Middle Oligocene layers are present south of the Žirovnica village, at the confluence of the Radovna and Sava Dolinka rivers. Beds are comprised of dark grey mica sandy silt, which transitions into clay.

Quaternary sediments occur in the bottom of the valley. In Srednja Radovna village, chalk deposited in the fluvioglacial lake is present and, in the past, it has been exploited. Chalk also outcrops in the north-western part of the valley, but it is mixed with sand. Unconsolidated fluvioglacial sediments are represented as gravel and sand and are only partly conglomerated. Moraines are separated according to the location where they occur: in the valley, on the slope and in the Pokljuka plateau. Moraines in the valley are homogeneous and are the result of accumulation due to glacial activity. Slope moraines occur on slopes of the Pokljuka plateau and are comprised of unsorted material, which is dominated by finer fractions with rare, round rocks of limestone. The youngest moraines are on the Pokljuka plateau and are represented as unconsolidated and unsorted grains: predominantly limestone. Flat heterogeneous alluvial deposits of the Holocene age are located along both banks of the stream in the central part of the valley. These deposits are covered with dark grey to black alluvial, containing a number of sharp-edged pieces of white and light grey Triassic limestone and dolomite (Buser, 1980; Jurkovšek, 1987).

The overall thickness of the Quaternary deposits is unknown, but only a few boreholes were made in the past along the valley, which can indicate the approximate thickness of the sediments. During the planning of a tourist centre in 1965, three boreholes were drilled in Krma valley, showing that the thickness of the glacial and alluvial deposits is at least 60 m (Žlebnik, 1966). Later between Srednja Radovna and Gabrje, in 1974, three boreholes were drilled for high-dam construction. The deepest borehole was 103 metres and did not reach the bottom of the valley (Drobne, 1975). Based on these data, we can conclude that, in the upper part of the Krma valley, the thickness of the sediment is at least 60 m and, in the central part of the valley, the thickness is greater than 100 m.

Hydrogeological settings

In the Radovna River valley and its recharge area, a combination of intergranular and karst aquifers is present. Intergranular aquifers are positioned at the bottom of the valley, while karst aquifers form valley slopes and a wider recharge area. In the valley, numerous springs are present. They can be classified into karstic springs, gravity (descending) springs, contact springs on the edge of moraines, seepage springs and diffuse springs from unconsolidated sediments (Kresic, 2010); some of which are present only during high water conditions.

The terminal spring of the river is positioned in Zgornja Radovna, in the area where the large and steep alluvial fan comes from the west and is in contact with the relatively flat fluvioglacial deposits of the river bottom in Gogala in the settlement of Zgornja Radovna. There are several diffuse springs with non-permanent positions. Because the alluvial fan is an unconfined aquifer, the groundwater table in the aquifer substantially fluctuates depending on precipitation and snowmelt infiltration. Consequently, the location of the springs moves up and down along the upper part of the valley.

In addition to the main terminal of the Radovna River spring, numerous springs are present in the valley; however, only two (Lipnik and Rečica) were investigated (Fig. 1). Springs appear throughout the valley, while short tributaries appear mainly in the central part of the valley. The recharge areas of all springs are in the karstic aquifers and are developed due to the contact between alluvial sediments in the central part of the valley and carbonate rocks on valley slopes. Due to the karstic nature of springs, their discharge fluctuates profoundly depending on the amount of precipitation and snowmelt infiltration. The following springs are positioned downstream from the terminal of the Radovna River springs on the north-west side. South of Mlinarjev rovt, the right-bank tributary is recharged by the karstic spring, Zmrzlek, where discharge substantially fluctuates and, thus, the position of the spring changes depending on hydrological conditions. Further downstream, on the left bank of the karstic spring, Zatrep is positioned. It is recharging in the area of Perniki. The next tributary is Lipnik, which is on the right bank, and is recharged from the karstic spring of the same name. Its recharge area is on Pokljuka plateau. The last tributary is the Rečica creek on the left bank, between Zgornje Laze and Poljane villages, flowing out from the south-eastern part of Mežakla plateau. The Rečica creek is supplied with several karstic springs.

