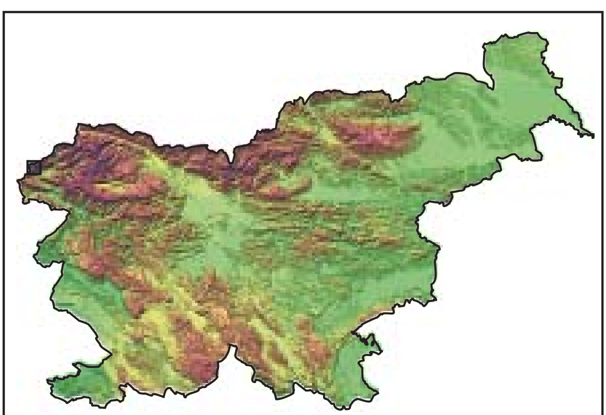
THE KARST SPRINGS OF THE KANIN MASSIF

KRAŠKI IZVIRI POD KANINSKIM POGORJEM

Blaž Komac

The Kanin massif from the Bovec Basin (photography Blaž Komac).
Kaninsko pogorje iz Bovške kotline (fotografija Blaž Komac).



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KEY WORDS: karst hydrology, karst springs, high mountain karst, Julian Alps, Bovec Basin, Kanin massif

In this article the author summarizes the geographical, hydrological, and geological studies of the Kanin massif done to date and on the basis of physical and chemical analyses of the water describes the basic geographical characteristics of the karst springs below the mountains. Using recession curve analysis, the extent of the Glijun spring catchment area has been determined.

Catchment areas, draining, and the location of a karst watershed depend on the quantity of water in the aquifer. Due to the overlapping of the catchment areas of various springs, the dumping of dangerous wastes in the high mountains can cause the pollution of many springs. Because the aquifers in the limestone and dolomite Kanin massif are closely linked to those in the Quaternary sediments of the Bovec Basin, protecting the high mountain karst also protects the sources of potable water in the valley.

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Kraški izviri pod Kaninskim pogorjem

KLJUČNE BESEDE: kraška hidrologija, kraški izviri, visokogorski kras, Julijske Alpe, Bovška kotlina, Kaninsko pogorje

Avtor v članku povzema dosedanje geografske, hidrološke in geološke raziskave Kaninskega pogorja, ter na podlagi fizikalnih in kemičnih analiz vode opisuje osnovne geografske značilnosti kraških izvirov pod Kaninskim pogorjem. Na podlagi analize krivulje praznjenja vodonosnika določi obseg zaledja izvira Glijuna v Bovški kotlini, kamor se izteka večina vode s Kaninskega pogorja.

Zaledja izvirov, raztekanje vode in položaj kraške razvodnice, so odvisni od količine vode v vodonosniku. Zaradi prepletanja zaledij različnih izvirov bi lahko izpust nevarnih snovi v zaledju v visokogorskem svetu povzročil onesnaženje mnogih izvirov. Ker je vodonosnik apnenčastih in dolomitnih gora tesno povezan s tistim v kvartarnih sedimentih Bovške kotline, pomeni varovanje visokogorskega sveta tudi varovanje virov pitne vode v dolinah in kotlinah.

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1. Introduction[1]

Slovenia is a country of mountains, waters, and divides and a country of transition from both the natural and human geography points of view. It is characterized by dominantly western air circulation, primarily mountainous and hilly relief, the modest occurrence of flatland regions, adequate precipitation, a diversity of soil types, a dominant forest ecosystem with relatively poor conditions for agriculture, and modest natural resources (Gams 1991).

Slovenia is also a country of karst situated primarily on limestone, dolomitized limestone, and dolomites. Karst covers almost half of the territory of the country and includes the research area in the Julian Alps in western Slovenia. The Julian Alps contribute their waters mainly to the Sava and Soča river basins. The relief of the Julian Alps differs significantly on the north and south sides. The wider Sava Valley to the north is situated at about 800 meters above sea level while the Soča Valley to the south is more deeply cut and lies about 200 meters lower than the floor of the Sava Valley. The difference is due to the fact that the Soča River has greater erosive power because the distance from its source to its mouth on the Adriatic Sea is shorter than the distance from the source of the Sava River to its mouth on the Black Sea. The upper Soča Valley is characterized by steep limestone and dolomite mountains, deeply cut valleys, and many karst springs. High-mountain karst has developed in the areas above the tree line (Kunaver 1983).

High-mountain karst is also characteristic of the Kanin massif, an oblong mountain range reaching 2,587 meters high in the western Julian Alps and covering almost 58 km^2. Its geographical position is tran-

Figure 1: Boka Waterfall during high water period (approximately 114-meter drop, photography Blaž Komac).
Slika 1: Približno 114 metrov visok slap Boka ob visoki vodi (fotografija Blaž Komac).

[1] The author's graduation thesis on which the present paper is based was awarded the University of Ljubljana's Prešeren Prize for students (Univerzitetna Prešernova nagrada za študente) for the year 2000. It was the first such award granted to a geographer.

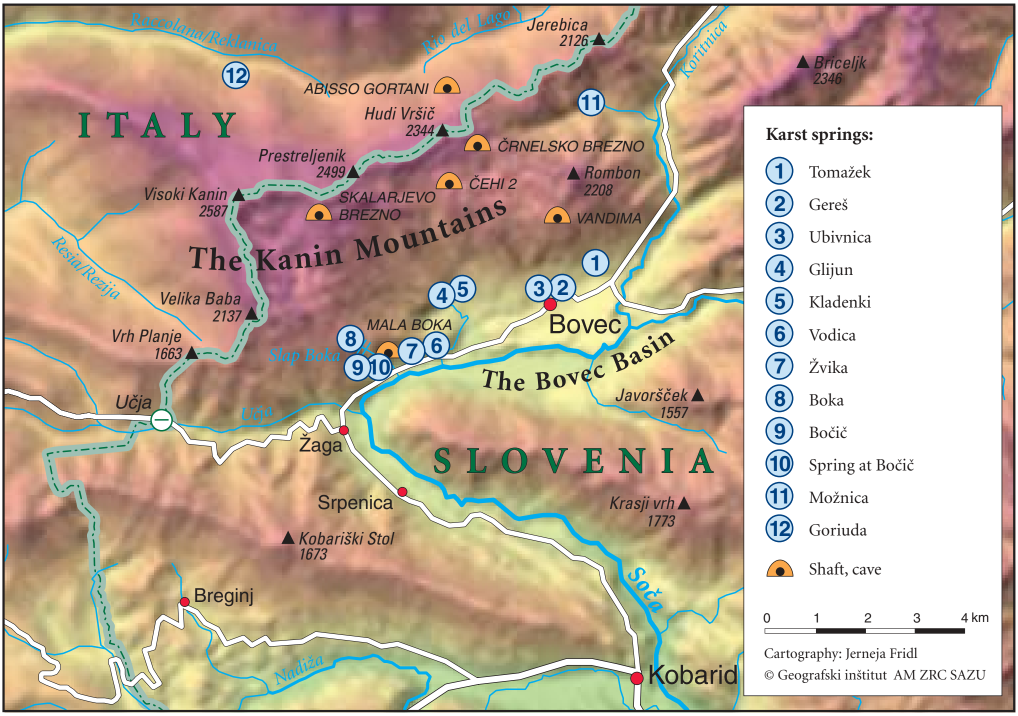

Figure 2: The location of karst springs, caves, and shafts in the Kanin massif.
Slika 2: Položaj kraških izvirov, jam in brezen na Kaninskem pogorju.

sitional as it forms a part of the alpine »hydrogeographical roof« and contributes waters to three rivers and two seas. It is bordered by the Možnica and Koritnica valleys in the northeast and east and by the Soča Valley in the south. On the west it is bordered by the Uccea (Učja) Valley, the Idrija fault zone, and the valley of the Resia (Rezija) River that flows into the Tagliamento (Tilment) River. The Raccolana (Reklanica) and Rio del Lago (Jezernica) valleys that form the northern boundary of the Kanin massif run along the Raccolana fault zone.

Due to their copiousness and constancy, the waters of the Kanin massif have been always important for the residents of the Bovec Basin for survival (drinking water), practical (protection from pollution and floods), economic (hydroelectric power), and symbolic reasons.

Since the quantity of water is limited and a great part of it is not accessible, great caution is necessary in planning the exploitation of water resources. For this reason, researchers have intensively studied the catchment areas of Kanin's karst springs for decades to determine the minimum discharges that will provide a sufficient water supply and the extent and permeability of the karst bedrock.

2. Geological structure

The first geological research of the Kanin massif was undertaken in the middle of the 19th century. Initially, a broad geological survey of this contact area between the Southern Alps, the Inner Dinarides, and the Outer Dinarides was done primarily for strategic reasons, and later research was done to locate mineral resources and sources of drinking water and electric energy.

The wider research area is a part of the Dinarides, which may be divided into the Southern Alps, the Inner Dinarides, and the Outer Dinarides (Jurkovšek 1987). The Southern Alps are composed of smaller tectonic units, which include the Krn (Julian) nappe. The Kanin and Polovnik mountains belong to the Krn nappe, which is composed of a 1,000-meter thick Dachstein limestone package. The nappe has thrust southward almost twenty kilometers over the Cretaceous flysch in the Bovec Basin (Buser 1978). The Southern Alps and the Outer Dinarides meet at the Bovec Basin (Figure 3). According to its paleogeographical development and orographical characteristics, the area of the Bovec Basin, Mount Stol, Mount Muzci, and the Kanin massif may be considered part of the Southern Alps; however, according to the thrust structure, it is also part of Podmelec nappe that mostly belongs to the Inner Dinarides. In the research area, the Krn nappe lies over the Podmelec nappe (Placer 1999).

The Bovec Basin is a large, east-west oriented, and deeply sunk syncline forming part of the contact area between the Southern Alps and the Outer Dinarides. The Kanin massif above the Bovec Basin belongs to the western Julian Alps, which are divided from the eastern Julian Alps by the Mojstrovka fault. Along this fault, the western Julian Alps have been pushed under the eastern Julian Alps. The syncline formed at the junction of the valleys due to constant tectonic compression. Tectonic movements from south-southeast to north-northwest have continued since the Miocene epoch and have caused the raising of the massif

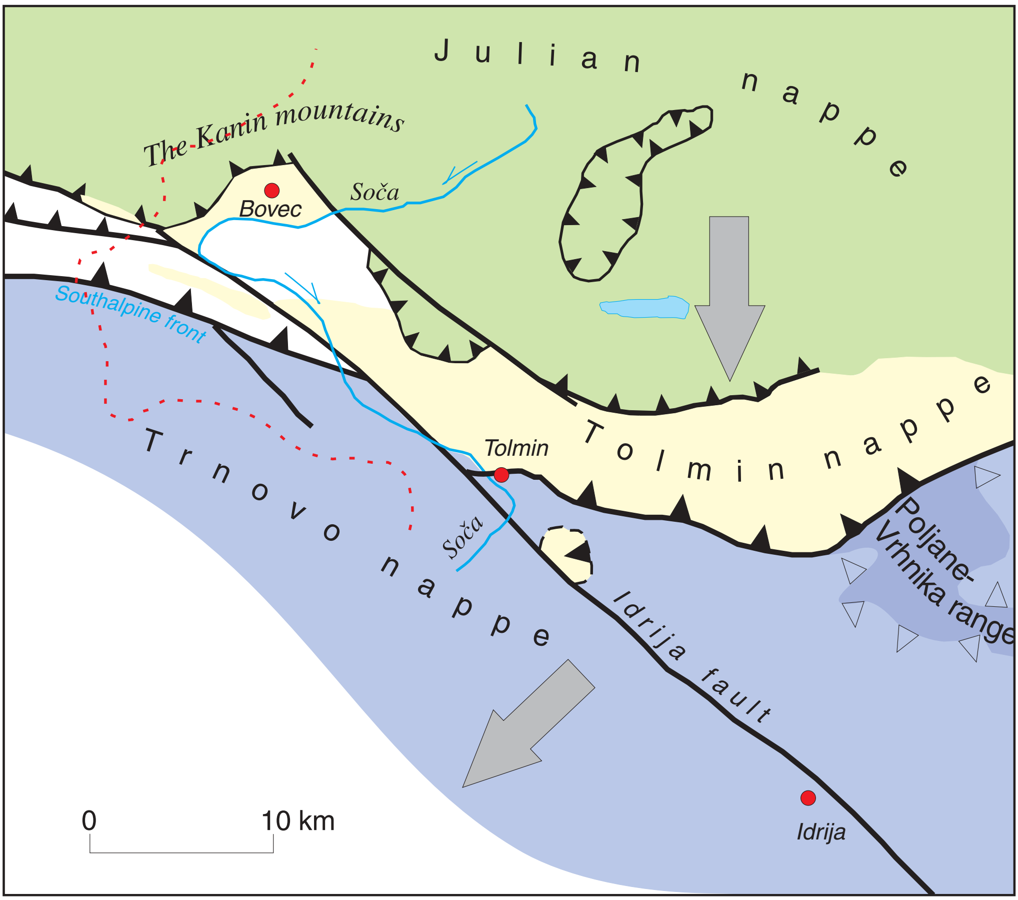

Figure 3: A section of a sketch of the macrotectonic subdivision of the border region between the Southern Alps and the Outer Dinarides (modified from Placer 1999: 226).
Slika 3: Izsek iz karte makrotektonske rajonizacije mejnega ozemlja med Južnimi Alpami in Zunanjimi Dinaridi (prirejeno po Placer 1999: 226).

as well as the deepening of the syncline. The Kanin massif comprises the northern wing of the syncline while the Polovnik anticline formed its southern wing (Placer 1999). On the Kanin massif, the normal superposition of stone beds pushing southward may be observed. The tectonic dynamic has determined the inclination of the Soča Valley between Kršovec and Trnovo ob Soči where it descends only sixty-two meters over a distance of about eleven kilometers.