Water intake structures

Several water intake structures for the capture and abstraction of water appear along the Radovna River. The structure that is furthest upstream is a small hydroelectric power plant (HPP), Klemenak, which has been in operation since 1993: it provides 40kW of power. This HPP diverts water from the riverbed. The Zmrzlek spodnji spring, which is positioned approximately 250 m downstream from the main Zmrzlek spring, is captured for water supply. Presently, water from this source is not used (Internet 2). Bellow Srednja Radovna is the Gorje HPP, which has been in operation since 1906 and is one of the oldest in Slovenia (Papler, 2004). The water is taken from the river at a nearby small dam and diverted to the HPP; during low water conditions between the intake structure and the outflow from the HPP (at a distance of 1000 m), the riverbed is occasionally completely dry, which profoundly influences the river's hydrologic regime. Further down the river at Ovčja jama on the left bank, a deep drainage reservoir for drinking water (with a capacity of 400 l/s) is positioned (Internet 2). In NW Slovenia, this is one of the most important water resources, as it supplies 14,500 inhabitants. In the village of Grabče, an intake structure on the right bank is positioned. The intake is intended to supply Bled Lake via tunnel transfer with fresh, aerated water. The tunnel was constructed between 1962 and 1964, and water transfer began in 1972. The tunnel has a transfer capacity of up to 2000 l/s (Podlipnik & Lukan, 1999). Until 1994, 200 l/s were transferred to the Bled Lake; later, the intake increased to 400 l/s (Remec-Rekar, 2004). In the village of Grabče, a small HPP (Mihova kovačnica, operating since 1990) is also positioned. The last water structure on the river is Vintgar HPP, which has been in operation since 1903; this is also one of the oldest HPPs in Slovenia (Remec-Rekar, 2004). Upstream from Vintgar HPP, a dam used for water capture is constructed. Beside the dam, there is a canal for water abstraction. Vintgar HPP abstracts most of the water from the river and transfers it downstream directly into the Sava Dolinka River at Zasip village. Consequently, the lower part Radovna River flows into the Sava Dolinka River only during high water conditions.

Methods and materials

Measuring sites and events

Discharge and EC of the river and spring water were measured at eight locations along the river and at tributaries. The locations on the river were named RMP-1 to RMP-8 (Fig. 1). At tributaries, measurements were made on Lipnik (LIP-1) and Rečica (REČ-1). Water coming out of the Gorje HPP in Srednja Radovna was also measured. For further interpretation, the discharges at locations RMP-5 and Gorje HPP were combined and used as one discharge. RMP-2 is the first location downstream from the main terminal spring (GKY 421837, GKX 142602). As the position of the main spring fluctuates substantially, the location was selected where the discharge is always present. RMP-1 is the next downstream location, which is situated where the otherwise braided riverbed becomes uniform. RMP-3 is situated after Kreda Lake. RMP-4 and RMP-5 are located before and after the lake, where most of the karstic springs discharge into the Radovna River. RMP-6 is located after Ovčja jama and before the Rečica flows into the Radovna River. RMP-7 is positioned before Vintgar gorge, where the maximum discharge in low flow conditions is measured. The last location, RMP-8, is located before the Radovna River discharges into the Sava Dolinka River.

Additional discharge data were provided by the Slovenian Environmental Agency. Measurements were performed daily at Podhom, which is positioned in front of the Vintgar gorge (GKY 430055, GKX 139215). The data gathered was from 1933–2013. For further interpretation, the average annual discharge of water flow was calculated.

Discharge measurements

The chemical integration method was used for discharge measurements in the Radovna valley. The method is based on the instantaneous injection of the tracer into the stream. The method is usually used for watercourses that have high velocities and uneven river bottoms (Boiten, 2008). As a tracer, kitchen salt was used. It is the most

Table 1. Discharge and electrical conductivity at gauging points.

Tabela 1. Pretok in elektroprevodnost na merskih točkah.

LOCATION	DATE	GKY	GKX	DISCHARGE (l/s)	ELECTRICAL CONDUCTIVITY (µS/cm)
RMP-2	3.2.2006	421837	142602	148	225
0 km	15.2.2008			408	225
	2.9.2008			1840	215
	16.3.2009			1100	209
RMP-1	1.2.2006	422188	142150	824	213
0,65 km	15.2.2008			1040	221
	2.9.2008			1580	218
	17.3.2009			1270	229
RMP-3	3.2.2006	423082	141082	554	224
2,40 km	15.2.2008			740	221
	2.9.2008			1720	222
	16.3.2009			1545	233
RMP-4	3.2.2006	423923	139420	857	228
6,96 km	14.2.2008			1440	229
	2.9.2008			2990	229
	16.3.2009			2010	240
RMP-5	3.2.2006	425832	138291	1221	286
7,04 km	14.2.2008			2052	283
	1.9.2008			3792	276
	17.3.2009			3596	287
RMP-6	2.2.2006	427249	137822	1010	246
8,77 km	14.2.2008			1815	242
	1.9.2008			2375	248
	17.3.2009			2240	259
RMP-7	2.2.2006	429975	138975	1510	256
12,68 km	14.2.2008			2760	252
	1.9.2008			4435	252
	17.3.2009			4600	271
RMP-8	2.2.2006	432988	140308	206	283
16,56 km	15.2.2008			40	283
	1.9.2008			32	276
LIP-1	1.2.2006	425635	138412	134	/
	15.2.2008			186	277
	1.9.2008			526	294
	16.3.2009			483	294
REČ-1	2.2.2006	429446	138863	64	374
	14.2.2008			146	289
	1.9.2008			108	352
	17.3.2009			443	330

commonly used tracer for this method because it is easily available, inexpensive, has good solubility and does little or no harm to animal life and flora in the water. Salt concentration was determined by the EC of, in our experiment, the Flo-Tracer of Flow-Tronic. Before each field campaign, the instrument was calibrated in the laboratory. A certain quantity of salt is injected at a point in the watercourse; then, downstream at a certain point, where the tracer has been sufficiently dispersed, the instrument is gauging the tracer cloud. The recommended quantity of salt is 2 to 12 g per 1 l/s (Internet 1). The salt quantity was chosen based on previous recommendations, the distance between the injection and gauging points, and according to the knowledge of the experienced technician who performed the measurements. The longer the distance, the bigger the tracer dilution and, as a result, the smaller the increase in salinity in the gauging area. Discharge calculations were based on the following expression (Boiten, 2008, Internet 1).

$$Q = \frac{m}{\int_{t_1}^{t_2} c(t)dt}$$

where Q is the flow to be determined, m is the mass of the tracer, t is the time, t_1 is the time at the beginning of the tracer's passage, t_2 is the time at the end of tracer's passage and c(t) is the time dependent tracer concentration.

Electrical conductivity

EC is a simple method for indirectly estimating the total dissolved solids in water. It is very often employed during filed hydrogeological mapping and is defined as the EC of one cubic centimetre of water at a constant water temperature of 25 °C. When the temperature increases by 1 °C, EC rises approximately 2 %. The international unit of EC is Si/cm (Todd & Mays, 2005), where Si is the Siemens unit. Measurements together with water temperature were performed with a WTW Multiline P3 instrument.

Results and discussion

Measurement campaigns were performed in February 2006, in February 2008, in September 2008 and in March 2009. Coordinates and distances of the measuring points from the terminal spring in the NW part of the valley are presented in Table 1. On all measurement campaigns, discharge was gauged at 11 locations, except in March 2009, when RMP-8 was not accessible due to weather conditions. EC was measured concomitantly at the same locations as the discharge. The spatial distributions of discharges and EC are plotted as curved lines (Figs. 2 and 4). To provide the representative discharge measurements at every location, discharges were measured twice, or, at some locations, three times. The average relative error was below 10 %; only at two locations was the error between 15 and 20 % (RMP-3 in February 2008 and RMP-5 in 2009). Representative discharge was calculated as an average. During the evaluation of measured values, the shape of the salt dilution breakthrough curve was verified.

In the past, at particular time intervals, discharges of the Radovna River were more closely monitored with several gauging stations. Overall, six gauging stations were in operation; however, their observation periods were different; Fužine (1953–1982), Grabče (1960–1982), Podhom (1933–current), Spodnja Radovna (1957–1966), Srednja