Since its formation the Kanin massif anticline has been dissected into numerous tectonic blocks that have moved along right-lateral strike slip faults (Antonini and Squassino 1982). It is supposed that the »Italian« tectonic block of the Kanin massif rose relative to the »Slovene« one (Gasparo 1982). Older Alpine-oriented (E–W) and younger Dinaric-oriented (NW–SE) tectonic dislocations dominate (Buser 1978). Between the Uccea (Učja) and Resia (Rezija) valleys, the Kanin massif is crossed by the Idrija fault, one of the greatest tectonic dislocations in the Southern Alps area, that extends from Croatia across the Notranjska lowlands to the upper Soča Valley (Čar and Pišljar 1993).

We should also mention the Možnica, Jalovec, and Mojstrovka faults and the Polovnik, Krn, and Ravne faults that run at right angles to them. The Polovnik fault stretches from Mala Baba (1,936 m) in the Kanin massif across the Polovnik mountains to the village of Drežniške Ravne. The Krn fault runs north from Mount Krn (2,245 m) past the village of Drežnica across the Polovnik mountains to the Kanin massif. The northwestern part of the Krn fault is also called the Ravne fault (Jurkovšek 1995). The Raccolana tectonic line borders the Kanin massif in the north (Chiappini et al. 1995).

Depending on the degree of fracturing that appears in the rock along the faults, we can distinguish crushed, broken, and fissured zones. Crushed zones are impermeable and vulnerable to mechanical erosion. In dolomite these zones are wider and millonitized compared to those in limestone where breccia usually forms. Areas of millonite are usually impermeable and form hydrological barriers. Broken zones are highly porous, very permeable, and hydrologically important in dolomites. Since the rock is usually broken into various large blocks, water flows easily around, along, or through these zones. Fissured zones are very permeable as well, and the most important karst conduits usually form in them (Čar and Janež 1992, Čar and Pišljar 1993). In dolomite, water flows along fault zones where it may wash out crushed rock, so we occasionally find dolomite sand in karst springs such as the periodic Kladenki spring west of the village of Plužna. Larger karst caverns frequently develop at the intersection of fault structures with stratigraphic and lithographic transitions.

The oldest rocks in the Bovec Basin are from the Triassic period when the area of today's Julian Alps and Kamnik-Savinja Alps was submerged by a shallow sea where limestone precipitated and later partly dolomitized. Today, the uppermost part of the Kanin anticline is formed of Upper Triassic Dachstein limestone that lies on a 1,000-meter package of Norian and Rhaetian Main Dolomite The dolomite outcrops along faults in the Krnica Valley and in normal superposition in the Možnica and Reklanica valleys forms the lower part of a steep mountain wall (Jurkovšek 1987).

TABLE 1: BREAKDOWN OF THE KANIN MASSIF AND BOVEC BASIN STRATIGRAPHIC STRUCTURE (ACCORDING TO VARIOUS SOURCES MENTIONED ABOVE).
PREGLEDNICA 1: SKICA STRATIGRAFSKE ZGRADBE KANINSKEGA POGORJA (PO RAZLIČNIH VIRIH, KI SO OMENJENI ZGORAJ).

Quaternary sediments	320 m
Flysch	600 m
Scaglia	75 m
Micritic limestone	50 m
Lias limestone	300 m
Dachstein limestone	1,000 m
Main Dolomite	1,000 m

A package of Norian and Rhaetian micritic Dachstein limestone up to 1,200 meters thick may be found at the surface of the north wing of the Bovec syncline lying concordantly on Main dolomite and forming part of the Krn nappe. This limestone is characterized by up to two meters thick strata and Megalodon

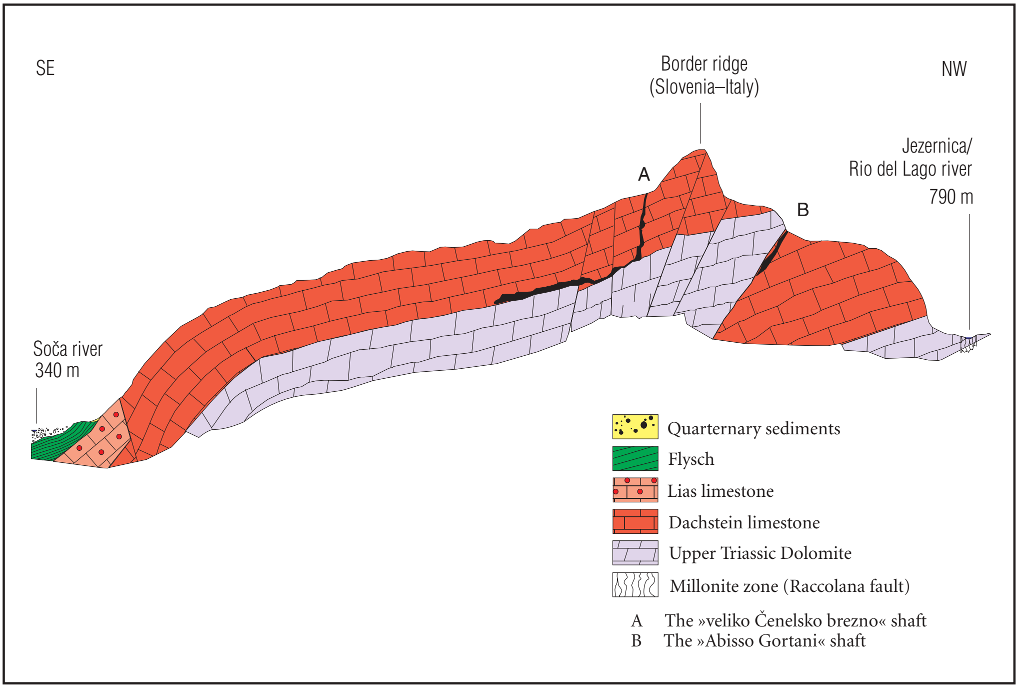

Figure 4: Stratigraphic cross-section of the Kanin massif from southeast (left) to northwest (right) (modified from Antonini and Squassino 1992, Audra 2000).
Slika 4: Stratigrafski prerez čez Kaninsko pogorje od jugovzhoda (levo) proti severozahodu (desno) (izdelano na podlagi virov: Antonini in Squassino 1992, Audra 2000).

fossils. Broken, stratified, and subvertically faulted Dachstein limestone is highly permeable and deeply karstified so that karst springs may respond to precipitation in few hours time (Gams 1974: 40). However, depending on water conditions, dolomite may also function as a barrier. Therefore, some parts of the aquifer have the characteristics of an aquiclude. The inclination of the limestone and dolomite strata is closely linked to the structure of the anticline as it is lower at the top of the Kanin massif (15°–20°) where a karst plateau has developed than on its southern slopes (up to 46°). In the upper Soča and upper Sava valleys, the southern slopes are harmonious and gently sloping while steep and discordant slopes form the northern side (Kunaver 1983). The great thickness of the Dachstein limestone strata has influenced the development of the karst and the nature and position of the karst springs.

In the Jurassic period, the Julian carbonate platform was broken into individual blocks that subsided rapidly and were covered by deep-sea sediments (Buser 1986). Thus, Triassic dolomite and limestone formed a foundation on which a 300-meter thick layer of marly limestone was deposited in the Jurassic period. Later the sea again lowered. Some areas surfaced and were karstified in the Lower Cretaceous period, and flysch and scaglia sediments were deposited during the Upper Cretaceous period. Today, 600-meter thick layers of flysch (mostly sandstones and marls) and 50-meter to 100-meter thick layers of limestone breccia and reddish marls known as scaglia cover the bottom of the Bovec Basin. In the Tertiary period, the area of the Julian Alps began to fold due to tectonic pressures from the north. In some places the folds broke and thrust toward the south. After the deposition and partial erosion of the flysch cover, the central part of the Bovec Basin was partly removed and later on covered with an up to 320-meter thick layer of Quaternary sediments. Today flysch only outcrops at the sides of the Bovec Basin on the southern slopes of the Kanin massif and in the Slatenik Valley below Mount Polovnik. The flysch layers are thicker in the eastern part of the Bovec Basin (200–500 m) and become thinner toward the west. Although composed of carbonates, flysch is impermeable and directs surface drainage but is also influenced by water corrosion to a certain extent. In the Quaternary period some parts of Julian Alps rose due to tectonic movements while other parts lowered or stagnated and were filled with sediments of fluvial (sand, gravel), fluvioglacial (gravel, conglomerate), and glacial (till) origin. These sediments were frequently shifted by the Koritnica and Soča rivers and today form a relatively large underground water reserve area that is exploited for drinking water (Kuščer et al. 1974, Jurkovšek 1987, Premru 1975).

The location and characteristics of the springs below the Kanin massif depend on the geological situation. They are usually situated where the geological structure allows water to outflow from the karst massif, mostly at fissure zones and along stratigraphic structures. The springs at the lowest elevations were mostly formed at the erosion base level or at the contact between permeable carbonate rock and less permeable flysch. We can assume that water from the karst aquifer may break through the flysch cover where the latter is thin or cracked. Since flysch contains many carbonate components, water from flysch has a very similar hardness to the water from limestones and dolomites. The water is also directed to the springs at the bottom of the Bovec Basin by the stratigraphic and tectonic structure (syncline) and by impermeable crushed zones formed at thrusts and faults.

3. Climate

The climate of the Bovec region is characterized by the circulation of air masses from west to east and by its location at the edge of variegated alpine relief where the influences of Alpine and Mediterranean climates intertwine. According to Ogrin (1996), a temperate climate prevails in the Soča and Koritnica valleys. The altitudes from 1,500 meters to 2,000 meters are characterized by the lower mountainous climate of western Slovenia that occurs on Mount Stol (1,673 m), from the Uccea (Učja) Valley to Mount Rombon (2,208 m) in the Soča Valley, and from the northern edge of the Koritnica valley to Mount Mangart (2,679 m). The highest parts of the Julian Alps and the Kanin massif have a high mountainous climate.

In the 1961–1990 period, the average annual air temperature in Bovec was 9.2° C with the highest monthly average in July (18.7° C) and the lowest in January (–0.7° C). Monthly temperatures are higher than average from May to October and are always higher in October than in April, which reflects the influence of the Mediterranean temperature regime. In winter, however, the mountain climates frequently influence the climate at the bottoms of the valleys.

Air temperatures in high mountains depend on elevation, insolation level, relief inclination and exposition, amount of moisture in the air, vegetation and snow (ice) cover, and relief microforms. The average atmospheric temperature gradient is rather low in Slovenia's mountain world (–0.42°/1,000 m) whereas the average atmospheric gradient is –0.65° C/100 m. In July, an average temperature of 11.3° C is usually expected at 1,600 meters and 10.6° C at the altitude of 1,700 meters. At the altitude of 1,530 meters there are 166 days with an average temperature below 0.0° C, while at the altitude of 2,500 meters, 250.7 days with an average minimum temperature below zero can be expected (*Climatography of Slovenia* 1991, Kerbler 1997, Lovrenčak 1987).