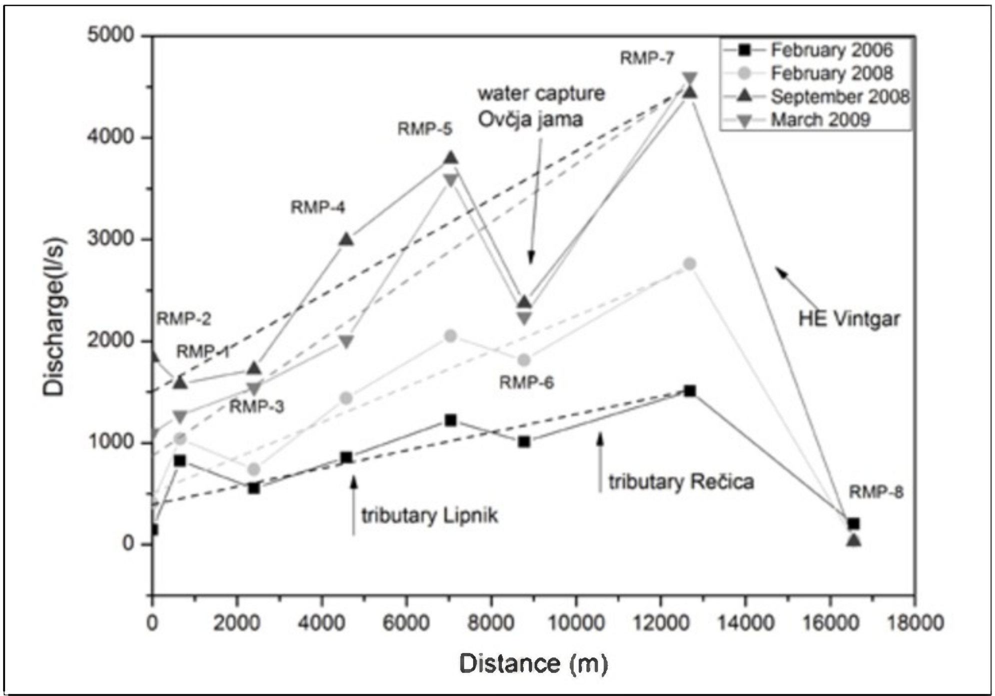

Fig. 2. Plot of discharge versus distance from the spring with trend lines.

Sl. 2. Diagram pretoka v odvisnosti od razdalje od izvira s trendnimi črtami.

Radovna (1952–1982) and Vintgar (1954–1966) (Fig. 1). Currently, the Podhom gauging station is the only station in operation, and we have applied only these data; others were statistically analysed elsewhere (Torkar, 2010). The average annual discharges for the Podhom gauging station were calculated and illustrated in Figure 3. The annual average discharge is between 5.1 m^3/s and 13.2 m^3/s, with one exception (in 1934, when the average annual discharge was 18.3 m^3/s) (Fig. 3). Lower annual average discharges are present after 1970, and are rarely above 10 m^3/s. A decrease in discharge could be attributed to the upstream construction of tunnels, which conduct fresh water to Lake Bled. Data in Figure 3 illustrate that measuring campaigns were performed during conditions that were lower than average.

Discharge measured in 2006 was between 148 l/s and 1510 l/s. In February 2008, discharge was between 40 l/s and 2760 l/s, and in September 2008, it was between 32 l/s and 3792 l/s. In the last campaign performed in March 2009, discharge was between 1100 l/s and 4600 l/s. During measuring campaigns, maximum discharges were not observed inside only one campaign. In September 2008, maximum discharges were measured at all points, except at RMP-7 and at RMP-8, which are positioned in the most distant part of the river valley (before the confluence with the Sava Dolinka River) (Table 1). In March 2009, maximum discharges were measured at points RMP-7 and RMP-8 (Table 1). Despite the difference between measuring campaigns, the relation

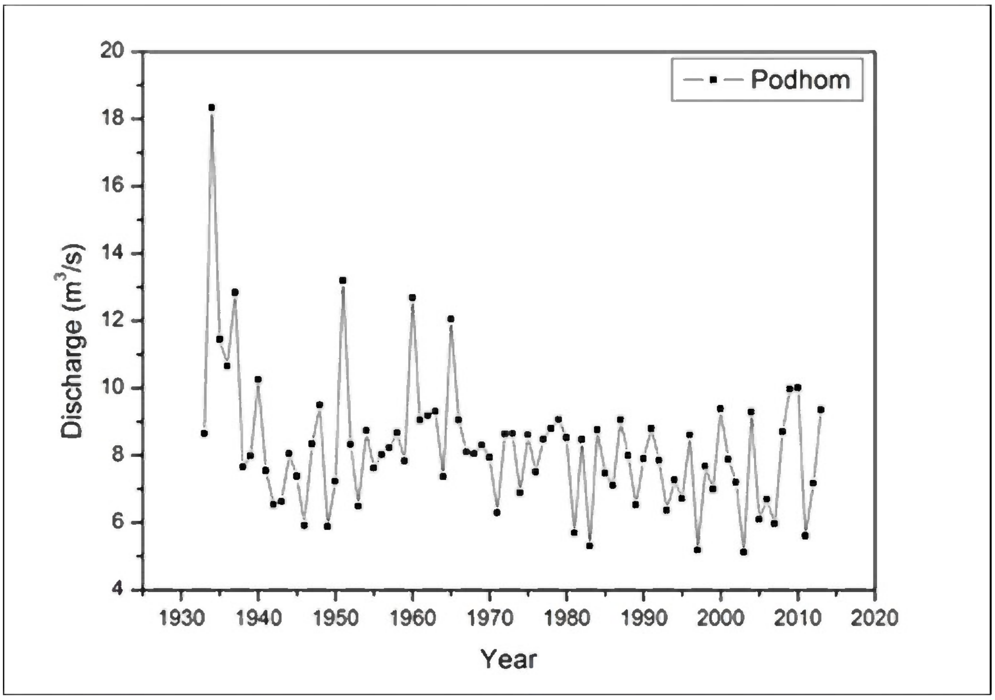

Fig. 3. Average yearly discharge at the location Podhom between 1933 and 2013.

Sl. 3. Povprečni letni pretoki za mersko mesto Podhom v letih od 1933 do 2013.

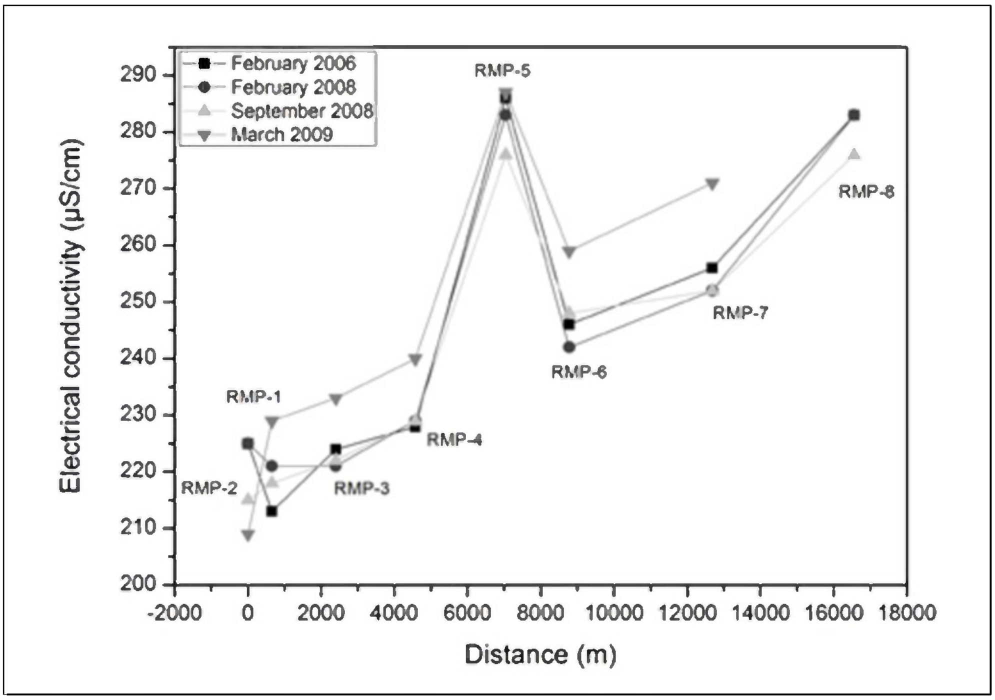

Fig. 4. Plot of electrical conductivity versus the distance from the spring.

Sl. 4. Diagram elektroprevodnosti v odvisnosti od razdalje od izvira.

between discharges measured at particular points and their spatial positions along the riverbed show similar behaviour (Fig. 2). The relative distances between measuring points are similar, but the differences between measurements at the particular measuring point for different sampling campaigns are more profound when high water conditions are present.