The origin and amount of precipitation is closely linked to relief, which is why the pattern of isohyetal lines in Slovenia reflects the relief pattern. The western Julian Alps get more precipitation than the eastern parts of the region, and there is less precipitation on the northern side than on the southern side. While higher altitudes normally receive more precipitation, an interesting phenomenon of precipitation inversion has been observed in the village of Žaga in the Soča Valley (Bernot 1978). The orographical factor tends to intensify precipitation although it is not crucial for its origin, which is more subject to cyclonic, frontal, and convective mechanisms. There is more than 3,000 mm of annual precipitation in the mountains above the Soča Valley. With the exception of the totalizer on the Kanin massif, there are no meteorological stations in the high mountainous regions, and the data from lowland meteorological stations is usually considered. At Žaga, 3,018 mm of precipitation were measured, 2,953 mm at Plužna, and 2,735 mm at Bovec in the 1961–1990 period (*Climatography of Slovenia* 1991). In Bovec, the highest amount

(3,620 mm) was measured in 1965 and the lowest (2,039 mm) in 1981. This large difference reflects the great precipitation variability characteristic of Slovenia described by Ogrin (1996).

In the 1953–1964 period, as much as 3,418 mm of average annual precipitation was measured by the totalizer on the Kanin massif while an annual average of 3,064 mm was measured in the 1990–1999 period. The measured amount of precipitation should be corrected for losses that are a result of measurement errors, wind influence, and evapotranspiration (Kolbezen and Pristov 1998). If we apply the correction factor used at the Kredarica weather station (2,514 m) on Mount Triglav, which has 3,228 mm of precipitation annually, we may assume that the actual amount of precipitation may even reach 3,900 mm.

Intense precipitation is characteristic of the climate in the Bovec region. Bovec usually has sixty days with precipitation higher than 10.0 mm and forty days with precipitation higher than 20.0 mm. There are 30 mm on an average day of precipitation in November, December, and October, and due to the high intensity of precipitation, more than 45% of the annual precipitation falls in only 15% of the year. At high elevations the spring precipitation maximum occurs later in the spring closer to summer while the autumn maximum may occur a month earlier than in the lowlands. Analyzing the ratio between precipitation and runoff in the upper Soča Valley, Radinja (1978: 104) determined that snow amounts to about 22% of the total annual precipitation.

In the upper Soča Valley, the first snowfall is usually recorded in October or November and the last in April or May, while on the Mangart saddle (2,060 m) snow occurs every month.

On Mount Triglav at the Kredarica weather station (2,514 m), the maximum snow cover exceeded 500 cm in the 1951–1990 period and was over 700 cm in 2001. In 1979, a total depth of 820 cm was measured in the area below the Triglav glacier (Košir 1986: 108). At the Kanin ski resort (2,200 m), the amount of snow is usually lower than on Mount Triglav, but it may still exceed ten meters in some areas depending on the amount of snowfall, the prevailing wind direction and strength, and the relief microforms. The snow cover thickness ratio between concave and convex relief forms may reach ratios from 1:2 to as high as 1:5. Annual runoff extends from 2,000 mm in convex relief areas to more than 4,000 mm in concave relief areas (Kunaver 1978).

The rate of evapotranspiration is relatively low in the high mountains because the area of vegetation cover decreases with altitude. On the Kanin massif, the actual evapotranspiration rate is even lower (about 40% at 2,200 m) due to the preponderance of karst drainage and totals around 550 mm (Kolbezen and Pristov 1998). Usually almost 40% of the precipitated water evaporates at the altitudes of 500–1,000 meters, one fifth at 1,000–1,500 meters, one third at 1,500–1,800 meters, about 15% at 1,800–2,000 meters, and one tenth at altitudes above 2,000 meters, even though the latter altitudes comprise almost a quarter of the mountain area. The remaining water drains to karst springs.

4. Karst springs

Most of the larger springs in the world are karst springs. There are about 125 larger karst springs in Slovenia with average discharges of around 35 m^3/s that drop to 27 m^3/s in dry periods. More than half of Slovenia's population is supplied with water from karst springs, and some of their catchment areas have already been exposed to strong pollution. Water from springs does not satisfy the need for drinking water in Slovenia (38.6 m^3/s), so underground water is also exploited (Plut 2000).

The geological structure of the Kanin massif causes springs to occur on its flanks, mainly in the Bovec Basin (Bočič, Boka, Sušec-Mala Boka, Živka, Vodica, Glijun, Kladenki, Srnica) and to the north (Možnica, Goriuda). Only a few periodic springs are located higher on the slopes of the mountains. Water is forced to the surface due to the piezometric level in the Quaternary sediments or by impermeable rock layers. The water from several smaller karst springs is collected to supply potable water to the Bovec Basin settlements.

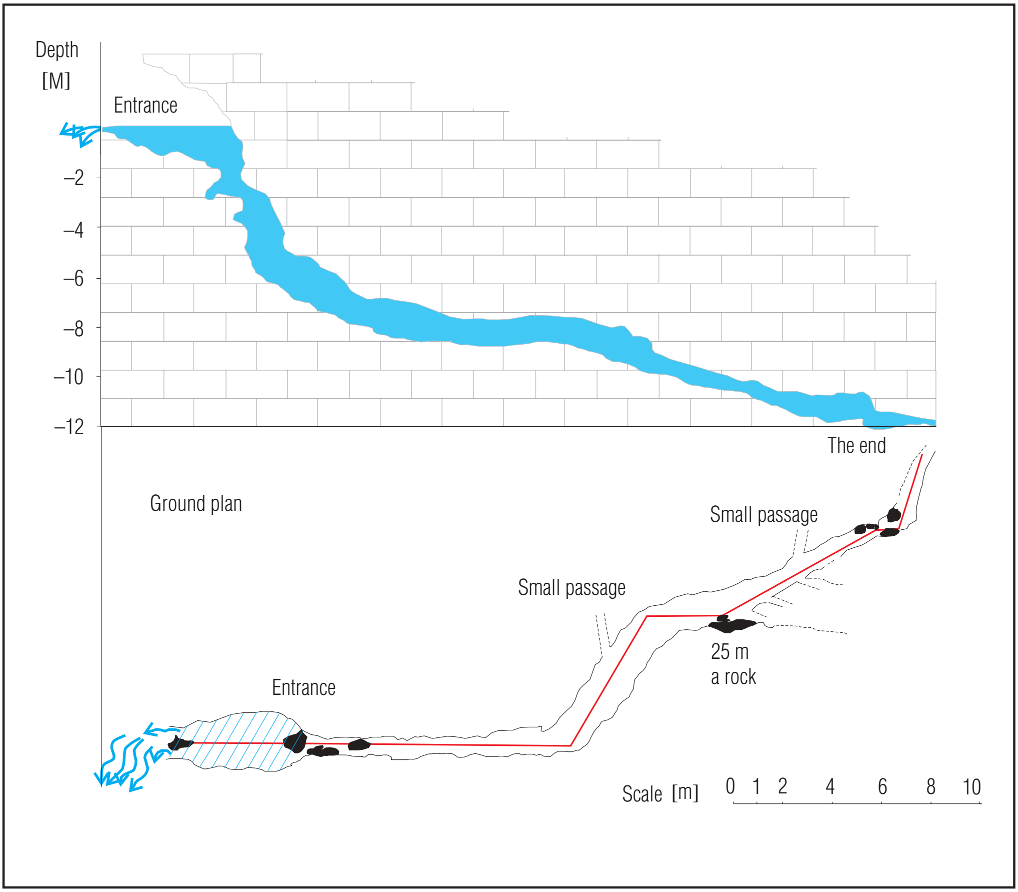

Figure 5: The Bočič spring near Žaga where an underwater survey was done in 1990 (source: Antonini and squassino 1992, Audra 2000).
Slika 5: Izvir Bočič pri Žagi, ki je bil preplavan leta 1990 (vir: Antonini and squassino 1992, Audra 2000).

As a result of the geological structure, climate, and quantity of water, three characteristic hydrogeological zones have developed in the Kanin massif: the unsaturated (vadose) zone, the periodically saturated zone, and the saturated (phreatic) zone. The saturated and unsaturated zones differ from one another in the direction and manner of the flow and the quantity of water. The quantity of water in the system depends primarily on the ratio between inflow and outflow, zones in the aquifer that allow the formation of water reserves (Prestor 1992), and the dominant type of channels in the aquifer (fissure, conduit, dispersed).

The saturated and unsaturated zones are separated by the actual piezometric level, which may oscillate more than 100 meters. Changes in the level can also be very rapid. The saturated zone is completely filled with slowly moving water. Its movement depends mostly on hydrostatic pressure rather than on gravity. There is no permanent water flow in the unsaturated zone, and water mostly flows in vertical direction depending on gravity and the structural and lithological circumstances.

At the bottom of the vadose zone at the contact with the phreatic zone, a zone of horizontal water outflow from the karst massif develops. The flow is directed toward the channels that most easily drain the water from the rock. For this reason, caves in the phreatic system develop from the bottom up (Mihevc 1998: 13).

The formation and development of the underground karst system depends on the geomorphological development of the surface and vice versa. The majority of springs in the upper Soča Valley are situated today at the foot of the massifs at the level of the local erosion base, while karst channels largely occur more deeply in the phreatic zone. The rapid tectonic rise of the Julian Alps encouraged the rapid and deep carving of valleys and changes in the river network following periods of glaciation with intensive mechanical weathering, deep corrosion, and glacial erosion. The rivers carried enormous quantities of gravel due to the intensified mechanical erosion processes at the end of the last glacial period and formed large fluvioglacial fans such as the one on the Koritnica River in the Bovec Basin. The underground water in the fluvioglacial sediments of the Bovec Basin is closely linked to the limestone and dolomite underground waters of the Kanin massif. The warming following glacial periods increased the erosive force of the rivers that carved their channels through the fluvioglacial sediments. The valleys deepened further, and karst processes in the mountains advanced. The karst water flow and consequently the springs had to adjust to the constantly changing local erosion base level (Žlebnik 1990).

The adaptation of the karst system is usually slower than the changes that require it, and limestone karst massifs may be karstified some dozens of meters above the present piezometric level due to the deepening of the valleys or the tectonic rising of mountains. Karst channels have thus been transformed during glacial periods and at higher elevations during interglacial periods as well. For this reason, numerous karst springs and former spring caves can be found high above valley bottoms. In the Kanin massif, karst aquifers have developed at many levels due to the numerous stages of development. Although the altitudes of individual levels is difficult to determine since phreatic channels develop in »tiers« that can extend over greater distances and elevations, three distinctive levels may be observed on the north side of the Kanin massif where caves are found at the altitudes of 870 meters, 1150 meters, and 1,500 meters (Muscio et al. 1983). Since chemical dissolution and the mechanical widening of old passages are more important for the orientation of the underground water flow than the creation of new channels, some hundred-thousand-year-old channels may still play an active role today in many places (Audra 2000).

The consequence of the evolution described above is that while lower-lying caves usually function as permanent springs, for example, the Glijun spring, caves at higher elevations such as the Mačkova jama and Srnica caves are dry or only intermittently active as springs. It is also interesting to observe the delay in the activation of the Boka spring compared to the Glijun spring. Studies show that the Boka spring catchment area is at a higher elevation and separated from the catchment areas of the Glijun, Bočič, and Sušec (Mala Boka) springs by faults and dolomite.

The deepening of the valleys increased the role of the lithological and tectonic structure of the karst massif with regard to the locations of springs and the formation of their catchment areas. Karst massifs are less karstified at greater depths than closer to surface where cave systems adapt more easily to changes in the erosion base level (Kuščer et al. 1974).

Speleological investigations have shown that the karst caves in the Kanin massif can be more attributed to the system of joints, cracks, and faults than to the influence of stratification and lithology. A multi-level aquifer has developed along the main fissured zones (Antonini and Squassino 1982, Casagrande et al. 1999, Gasparo 1983).