Along the river, an increase in discharges was expected and observed. Trend lines neglecting measuring points RMP-6 and RMP-8, representing a strong deviation from the trend, are calculated and illustrated in Figure 2. These trends indicate an average increase of discharge along the riverbed. In February 2006, the average discharge increase was 88 l/s km^{-1}; in February 2008, the discharge increase was 174 l/s km^{1}; in September 2008, the discharge increase was 237 l/s km^{-1}; and in March 2009, the discharge increase was 287 l/s km^{-1}. The diagram in Figure 2 indicates that the average discharge increase also specifies hydrological conditions along the river. In low water conditions is lower than at the higher conditions.

An increase in discharge is a consequence of direct inflows to the riverbed as well as of recharge from karstic springs from both sides of the valley. Discharges from the Lipnik tributary (LIP-1) were between 134 l/s and 526 l/s, and were between 64 l/s and 443 l/s from Rečica (REČ-1) (Table 1). Slight irregularities were observed at RMP-1, RMP-2 and RMP-3. In this part of the valley, a hyporheic flow is present. These differences can also be attributed to the changes in the riverbed due to the high spatial fluctuations of the terminal spring position and relatively braided riverbed where certain changes in riverbed morphology can occur over time.

During all four campaigns, a significant drop in discharges can be seen at RMP-6 and RMP-8. RMP-6 is positioned after Ovčja jama, where a large drinking water resource is positioned. It is expected that a certain amount of water is diverted from the riverbed by water abstraction from the drainage; consequently, a drop in the river discharge is expected. However, the drop in discharge in relatively high water conditions in September 2008 and March 2009 is too big to be attributed only to water abstraction. At this point, it is possible that certain discharge is flowing in the alluvial sediments parallel to the river course. Because the RMP-6 gauging profile river water flow is relatively idle, possible discharge differences can also be attributed to the applied discharge measuring method. The chemical integration method is most suitable for turbulent flows. At RMP-6, the water current slows, which does not favour the mixing of diluted salt. The large drop between RMP-7 and RMP-8 is due to water intake for the Vintgar HPP. From the diagram, it can be clearly seen that nearly all the water is taken from the riverbed, and water reaching the Sava Dolinka River via natural river flow is negligible compared to the discharge before the Vintgar HPP intake structure. Such conditions have substantial hydromorphological and ecological consequences, which, for the river flowing in the Triglav National Park, are unacceptable.

EC is an indicator of total dissolved solids and indirectly points to lithology in the recharge area, groundwater residence time in the aquifer and possible pollution. Higher EC occurs where water is in contact with more soluble minerals for longer periods. Measured EC is between 213 µS/cm and 287 µS/cm. EC values are not high due to carbonate lithology in the recharge area and indicate a very permeable aquifer with a low residence time. In general, EC increases along the river course. There is only one significant deviation from this trend: RMP-5. This is the observation point where the Lipnik tributary flows into the Radovna River and where discharge in the riverbed is relatively depleted due to water removed by the Gorje HPP. An increase in the EC of the Radovna River is due to the inflowing waters with higher ECs (e.g., Rečica); however, there could also be processes in the river water responsible for this trend, which remains to be investigated.

Conclusions

Discharge measurements at all four measuring campaigns on the Radovna River indicated their gradual increase along the riverbed. The average discharge increase was from 88 l/s km^{-1} to 287 l/s km^{-1} depending strongly on hydrological conditions. Due to the presence of several water intake structures along the valley, the increase was not regular, and significant drops in the discharge are present. An analysis of the EC indicated a monotone increase in the downstream direction and, consequently, low residence times in permeable intergranular and karstic aquifers recharging the river. In the upper part of the river, changes in the discharge trend were also consequences of the stream's hyporheic flow. With the lack of significant tributaries, it was evident that the flow of Radovna is mainly supplied by groundwater directly flowing into the riverbed.

With the results represented, we have illustrated the fact already known from the direct hydrogeological observations that Radovna River is groundwater dominated river. However, in the hydrology of the Radovna River, several questions remain. In the future, more precise discharge measurements along the river are needed for better understanding of groundwater and surface water exchange. The chemical integration method is suitable for use with the torrential flow in the upper part of the Radovna River, but is not precise enough for the lower part, where the water flow is slower and the riverbed is wider. There are also many questions related to the water balance of the river basin as a whole, as well as particular tributaries and karstic springs on the rim of the Radovna Valley.

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