Furthermore, two types of caves can be distinguished: those that have been part of a phreatic system and those that came into existence through percolating rainwater and water from melting snow flowing from the edge of a glacier or by water percolating through tectonically predisposed fissures under the glacier.

Thick unsaturated and periodically saturated zones caused a duality in the formation of caves of the Kanin massif. (Sub)vertical shafts developed in the upper part while (sub)horizontal caves dominate at lower elevations. (Sub)horizontal passages in many cases follow the lithological contact between Main dolomite and Dachstein limestone. The Kanin massif is famous for its numerous and very deep vertical shafts, some of them exceeding the 1,300 m mark. Since water does not deposit sinter in high-mountain karst, some of the shafts were formed by the action of percolating water. Research that compared water hardness at the entrance of the Triglav shaft and in the spring below the mountain show that percolating water is capable of corroding carbonate rock to the depth of 1,000 meters (Gams 1993). Sinter was found in some caves of the Kanin massif such as the Mala Boka cave or the Veliko Črnelsko brezno cave that was probably formed in a warmer climate than today's.

More than eight hundred karst caves and shafts have already been discovered in the Kanin massif, of which eleven are more than five hundred meters deep. The deepest cave is Čehi II (1,500 m), and the world's longest vertical section (643 m) in a cave was discovered in 1996 in the Vrtiglavica cave. The world's deepest cave is the 1,710-meter deep Veronja Cave in Georgia, while six caves are deeper than 1,500 meters and seventy are deeper than 1,000 meters (NSS World Deep Cave List).

4.1. Water flow from the Kanin massif and discharges in the Bovec Basin

A number of water tracing investigations have been undertaken in the Kanin massif in recent decades. The primary aim of the research has been to determine the quality, quantity, and availability of potable water. The results show that due to specific geological structures, the majority of the water from the Kanin massif flows to springs (Glijun, Žvika, Boka, Bočič) between Žaga and Bovec in the Bovec Basin. The western part of the massif is drained toward Boka, while its central and eastern parts drain toward Glijun. Only a small amount of water flows to the Italian side of the Kanin massif and to springs in the Možnica Valley. Water tracings prove that water drains to the Bovec Basin springs from the Italian part of the Kanin massif as well (Cucchi et al. 1997, Novak 1992).

An estimated average of 5.5 m^3/s of water flows from the Kanin massif under normal water conditions. The Kanin massif covers about fifty square kilometers, and the Soča River receives the greater part of its discharge (4.76 m^3/s). Only a small amount of water (0.76 m^3/s) flows to springs in Italy, which have a much smaller catchment area of eight square kilometers. The discharge ratio between Italian and Slovene sides of the Kanin massif is 1:5.5 and the catchment area ratio is 1:6.25 (Novak 1978).

The Glijun spring typically has a discharge of around 1 m^3/s, but this can oscillate between a minimum of 0.15 m^3/s to a maximum of 15 m^3/s. The Boka spring has an average discharge of 0.2 m^3/s with a maximum flow that may reach as high as 50 m^3/s during periods of heavy precipitation (the exact flow has not yet been measured) but may also dry up completely. The Žvika spring has an average discharge of about 0.1 m^3/s with a maximum of 1 m^3/s and a minimum of barely 10–15 l/s. The discharge of the Sušec spring may reach more than 10 m^3/s during high water levels but is dry for most of the year. The Goriuda spring on the Italian side has an average discharge of about 0.15 m^3/s (0.03–10 m^3/s) (Gasparo 1991, Kunaver 1978, Novak 1979, Cucchi et al. 1997).

The relationship between water inflow, evapotranspiration, and drainage can be expressed by runoff coefficients. Jenko (1959) estimated the runoff coefficient for high-mountain karst to about 80–90%. Some years later, Kunaver (1978) calculated a runoff coefficient of 90% for the Kanin massif and of 85% for the Soča Valley above Kobarid. Kolbezen and Pristov (1998) calculated a runoff coefficient of 79.3% for the Soča Valley above Kršovec in the Bovec Basin and of 81.5% for the Soča Valley above Log Čezsoški. The discharge values calculated from the precipitation and evapotranspiration data differ from the measured river discharge due to the discrepancy between the relief and the actual karst watershed. It is assumed that the Kanin massif karst watershed follows a line from Oslova glava (2,025 m) and Bela Peč (2,149 m) to the northern slopes of Kuntar (2,124 m) and Hudi Vršič (2,344 m) (Novak 1978). Considering the data above and our own calculations, we can conclude that the Kanin massif runoff coefficient is higher than 90.0% and can in fact reach 93.5% (Komac 2000). The calculated specific runoff on the Kanin massif amounts to 94.8 $l/s/km^2$, which is close to the findings of several other authors and comparable to the specific runoff in other parts of Julian Alps (Komac 2000).

Long term observations and measurements of discharges in the Soča and Koritnica valleys show that there are strong springs in the Bovec Basin. Most are situated on the right bank of the Soča River since the majority of the Bovec Basin's inflow originates in the Kanin massif. Between Kršovec and Log Čezsoški in the

Bovec Basin, an average discharge of 6.15 m^3/s has been calculated with a minimum in February (2.72 m^3/s) and a maximum in May (10.4 m^3/s). An average maximum discharge of 102.89 m^3/s and a minimum average discharge of 0.7 m^3/s have been recorded.

TABLE 2: CALCULATED VALUES OF MEAN, MAXIMUM, AND MINIMUM MONTHLY DISCHARGES FROM BOVEC BASIN SPRINGS INTO THE SOČA RIVER (KOMAC 2000).
PREGLEDNICA 2: IZRAČUNANE VREDNOSTI SREDNJIH, MINIMALNIH IN MAKSIMALNIH MESEČNIH PRITOKOV SOČE V BOVŠKI KOTLINI (KOMAC 2000).

Month / Discharge (m^3/s)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual mean
Average discharge	3.68	2.72	4.06	7.22	10.4	9.6	5.97	5.27	6.31	6.57	7.55	4.45	6.15
Maximum discharge	223.4	108	94.7	160.4	137.8	53	55	15	48	93.2	118	128.2	102.89
Minimum discharge	0.88	0.71	0.67	0.11	0.49	3.12	0.29	0.61	0.87	0.0	0.81	0.0	0.7

About half of the inflow (40–60%) comes from underground sources of the Soča River in the Bovec Basin while some 30–35% of its water originates directly from precipitation and about 20–25% from melting snow. We estimate that about three quarters of the water (4.76 m^3/s) flows from the right bank of the Soča River (the Kanin massif) and a quarter from the left bank. Radinja (1978) estimates that 52% of the inflow to the Soča River comes from underground sources.

TABLE 3: ESTIMATED AVERAGE UNDERGROUND AND SURFACE INFLOWS TO THE SOČA RIVER IN THE BOVEC BASIN. THE VALUES WERE CALCULATED FROM THE MEAN MONTHLY DISCHARGES OF THE SOČA RIVER AT KRŠOVEC AND LOG ČEZSOŠKI AND OF THE KORITNICA RIVER AT KAL-KORITNICA (KOLBEZEN AND PRISTOV 1998).
PREGLEDNICA 3: OCENA POVPREČNIH PODZEMELJSKIH IN POVRŠINSKIH DOTOKOV V REKO SOČO V BOVŠKI KOTLINI. VREDNOSTI SO IZRAČUNANE IZ SREDNJIH MESEČNIH PRETOKOV SOČE PRI KRŠOVCU IN LOGU ČEZSOŠKEM TER REKE KORITNICE PRI KALU-KORITNICI (KOLBEZEN IN PRISTOV 1998).

Bovec Basin 6.15 m^3/s	Right bank 4.76 m^3/s	Underground inflow 2.48 m^3/s
		Surface inflow 2.28 m^3/s
	Left bank 1.39 m^3/s	Underground inflow 0.556 m^3/s
		Surface inflow 0.834 m^3/s

4.2. Water consumption

A considerable amount of water flows from springs below the Kanin massif, but only a minimum of 10 l/s/km^2 is available for human use (Čar and Janež 1996). In normal circumstances the inhabitants of the Bovec Basin require 65 l/s of water, and water consumption increases in summer and winter due to tourist activity. Bovec receives most of its potable water from wells near the village of Čezsoča. Until recently, the inhabitants of some older parts of Bovec obtained water from small local springs that altogether yield around 2–3.2 l/s of water at low discharge (the V Bisnah, Praprotnici, Na Skali, and Tomažék springs and a spring beside the Koritnica River). Two wells were subsequently dug in the Quaternary sediments near Čezsoča to ensure a better and more regular water supply. These wells now supply water for Bovec and Čezsoča, but this resource is threatened by pollution due to the proximity of the Soča River and there is a constant threat of the water supply being cut off during power breakdowns.

Water tracing experiments show that water from the area of the Kanin ski resort flows to springs between Žaga and Bovec that provide drinking water for some households in the area. Some of the larger karst springs (Glijun, Možnica, Žvika) have not been exploited as sources of potable water since they are occasionally polluted with organic substances from the ski resort on the Kanin massif. High-mountain karst is particularly vulnerable to pollution due to the lack of plant cover, concentrated activity during the tourist season, and the relatively fast flow of water through the system (Novak 1992).

4.3. Physical and chemical characteristics of karst springs

Several of the springs below the Kanin massif were monitored from November 1999 to May 2000. Water samples were taken once a month for chemical and physical analyses from November 21, 1999, to May 15, 2000. The chemical analyses and physical observations were done in the field and at the Laboratory of Physical Geography, Department of Geography, Faculty of Arts, University of Ljubljana.

Water from the following springs was analyzed in detail (See Map 1 for the exact location of each spring). The springs on flysch are listed in the first group and limestone karst springs in the second.

GROUP I – »flysch« springs that may be denoted as partly karst and partly non-karst springs in the flysch covered region on the lower slopes of the Kanin massif:

- the Tomažék spring east of Bovec;
- the Geršpotok springs (above and below Bovec);
- the Ubivnica spring above Bovec.

GROUP II – »limestone« springs that are mostly karst springs of the Kanin massif:

- the Glijun spring near Plužna;
- the Kladenki spring near Plužna;
- the Vodica spring;
- the Žvika spring;
- the Boka spring;
- the Bočič spring (cave);
- the Bočič spring (spring near Bočič in Quaternary sediments).

Water taken from the Soča River near Log Čezsoški was analyzed to provide a basis for comparing the data. The Boka spring was only sampled once.

The amount of dissolved oxygen, oxygen saturation, the acidity of the water, and the water temperature were measured using a portable measuring device. The nitrate content was measured using the *Visocolor Nitrate 50* device, while the amounts of free CO_2, phosphates, nitrates, and sulfates and water hardness were measured by titration in the laboratory. The pH values and water conductivity were measured using an electronic meter. The data collected helped to augment the basic typology of karst springs (springs on limestone and springs on flysch) and to make a simple water balance scheme and an assessment of conditions for the Kanin massif. The data also provided a basis to describe the main chemical and physical characteristics of the springs. Long-term observations show there is a positive correlation between discharge regimes, types of circulation in the aquifer, and variations in the physical and chemical characteristics of spring water (Tyc 1997).

Overall, there were no significant differences between flysch springs and limestone springs. To mention only the basic differences, we can say that flysch springs usually have lower discharges compared to limestone springs. This is primarily due to their smaller catchment areas. They are also more frequently covered with ice in winter and may therefore dry up in winter as well as in summer.

Flysch springs have different temperature regimes than limestone karst springs due to their lower discharge and different discharge regimes. They usually have lower temperatures in winter and higher temperatures in summer. Limestone springs usually have their lowest temperatures in summer.

Flysch springs usually have higher total calcium and magnesium hardnesses and lower carbonate hardnesses than limestone springs. We believe the differences are related to the flow of water through soil where it is enriched with CO_2 and also to the mixing of underground karst waters with (sub)surface waters. There are more chlorides but fewer sulfates in limestone springs than in flysch springs. Flysch springs also have lower nitrate values, a lower Mg/Ca ratio, and higher amounts of free CO_2 compared to limestone springs. The conductivity of flysch springs is also higher.

TABLE 4: AVERAGE RESULTS OF CHEMICAL AND PHYSICAL ANALYSIS OF WATER FROM KARST SPRINGS BELOW THE KANIN MASSIF. »DH« DENOTES WATER HARDNESS IN GERMAN DEGREES (KOMAC 2000) (»–« NO DATA).
PREGLEDNICA 4: POVPREČNI REZULTATI KEMIČNIH IN FIZIKALNIH ANALIZ VODE KRAŠKIH IZVIROV POD KANINSKIM POGORJEM. Z OZNAKO DH OZNAČUJEMO NEMŠKE STOPNJE TRDOTE VODE (KOMAC 2000) (»–« NI PODATKA).

Spring[2]	Temperature °C	pH	Carbonate hardness °DH	Carbonate hardness mg $CaCO_3$/l	Total hardness °DH	Calcium hardness °DH	Calcium hardness mg CaO/l	Magnesium hardness	r mg/Ca	Chlorine ions mg/l	Sulfate ions SO_4–	Nitrate ions mg/l	Conductivity (uS/cm)
Tomažék	8.63	7.76	6.41	114.12	7.93	6.36	63.57	1.57	0.25	3.30	2.76	2.00	248.67
Geršpotok 1	7.58	8.03	7.70	137.11	8.90	7.73	77.29	1.17	0.16	4.41	2.30	0.00	289.68
Geršpotok 2	6.68	8.15	7.84	139.50	7.94	7.88	78.79	1.19	0.15	4.15	8.26	0.00	317.67
Ubivnica	6.95	8.06	8.79	174.29	9.21	8.80	88.00	1.84	0.21	3.91	49.61	0.00	398.17
Glijun	6.50	7.97	5.42	96.53	5.47	4.93	49.29	1.24	0.27	3.22	12.14	–	197.83
Kladenki	9.31	7.90	6.33	112.60	6.41	6.41	64.14	1.00	0.16	3.45	18.62	2.00	281.83
Vodica	8.68	8.03	4.94	87.88	5.11	4.80	48.00	1.13	0.24	3.65	49.63	4.00	215.60
Žvika	7.33	8.01	5.09	90.58	5.09	4.87	48.71	1.00	0.21	4.72	44.54	2.50	200.17
Bočič-cave	7.48	8.02	4.83	86.02	5.06	4.43	44.29	1.36	0.32	4.45	53.71	5.00	186.68
Bočič-spring	8.58	8.06	4.50	80.05	4.64	4.46	44.57	0.89	0.21	3.77	34.65	3.00	118.52
Boka[3]	4.40	8.17	3.36	59.81	4.10	3.40	34.00	0.70	0.21	3.90	–	–	153.80
Soča	8.44	7.00	5.71	101.56	5.94	5.09	50.86	1.60	0.31	3.65	28.99	3.50	233.17

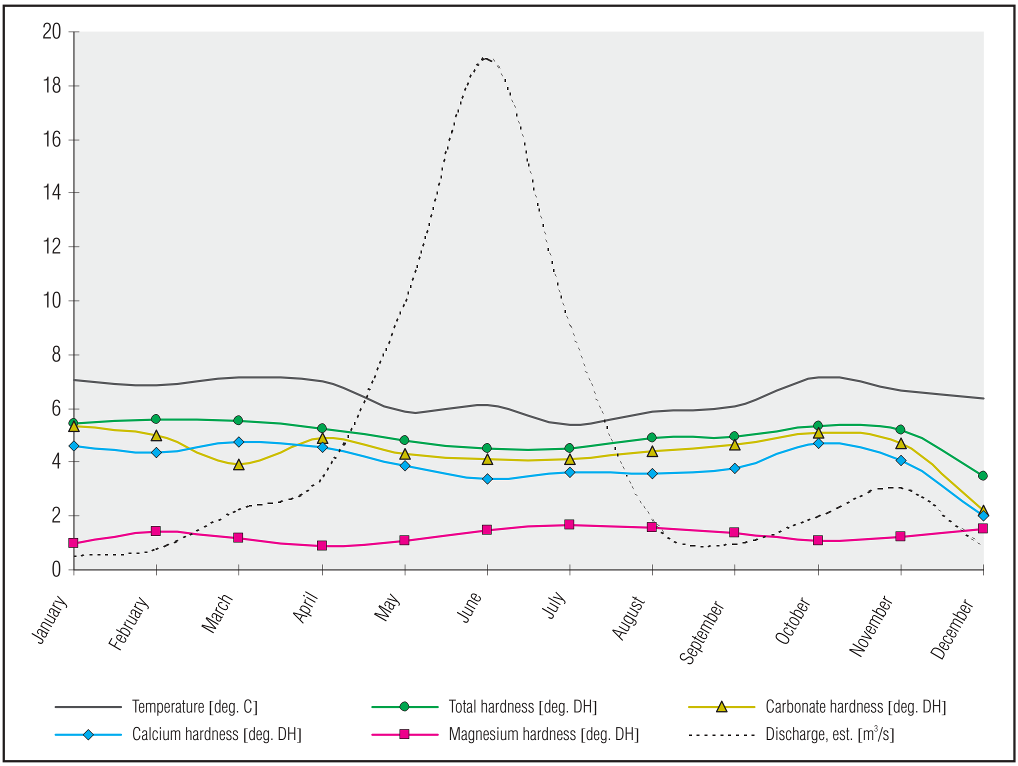

Figure 6: Mean monthly values of physical and chemical parameters for the Glijun spring. The table summarizes data collected by Novak (1979; 31 measurements), Kunaver (2000; 112 measurements), and our seven measurements.
Slika 6: Povprečne mesečne vrednosti fizičnih in kemičnih parametrov vode v izviru Glijuna. Graf smo izdelali s pomočjo podatkov Novaka (1979; 31 meritev), Kunaverja (2000; 112 meritev) in naših 7 meritev.

[2] See Figure 2.

[3] Water sample from the Boka spring was taken on May 14, 2000.

TABLE 5: SOME BASIC PHYSICAL AND CHEMICAL CHARACTERISTICS OF LIMESTONE AND FLYSCH SPRINGS IN THE BOVEC BASIN.
PREGLEDNICA 5: NEKATERE KEMIČNE IN FIZIKALNE LASTNOSTI IZVIROV NA FLIŠU IN APNENCU V BOVŠKI KOTLINI.

	Water temperature (deg. C)	pH	Total hardness (German deg.)	Carbonate hardness (German deg.)	Calcium hardness (German deg.)	Magnesium hardness (German deg.)	Chlorides (mg/l)	Sulfates (mg/l)	Conductivity (uS7cm)
Limestone springs	7.47	8.02	5.13	4.92	4.76	1.05	3.88	35.55	193.49
Flysch springs	7.46	10.67	8.50	7.69	7.69	1.44	3.94	15.73	313.55

The Glijun spring was taken as a sample spring and studied in more detail. Conductivity, temperature, and water level data was collected at the Glijun and Žvika springs with an automatic water sampler from November 12, 1999, to January 12, 2000.[4] The data gained allowed us to calculate the catchment area of the Glijun spring, but unfortunately, the data from the Žvika spring was unusable for further calculations due to the improper positioning of the sampler where it was too exposed to the sun.

The following analysis of the basic chemical and physical characteristics of the Glijun spring was done by comparing the data collected by Novak (1979), Kunaver (2000), and the author.

The average water temperature of low-altitude karst springs usually shows the strong influence of the average air temperature in a particular region. However, in the springs below the Kanin massif, the temperature is lower due to the influence of the rapid flow through the system and of water from melting snow. The average temperature of the Glijun spring is 6.47° C. The lowest temperature (5.41° C) is usually recorded in July due to melting snow. The water temperatures are higher than average in the period from January to April and in October and November. The maximum temperature is recorded after the October precipitation (7.16° C). A secondary maximum usually occurs in March, and a secondary minimum temperature in December. The difference between the mean annual maximum and minimum temperatures amounts to 26.7% of the average annual temperature. Water temperature changes are inversely proportional to the changes in the rate of discharge.

The changes in calcium, carbonate, total hardness, and precipitate amount are directly proportional to changes in the water temperature while in contrast, changes in magnesium hardness are inversely proportional to water temperature changes. The annual average for total hardness is 4.95° DH. It depends primarily on water temperature and discharge, and its minimum is usually recorded in winter (December) while a secondary minimum occurs (June). The total hardness maximum (5.56° DH) is usually recorded in February while a secondary maximum occurs in October (5.34° DH). The difference between the average minimum and maximum amounts to 21.4% of the annual average.

Carbonate hardness minimums usually occur in summer (June, July; 4.14° DH) and winter (December; 2.23° DH), and its maximums in autumn and spring. The mean annual average for carbonate hardness is about 0.5° DH lower than the total hardness average. Carbonate hardness fluctuates in the same way as total hardness, but the difference between the lowest and the highest values amounts to almost one third of the annual average. Carbonate hardness depends more on precipitation than other hardnesses do: the more precipitation there is, the lower the carbonate hardness.

The figures for calcium hardness vary more than those for total and carbonate hardness. The annual average is about 0.5° DH lower than for carbonate hardness with a maximum during the period of lowest discharge (February; 4.35° DH) and a minimum in summer (June; 3.36° DH). The difference between the maximum and minimum amounts to more than one third of mean annual calcium hardness average.

Magnesium hardness is the most variable compared to total, carbonate, and calcium hardness. The difference between its minimum and maximum amounts to almost 60% of the mean annual average, which

[4] The measurement devices are the property of the Institute of Geology and Palaentology, University of Trieste, Italy, with whom we cooperated. The author here thanks Paolo Manca and Giacomo Casagrande for their help and the data they provided.

rarely exceeds 1.5° DH (1.29° DH). The maximum magnesium hardness is usually recorded in July, about a month after the maximum discharge occurs. Its minimum usually occurs in May with a secondary minimum occurring in the autumn. Following heavy rains, the quantity of Mg^{2+} ions measured in the Boka, Glijun, and Goriuda springs was lower than 1 mg/l, indicating the flow of water predominantly through conduits in Dachstein limestone (Cucchi et al. 1997, 147). During periods of high precipitation, more water passes through conduits in limestone than in the more tectonically crushed dolomite, and consequently the magnesium hardness is lower.

The amount of precipitate in the water is low during periods of high discharge and high during periods of low discharge. The difference between the minimum and maximum amounts of precipitate is considerable (30%) and confirms their dependence on discharge conditions.

Discharge is one of the most variable characteristics of karst springs. The variability occurring at a particular spring is linked to changes in climate conditions (precipitation, temperature), the melting of snow in the mountains, the amount of water in the karst system and its conductibility, and the location of the spring relative to nearby springs (Tyc 1997). Novak's measurements of the Glijun spring (1979) show that discharge is low in winter (January; 0.53 m^3/s) and high in early summer (June; 20 m^3/s) due to snow melting in the mountains. A secondary maximum appears in autumn due to rainfall. According to Novak's figures, the average annual discharge is 4.57 m^3/s, but the majority of other studies show average annual discharge amounts of around 1 m^3/s (e. g., Audra 2000). This discrepancy is probably due to the different methods of measurement employed and the large spread between minimum and maximum discharge figures that is typical of karst springs and can also be observed at springs in the Vipava Valley (Janež et al. 1997).

Between 1987 and 1991, there were 70–120 days per year with discharges higher than 3.3 m^3/s at the Glijun spring. The data shows that the direct influence of precipitation is more obvious in the warm part of the year (August–February) than in the period from March to June.

TABLE 6: NUMBER OF DAYS PER YEAR WHEN THE GLIJUN SPRING DISCHARGE (D) WAS HIGHER THAN 3.3 M^3/S AND MONTHLY PRECIPITATION IN MM (P) (1987–1991). THE FIGURE 3.3 M^3/S IS THE MAXIMUM AMOUNT OF WATER THAT CAN BE USED BY THE PLUŽNA HYDROELECTRIC STATION (AVERAGE ANNUAL ELECTRICITY PRODUCTION IS 6,300,000 KWH AND 1.75 MW OF POWER). WHEN THE DISCHARGE EXCEEDS THIS AMOUNT, WATER POURS OVER THE DAM AND CAN NO LONGER BE MEASURED. THE DATA WAS COLLECTED AND PROVIDED BY THE STAFF AT THE PLUŽNA HYDROELECTRIC STATION (SENG, SOČA RIVER HYDROELECTRIC STATIONS, NOVA GORICA).
PREGLEDNICA 6: ŠTEVILO DNI V LETU, KO IMA GLIJUN PRETOK VIŠJI OD 3.3 M^3/S IN MESEČNA KOLIČINA PADAVIN (1987–1991). VREDNOST 3.3 M^3/S PREDSTAVLJA MAKSIMALNO KOLIČINO VODE, KI JO ŠE LAHKO UPORABLJA HIDROELEKTRARNA PLUŽNA Z LETNO PROIZVODNJO ELEKTRIČNE ENERGIJE 6.300.000 KWH IN MOČJO 1.75 MW. KO JE PRETOK VIŠJI OD TE VREDNOSTI, SE VODA PRELIVA ČEZ JEZ IN NJENE KOLIČINE NI VEČ MOGOČE IZMERITI. PODATKE SO ZBRALI IN AVTORJU ČLANKA POSREDOVALI SODELAVCI HE PLUŽNA, SENG (SOŠKE ELEKTRARNE NOVA GORICA).

	1987		1988		1989		1990		1991	
	D.	P.	D.	P.	D.	P.	D.	P.	D.	P.
January	0	105.1	0	455.7	0	0	2	303.2	0	494
February	5	377.5	0	343.7	0	289.1	0	21.9	0	166.6
March	0	276.6	0	149	4	150.3	0	108.4	8	276.9
April	21	173.9	16	203.9	16	578.9	6	250.8	2	188.8
May	28	440.6	31	339.4	22	52.7	21	116.6	16	102.4
June	30	416.0	24	184.6	16	229.5	17	345.5	30	320
July	14	308.3	11	288.6	4	143.1	7	235.3	23	298.3
August	6	487.7	3	221.4	0	174.1	0	84.2	0	209.6
September	3	151.5	5	193.7	0	123.3	4	226.3	4	90.2
October	13	527.7	2	186.2	0	19.1	5	286.6	11	493.7
November	0	459.7	0	19.3	3	273.1	16	748.4	8	325.9
December	0	39.7	0	123	9	292.7	0	211.6	0	569.7
TOTAL	120	3,764.3	92	2,698.5	76	2,325.9	78	2,838.8	102	3,091.5

4.4. Recession curve analysis

Discharge can be measured by various methods. We used a special measurement device that was placed at the Glijun spring in the period from December 11, 1999, to December 26, 1999. The measuring device automatically recorded the water temperature, its conductivity, and the water level at half-hour intervals. Using the data collected, we described the changes in the discharge and did a recession curve analysis to determine some characteristics of the karst aquifer. On the basis of water level data and by measuring the discharge profile, the discharge of the Glijun spring was calculated following the equation

$$Q = 3.8197 \times h_{water} + 29.508$$

Precipitation[5] was reflected in rapid changes in the Glijun spring discharge, which rose from 0.3 m^3/s on December 10, 1999 to 2.1 m^3/s on December 11, 1999, when the highest discharge was recorded, and fell again to 0.03 m^3/s on December 24. Subsequently, the discharge decreased more rapidly and approached the zero value.

Statistical and mathematical analysis of the recession curve can help us determine the characteristic parameters of a spring and its catchment area and discharge conditions. Although the following calculations are approximate since several recession curves should be analyzed for a precise determination, the results are informative and provide a glimpse into the hydro-geographical mechanisms of high-mountain karst springs. As we have noted above, the karst aquifer is very heterogeneous and the water conditions at its springs may differ significantly depending on their location in the system, the quantity of water, and the hydrogeological structure.

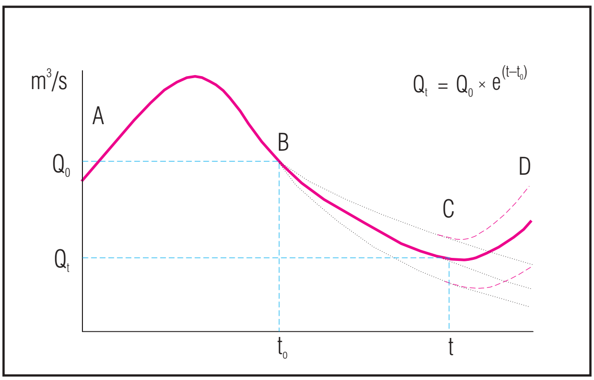

Figure 7: Typical recession curve (modified from Mijatović 1968: 46).
Slika 7: Tipična krivulja praznenja (po Mijatoviću 1968: 46).

The recession curve analysis was performed according to the findings of B. F. Mijatović (1968: 43–81). Some basic karst spring characteristics may be presumed by accepting that the recession curve follows the equation

$$y = e^{-\alpha(t-t_o)}$$

where the coefficient α denotes the type of drainage according to certain characteristics of the karst aquifer, e is a natural logarithm, and t_o (t) is the time at the beginning (end) of the recession (time is usually measured in days). Following the equation mentioned above, E. Maillet (1903) set the recession curve equation

$$Q_t = Q_o \times e^{-\alpha(t-t_o)}$$

where Q_t denotes the discharge at time t, and Q_o the discharge at the beginning of the recession. The coefficient α determines the BC straight-line inclination (see Figure 7). The lower the coefficient is, the steeper the straight line and the faster the recession.

[5] There were 190.3 mm of rain measured at Plužna (November 15–22, December 6 and 11–14) and 150.6 mm at the Bovec meteorological station in the period from December 11, 1999, to December 26, 1999.

The volume of water in a karst system may therefore be defined by discharge and α coefficient.

$$V_t = \frac{Q_t}{\alpha}$$

where Q_t denotes the discharge in time t and V_t the disposable volume of karst system, that is, the total volume filled with water before the recession.

We can see that coefficient α is defined as a proportion between the discharge and the volume of water reserves in the karst system that indirectly reflects the extent of the drainage basin. As it reflects typical sequences of discharge recession, the coefficient α describes the actual hydrogeographical characteristics of a spring:

$$\alpha = \frac{[\log Q_o - \log Q_t]}{[0.4343 \times (t - t_o)]}$$

The recession curve, when placed on a Cartesian coordinate system with discharge (m^3/s) on the ordinate and time (day) on the absciss, has the form of hyperbola. However, when placed on a normal logarithmic scale, the diagram is no longer a curve but consists of linked straight lines, and coefficient α represents tangents of the angle between the recession curve and the absciss (see Figure 8). The theory assumes that changes in the α angle reflect the changes of aquifer characteristics.

Water flows from different parts of a karst system depending on the water level (piezometric pressure), so its chemical and physical characteristics may change rapidly. These changes are mainly ascribed to the inflow of water from epikarst zone and vadose zone conduits. Vadose zone water is pushed out by thaw, thaw-rainfall, and rainfall water (Tyc 1997). The Glijun spring is thereby mostly fed by dispersed flow.

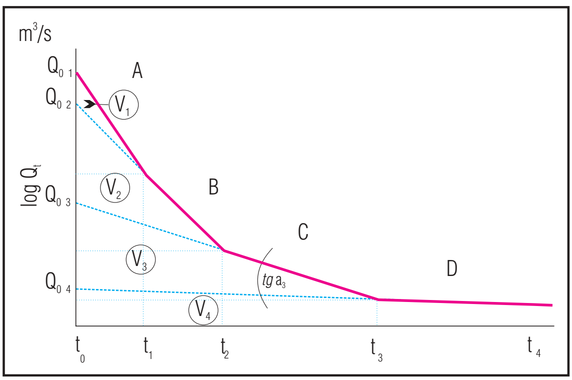

Figure 8: The recession curve on a normal logarithmic scale (modified from Mijatović 1968: 51).
Slika 8: Krivulja praznenja na normalni logaritemski skali (po Mijatoviću 1968: 51).

The model is based on theoretical findings and may be used in practice. The recession is fastest when water flows through conduits and large fissures (m^1) and when the flow is turbulent ($\alpha - n \times 10^{-1}$). When flow through narrower conduits prevails (m^{-1}), coefficient α is lower ($\alpha - n \times 10^{-2}$) and the recession curve becomes gently sloping. Dispersed flow through fractures, fissures, and narrow passages (m^{-2}, m^{-3}) is usually slow but under high hydrostatic pressure ($\alpha - n \times 10^{-3}$).

In normal conditions, water flows through all the types of passages mentioned above at the same time. The ratio between different types of passages depends on the hydrostatic pressure and it is thus connected to the changes of piezometric level and quantity of water (left) in the system.

Conduit flow dominates and water reserves empty proportionally faster at the beginning of the recession. After some time (days), dispersed flow prevails over conduit flow and the discharge slowly and asymptotically approaches the zero value. Four different discharge recession regimes that follow one another and are separated by an instant change of coefficient α may usually be distinguished (A, B, C, and D in

Figure 8). The ratio between conduit and dispersed flow can be calculated. Discharge is determined by the extent of the catchment area and underground passages that control the maximum discharge. The discharge of a spring may recess, depending on the ratio between dispersed and conduit flow, from a period of a few days (e. g., the Aliou spring) to several months (e. g., the Torcal spring) (Pulina 1999).

Later, the graphic method was used to determine the characteristic points (times) of the Glijun recession curve. »Zero point« was determined at the time of the highest discharge (1.798 m^3/s). Other characteristic points helped us to determine coefficient α and the proportion of water flowing through the different types of passages. The second characteristic point was determined after one day and the third nine days after the maximum discharge.

TABLE 7: COEFFICIENT α AT CHARACTERISTIC POINTS (TIMES) FOR THE GLIJUN SPRING.
PREGLEDNICA 7: KOEFICIENT α OB ZNAČILNIH TOČKAH (ČASIH) ZA IZVIR GLIJUN.

	Discharge (m^3/s)	Log (discharge)	α coefficient	α – angle in degrees
Point/time »0«	1.8	0.255	–	–
Point/time »1«	0.7	–0.161	0.9572847	43.75
Point/time »2«	0.2	–0.699	0.1376463	7.84
Point/time »3«	0.1 (assumed)	–1.000	0.0099020	0.57

The calculations show that total volume of water stored in joints and fissures (belonging to Glijun catchment area) amounted to 82.6% of the total water volume at the beginning of the recession. This volume also presents the ratio of dispersed flow at the end of the recession. The middle size conduits (dm) contributed up to 13.9% of the total discharge whereas the fastest flowing conduit water contributed only 3.5% of the water volume. The proportion between volumes is 1:4:20, similar to the proportion between the discharges at the beginning, middle stage, and end of the recession (1:3:9).

There were about 2.5 million cubic meters of water in the Kanin massif (Glijun) aquifer at the beginning of the recession (2,535,710 m^3) and about 2.0 million at its end (2,094,122 m^3). About 500,000 m^3 of water drained from the system.

TABLE 8: MEAN MONTHLY VALUES OF SELECTED PHYSICAL AND CHEMICAL CHARACTERISTIC OF THE GLIJUN SPRING BASED ON THE DATA FROM KUNAVER (2000), NOVAK (1979), AND OUR MEASUREMENTS. TEMPERATURE IS EXPRESSED IN DEGREES CELSIUS (° C), HARDNESS IN GERMAN DEGREES (° DH), AND DISCHARGE IN M^3/S. VALUES HIGHER THAN AVERAGE ARE SHOWN IN BOLD TYPE. (»H« – HARDNESS; »EST.« – ESTIMATE).
PREGLEDNICA 8: POVPREČNE VREDNOSTI IZBRANIH FIZIKALNIH IN KEMIČNIH PARAMETROV ZA IZVIR GLIJUN, KI TEMELJIJO NA RAZISKAVAH KUNAVERJA (2000), NOVAKA (1979) IN NAŠIH MERITEV. TEMPERATURA JE IZRAŽENA V STOPINJAH CELZIJA, TRDOTA V NEMŠKIH TRDOTNIH STOPNJAH IN PRETOK V KUBIČNIH METRIH NA SEKUNDO (»H« – TRDOTA, »EST« OCENA).

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Temperature (° C)	7.05	6.84	7.14	7.03	5.88	6.15	5.41	5.88	6.07	7.16	6.68	6.38	6.47
Total h. (° DH)	5.43	5.58	5.53	5.23	4.79	4.53	4.52	4.89	4.97	5.34	5.18	3.47	4.95
Carbonate h. (° DH)[6]	5.34	5.00	3.93	4.89	4.32	4.14	4.14	4.39	4.65	5.10	4.72	2.23	4.40
Calcium h. (° DH)	4.59	4.35	4.77	4.57	3.88	3.36	3.65	3.57	3.78	4.70	4.06	2.02	3.89
Magnesium h. (° DH)	0.99	1.43	1.17	0.90	1.07	1.45	1.66	1.59	1.39	1.08	1.21	1.53	1.29
Dry remain (mg/l)	90.5	102.00	90.7	94.0	75.00	93.50	78.50	78.50	91.00	87.00	100.50	96.00	89.76
Discharge (est.) (m^3/s)	0.53	0.80	2.25	3.50	10.0	20.00	9.00	1.80	0.96	2.03	3.10	0.81	4.57

A comparison of the discharge (Glijun) and precipitation (Plužna) data shows that Glijun receives water from about 8.5 km^2 of surface area. However, since the discharge varies seasonally, the catchment area is

[6] Average carbonate hardness values were calculated from the measurements of Novak (1979) and Komac (2000). During the sampling in March 2000 there was some rain, and the carbonate hardness amounted to only 2.9° DH. Novak's measurements show that the carbonate hardness value in March is usually higher and amounts to 4.95° DH. The average carbonate hardness value calculated in Table 8 is therefore too low.

very likely somewhat larger given the lower discharge in winter when precipitation is held in the snow blanket and may extend to about 10 km^2, encompassing about one fifth of the surface of the Kanin massif above 500 meters. As noted above, the chemical and physical properties of the water may also differ significantly according to the changes in the piezometric level and the quantity of water in the system. Studies at the Lintvern spring near Vrhnika show that the actual catchment area may be twice as large as the one suggested by morphological and relief factors (Habič 1970).

5. Conclusion

The field and laboratory work carried out during this study has provided some new information. The hydrogeographical importance of the springs at the foot of the Kanin massif is determined by its position in the Julian Alps in western Slovenia. The karst Kanin massif is a part of the Southern Alps and the Krn nappe and forms the northern part of the east-west oriented Bovec syncline composed of Triassic, Jurassic, and Cretaceous rock. The carbonate rock layers are 2,600 meters thick, flysch amounts to 600 meters, and Quaternary sediments have been bored down to 320 meters.

The Kanin massif contributes waters to three river basins, the Adriatic Sea, and the Black Sea. The watersheds of the springs are mainly determined by the geological structure (runoff to the Slovene part of the Kanin massif is six times greater than to the Italian part) while their climatic conditions depend on their location, altitude, etc., and control the formation of characteristic mountain vegetation belts. The area is characterized by high and rapid water drainage linked to high precipitation, low evapotranspiration, a complex geological structure, and karst phenomena.

Differences in physical and chemical characteristics of karst springs in limestone and flysch at the foot of the Kanin massif are negligible since the flysch is also composed of carbonates (Komac 2000).

The exact extent of the catchment areas of the karst springs in the Kanin massif is (still) unknown. Our calculations show that the Glijun spring drains about a fifth (10 km^2) of the Kanin massif. This catchment area is very likely larger, but the exact outline of the karst watershed, which depends on geological structure and actual water quantity in the system, is unclear and unknown because the water flows in different directions at different levels. About fifty square kilometers of the Kanin massif contribute water to the Slovene side while eight square kilometers contribute water to the Italian side. The discharge to the Slovene side is about six times greater than the discharge to the Italian side. The runoff coefficient amounts to about 90.6–93.5% while specific runoff amounts to 94.8 $l/s/km^2$.

Karst springs collect water from different levels and have differing discharge regimes as well. Springs at higher elevations react quickly to precipitation, dry up in winter, and have their highest discharge in spring due to snow melting in the mountains. Springs at lower elevation collect diffuse water in dry periods. The Boka, Glijun, and Goriuda springs also collect water from the vadose zone while the Žvika, Vodica, and some other smaller springs collect diffuse water from lower elevations and deeper parts of the massif. A chemical analysis done during a period of high water on November 14, 1997, showed low values of Mg^{2+} ions at the Boka, Glijun, and Goriuda springs compared to amounts in other springs. The difference indicates that these three springs collect water from conduits that pass through Dachstein limestone. The rapid flow through larger channels in the system was also proven by the higher amount of organic substances found in these springs (Cucchi et al. 1997).

The research area is highly vulnerable to water pollution due to its karst character, low discharges during dry periods, and fast throughflows at maximum water levels (precipitation, melting of snow); however, this area is also extremely important since it provides possibilities for the water supply of the Bovec Basin (and beyond).

We should seriously consider the fact that water is polluted by organic pollutants due to tourist activity (ski resorts) on the Kanin massif. More detailed water tracing investigations should therefore be undertaken to provide a significant amount of data for ensuring the protection of the area. The decision-making authorities should further consider the importance of high-mountain karst areas in Slovenia, their role in everyday life, and the use of their resources today and tomorrow. In all probability, the importance of the Kanin massif will increase due to its international position and the proximity of densely populated areas that lack good (potable) water resources. It appears that all alpine karst water aquifers are going to be increasingly important in future, and protecting them now would definitely be worth the money and effort involved.

6. Bibliography

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7. Summary in Slovene – Povzetek

Kraški izviri pod Kaninskim pogorjem

Blaž Komac

1. Uvod

Slovenija je dežela gora, voda, povirna dežela in dežela prehodnosti v naravno- ter družbenogeografskem smislu. Označuje jo prevlada zahodne zračne cirkulacije, reliefna razčlenjenost pretežno goratega in hribovitega ozemlja, skromna zastopanost ravninskega sveta, dobra namočenost, pestrost tipov prsti ter prevladujoči gozdni ekosistemi ob skromnih razmerah za poljedelstvo in skromni naravni viri (Gams 1991).

Slovenija je tudi dežela krasa, ki je nastal predvsem na apnencih, dolomitiziranih apnencih in dolomitih. Kras zaznamuje skoraj polovico površine državnega ozemlja in tudi preučevano območje v Julijskih Alpah v zahodni Sloveniji. Julijske Alpe večinoma pripadajo Posavju in Posočju. Relief na severni strani Julijskih Alp se razlikuje od tistega na južni strani, saj so dolinska dna na različni nadmorski višini. Zgornja Savska dolina leži na 800 m, Soča pa je svojo dolino vrezala za približno 200 m nižje. Razlika je posledica dejstva, da ima Soča večjo erozijsko moč, saj je njen izliv v Jadranskem morju bližje, kot je Zelencem izliv Save v Črnem morju. Za Posočje so značilna strma pobočja apneniških in dolomitnih gora in številni kraški izviri na njihovem vznožju, nad gozdno mejo pa se je razvil visokogorski kras (Kunaver 1983).

Visokogorski kras je značilen tudi za Kaninsko pogorje, podolgovat kraški masiv v zahodnih Julijskih Alpah, ki sega 2587 m visoko in obsega približno 58 km^2. Za pogorje je značilna prehodna lega, saj je del alpske »hidrogeografske strehe« in prispeva vodo v tri reke in dve morji. Na severovzhodu in vzhodu ga omejujeta dolini Možnice in Koritnice, na jugu pa soška dolina. Na zahodu je pogorje omejeno z dolino Učje, idrijsko prelomno cono in dolino Rezije, ki teče v Tilment. Dolini Reklanice in Jezernice, ki pogorje omejujeta na severu, sta nastali ob reklanski prelomni liniji.

Kaninsko pogorje je območje zalog pitne vode in izvirov, ki so za prebivalce Bovškega zaradi svoje vodnatosti in stalnosti že od nekdaj pomembna obeležja v življenjskem (pitna voda), praktičnem (varovanje pred onesnaževanjem in poplavami), gospodarskem (pridobivanje električne energije), ter simbolnem pomenu.

Količina vode je omejena, velik del za človeka ni dostopen, zato je treba biti pri načrtovanju njene rabe zelo previden. V ta namen raziskovalci že desetletja intenzivno preučujejo zaledja posameznih izvirov, določajo najmanjše pretočne količine, ki še zagotavljajo zadostno oskrbo in obseg in prepustnost kraških kamnin.

2. Geološka zgradba

Prve geološke raziskave v Julijskih Alpah segajo v 19. stoletje. Sprva so bile raziskave stičnega ozemlja med Južnimi Alpami ter Notranjimi in Zunanjimi Dinaridi namenjene predvsem strateškim potrebam, kasneje pa iskanju mineralnih surovin, zagotavljanju virov pitne vode in proizvodnji električne energije.

Širše območje tektonsko uvrščamo v Dinaride, ki jih sestavljajo Južne Alpe, Notranji Dinaridi in Zunanji Dinaridi (Jurkovšek 1987). Južne Alpe sestojijo iz manjših tektonskih enot, med katerimi je tudi Krnski (Julijski) pokrov. Sestavlja ga 1000 m debela in široka plošča dachsteinskega apnenca, ki obsega skoraj celotne Julijske Alpe in je bila narinjena od severa proti jugu za približno 20 km čez kredni fliš v Bovški kotlini. Kaninsko pogorje je del Krnskega pokrova (Buser 1978). Na območju Bovške kotline se srečujejo Južne Alpe in Zunanji Dinaridi (slika 3), zato lahko ozemlje med Bovško kotlino, Stolom in Muzci ter Kaninskim pogorjem na podlagi paleogeografskega razvoja in orografskih značilnosti uvrstimo v Južne Alpe, glede narivne pripadnosti k podmelškemu pokrovu, ki pripada Notranjim Dinaridom. Na obravnavanem območju leži Krnski pokrov na Podmelškem (Placer 1999).

Bovška kotlina je velika, od vzhoda proti zahodu usmerjena in globoka sinklinala, ki gradi stično ozemlje med Južnimi Alpami in Zunanjimi Dinaridi. Geološka zgradba Bovške kotline in njene okolice je sila pestra, v podrobnostih pa raznolika in zapletena. Pripada zahodnim Julijskim Alpam, ki jih od vzhodnih loči Mojstrovški prelom. Pod tem prelomom so zahodne Julijske Alpe podrinjene pod vzhodne. Bovška kotlina je nastala na sotočju dolin in je bila močno preoblikovana s tektonskimi premiki in rečno ter ledeniško erozijo. Oblikovali so jo tektonski premiki v smeri od jug–jugovzhod do sever–severovzhod, ki trajajo od miocena dalje, zato je v jugozahodnem delu, kamor tone njena os, močno stisnjena. Kaninsko pogorje gradi severno krilo sinklinale in vse kamninske plasti ležijo normalno ene na drugih ter vpadajo proti jugu. Južno krilo sinklinale gradi antiklinala Polovnika (Placer 1999). Tektonska dinamika je pripomogla k nizki legi kotlinskega dna. Strmec doline je zaradi neotektonske aktivnosti dokaj uravnan (5,6 ‰) in reka Soča se med Kršovcem in Trnovim ob Soči na razdalji dobrih enajstih kilometrov spusti le za 62 m.

Nekdaj enotna karbonatna platforma Kaninskega pogorja iz dachsteinskega apnenca je bila s prelomi razkosana v posamezne tektonske bloke. Nekateri so bili dvignjeni, prišlo je do zdrsov, ponekod pa do horizontalnih zmikov (Antonini in Squassino 1982). Domneva se, da je bil italijanski blok dvignjen glede na slovenskega (Gasparo 1982). Prevladujejo starejše dislokacije alpske (V–Z) in mlajše dinarske smeri (SZ–JV) (Buser 1978). Kaninsko pogorje prečka med dolinama Učje in Rezije Idrijski prelom, ki je ena največjih tektonskih con v južnoalpskem prostoru, ki se razteza v dinarski smeri iz Hrvaške preko Notranjskega podolja do Zgornjega Posočja (Čar in Pišljar 1993).

Velja omeniti tudi Možniški, Jalovški in Mojstrovški prelom ter prečno potekajoče Polovniški, Krnski in Ravenski prelom. Polovniški prelom poteka z južnega pobočja Kanina med Malo Babo (1936 m) in planino Ban, prek izvira Boke na Polovnik in Drežniške Ravne. Krnski prelom preide s Kanina v Bovško kotlino in teče preko Polovnika ter poteka severno od Drežnice na Krn (2245 m). Severozahodni del Krnskega preloma imenujemo tudi Ravenski (Ravnikarski) prelom (Jurkovšek 1987). Na severu Kaninsko pogorje omejuje reklanska tektonska linija (Chiappini in ostali 1995).

Na podlagi pretrtosti kamnin ob prelomih ločimo zdrobljene, porušene in razpoklinske cone. Zdrobljene cone so za vodo neprepustne sicer pa mehansko slabo odporne. V dolomitu so praviloma širše in milonitizirane, v apnencu pa nastajajo breče. Porušena cona je močno porozna, zelo dobro prepustna za vodo in hidrološko pomembna predvsem v dolomitih. Ker je kamnina v porušeni coni razpokana v različno velike bloke in se voda pretaka okrog njih, lahko teče vzdolž cone ali pa prečno nanjo. Razpoklinske cone so zelo dobro prepustne za vodo, zato se v njih oblikujejo najpomembnejši kraški prevodniki (Čar in Janež 1992, Čar in Pišljar 1993). V dolomitu se voda usmerja vzdolž prelomih con, kjer lahko voda spira zdrobljeno kamnino. Včasih v kraških izvirih najdemo dolomitni pesek, kot na primer v enem od občasnih izvirov Kladenkov zahodno od vasi Plužna. Na presečiščih prelomnih struktur s stratigrafskimi in litografskimi prehodi pogosto nastanejo kraške votline.

Najstarejše kamnine na Bovškem so iz triasa, ko je ozemlje Julijskih in Kamniško-Savinjskih Alp preplavilo plitvo morje, kjer se je odlagal apnenec, iz katerega je z dolomitizacijo nastal zgornjetriasni dolomit. Najprej je nastala okrog 1000 metrov debela skladovnica kamnine, ki jo danes poznamo kot karnijski in norijski (glavni) skladoviti mikritni dolomit, nanjo pa se je odložil dachsteinski apnenec. Dolomit izdanja ob prelomih v dolini Krnice, normalno pa leži pod dachsteinskim apnencem v Možnici in dolini Reklanice (Jurkovšek 1987).

Na površju severnega krila bovške sinklinale najdemo do 1200 metrov debelo skladovnico norijsko-retijskega mikritnega dachsteinskega apnenca, ki v leži konkordantno na glavnem dolomitu in tektonsko pripada krnskemu pokrovu. Zanj so značilne do 2 metra debele plasti in fosili megalodontidnih školjk. Pretrt in zaradi subvertikalnih prelomov globoko zakrasel dachsteinski apnenec je za vodo zelo dobro prepusten, tako da lahko kraški izviri na zunanje padavine reagirajo že po nekaj urah (Gams 1974: 40). Dolomit lahko v odvisnosti od vodnih razmer deluje tudi kot bariera. Zato imajo nekateri deli kraškega podzemlja značilnosti akvikluda. Nagnjenost kamninskih skladov na Kaninskem pogorju je odvisna od strukture sinklinale, zato je na severu (15°–20°) manjša kot na jugu, kjer presega 40°. Južna pobočja Kaninskega pogorja so skladna in položna, severna pa strma in neskladna, kar je značilnost povirnih dolin Soče in Save (Kunaver 1983). Velika debelina dachsteinskega apnenca je vplivala na razvoj krasa in naravo ter položaj kraških izvirov.

Kmalu po začetku jure je bila julijska karbonatna platforma razkosana na posamezne bloke, ki so se hitro pogrezali. Na njih se je začela sedimentacija globljevodnih sedimentov (Buser 1986) in na podlago iz triasnega dolomita ter apnenca so se v liasu odložile 300 m debele plasti lapornatega apnenca. Kasneje se je morje poglobilo. V spodnji kredi so nekatera območja zaradi okopnitve zakrasevala, v zgornji kredi pa so nastali globoki morski bazeni, kjer se je odlagal fliš, nanj pa 50–100 m debele plasti apnenčeve breče in rdečega laporja v geološki literaturi znane kot scaglia. V terciarju se je začelo območje Julijskih Alp zaradi pritiskov od severa gubati, kjer so se gube prelomile, pa je prišlo do narivanja proti jugu. Fliš, ki pokriva celotno kotlinsko dno, je bil deloma odstranjen in je bil kasneje večinoma prekrit s plastjo kvartarnih sedimentov, ki sega 320 metrov pod površje, izdanjen pa je na severnem obrobju kotline in v dolini Slatenika.

Fliš je debelejši v vzhodnem delu kotline, kjer dosega debelino 200–500 m, proti zahodu pa se izklinja. V kvartarju se je ozemlje Julijskih Alp dvigalo, nekatera ozemlja pa so zastajala in nastale so udorine, v katere so se odlagali sedimenti. V Bovški kotlini so se usedali rečni (pesek, prod), jezerski (jezerska kreda), rečno-ledeniški (prod, konglomerat) in ledeniški nanosi (ledeniške morene). Soča in Koritnica sta večkrat premeščali nanose, ki so danes območje zalog pitne vode (Kuščer in ostali 1974, Jurkovšek 1987, Premru 1975).

Izviri pod Kaninskim pogorjem so odvisni od geološke zgradbe. Nastali so predvsem tam, kjer geološka zgradba omogoča iztekanje vode iz kraškega masiva. Predvsem gre za odtekanje po prepustnih razpoklinskih conah in vode vzdolž stratigrafske zgradbe. Izviri v najnižji legi so nastali predvsem na nivoju lokalne erozijske baze oziroma na stiku prepustnih karbonatnih kamnin z manj prepustnimi, kot je na primer fliš. Domnevamo, da voda iz kraškega podzemlja priteka na površje tudi skozi flišni pokrov, kjer je ta tanjši ali razpokan. Ker fliš vsebuje veliko karbonatnih sestavin, ni bistvenih razlik med trdoto voda, ki izvirajo na flišu in trdoto voda, ki izvirajo na apnencu. Vode v izvire na dnu Bovške kotline usmerjajo tudi sinklinalno zasnovana tektonska zgradba in pretrta kamnina ob narivnih stikih.

3. Podnebje

Podnebne razmere na Bovškem označuje gibanje zračnih mas od zahoda proti vzhodu, lega v reliefno pestro izoblikovanem svetu in položaj na obrobju alpskega sveta, kjer se prepletajo vplivi alpskega podnebja z nekaterimi elementi sredozemskega. Ogrin (1996) uvršča dno doline Soče in Koritnice med območja z zmernokontinentalnim podnebjem zahodne Slovenije. Območja v višinah 1500–2000 m uvršča med območja s podnebjem nižjega gorskega sveta v zahodni Sloveniji. Sem spada območje Stola (1673 m), nižji deli Kaninskega pogorja od doline Učje do Rombona (2208 m) in severno obrobje doline Koritnice do Mangarta (2679 m). Za najvišje dele Julijskih Alp, kot tudi Kaninsko pogorje, je značilno podnebje višjega gorskega (visokogorskega) sveta.

Povprečna letna temperatura zraka v Bovcu je bila 9,2° C v obdobju 1961–1990. Srednja mesečna temperatura zraka je najvišja julija (18,7° C), najnižja pa januarja (–0,7° C). Srednje mesečne temperature zraka dosegajo nadpovprečne vrednosti od maja do oktobra, podpovprečne pa od oktobra do aprila. Temperature so oktobra še vedno višje kot aprila, kar kaže na sredozemskost temperaturnega režima. Pozimi je pogosto tudi v dnu doline občuten vpliv gorskega podnebja.

Na večjih nadmorskih višinah so temperature odvisne od ekspozicije in naklona površja, osončenosti, vsebnosti vlage v zraku, snežnega in rastlinskega pokrova, kot tudi reliefnih mikrooblik. Z višino narašča število dni z minimalno temperaturo pod 0° C, ki traja v višinah nad 2500 m več kot šest mesecev. Na Kredarici (2514 m) je povprečno 250,7 takšnih dni, na Komni (1520 m) pa 166 (Klimatografija Slovenije 1991). V gorskem svetu obstaja izrazita vertikalna temperaturna conalnost. Povprečni temperaturni gradient je v atmosferi –0,65°/100 m, v alpskem svetu Slovenije pa –0,42°/100 m. Na nadmorski višini 1600 m lahko julija pričakujemo povprečno temperaturo 11,3° C, sto metrov višje pa temperaturo 10,6° C. Na višini 1530 m je povprečno 166 dni s temperaturo nižjo od 0° C, na višini 2500 m pa lahko pričakujemo 250,7 mrzlih dni (Klimatografija Slovenije 1991, Kerbler 1997, Lovrenčak 1987).

Nastanek padavin je odvisen od ciklonskih, frontalnih in konvektivnih mehanizmov, vendar na količino padavin vpliva relief, zato lahko v razporeditvi izohiet vidimo njegov odsev. V Julijskih Alpah prejmejo zahodne in južne lege več padavin kot vzhodne in severne. Običajno prejmejo višje lege višjo količino padavin, v Zgornjem Posočju (Žaga) pa lahko opazujemo zanimiv pojav padavinske inverzije, ko nižje lege prejmejo več padavin kot višje (Bernot 1978). V gorah nad dolino Soče pade v enem letu običajno več kot 3000 mm padavin. Ker z izjemo totalizatorja na Kaninskem pogorju v gorskem svetu ni padavinskih postaj, si moramo pri interpretaciji pomagati s podatki padavinskih postaj v dolini. Tako je v obdobju 1961–1990 na Žagi padlo 3018 mm, na Plužnah 2953 mm in v Bovcu 2735 mm padavin. V Bovcu so najvišjo količino padavin izmerili leta 1965 (3620 mm), najnižjo pa leta 1981 (2039 mm) (Klimatografija Slovenije 1991). Velik razpon kaže na izredno variabilnost padavin, ki jo za slovenske razmere opisuje Ogrin (1996).

Na Kaninskem pogorju so v obdobju 1953–1964 s totalizatorjem izmerili 3418 mm povprečnih letnih padavin, v obdobju 1990–1999 pa 3064 mm. Izmerjeno količino padavin v visokogorju moramo korigirati zaradi izgub, ki so posledica napake merjenja, vetra, izhlapevanja (Kolbezen in Pristov 1998). Če privzamemo, da za Kaninsko pogorje velja enak korekcijski faktor kot za Kredarico (2514 m), kjer pade povprečno 3228 mm padavin, bi znašala korigirana vrednost količine padavin na Kaninskem pogorju kar 3900 mm.

Za podnebje na Bovškem je značilna tudi visoka intenzivnost padavin. V Bovcu so običajno 60 dni v letu padavine, ki so višje od 10 mm in 40 dni v letu padavine, ki so višje od 20 mm. Na običajni padavinski dan novembra, decembra in oktobra pade 30 mm padavin. Zaradi visoke intenzivnosti pade običajno več kot 45 % letne količine padavin le v 15 % dni. V višjih legah se spomladanski višek padavin pomika v poletje in nastopi v visokogorskem svetu julija, jesenski pa se začenja mesec dni prej kot v nižinah. Z analizo razmerja med padavinami in odtokom je Radinja (1978: 104) ugotovil, da sneg v Zgornjem Posočju običajno prispeva 22 % količine padavin.

V Zgornjem Posočju sneži prvič oktobra oziroma novembra, zadnjič pa aprila oziroma maja, na Mangartskem sedlu (2060 m) pa ne mine mesec brez snežnih padavin. Debelina snežne odeje je v obdobju 1951–1990 na Kredarici večkrat presegla 500 cm, leta 2001 je bila višja od 700 cm. Pri merilni letvi na spodnjem koncu ledenika je snežna odeja spomladi leta 1979 dosegla celo debelino 820 cm (Košir, 1986: 108). Na Kaninskem smučišču je količina padavin običajno nižja, vendar lahko na nekaterih območjih preseže 10 m zaradi vpliva vetrov, in poglobljenih reliefnih oblik. Konkavna območja (kotliči, vrtače, vznožja strmejših skokov in plazišča) so območja zbiranja snega, pospešene korozije in hitrejšega poglabljanja površja glede na konveksno okolico. Prihaja do razlik v debelini snega, ki dosegajo razmerje od 1 : 2 do največ 1 : 5, zato se na konkavnih reliefnih območjih zbira snežnica in tudi vodni odtok je lahko na konkavnih območjih (4000 mm) en krat večji kot na konveksnih (2000 mm) (Kunaver 1978).

Na Kaninskem pogorju je evapotranspiracija razmeroma nizka zaradi prevlade kraškega odtoka in manjšanja pokritosti s prstjo in rastlinskim pokrovom z višino. Na višini 2200 m zmanjšanje doseže 40 % in obsega okrog 550 mm (Kolbezen in Pristov 1998). Približno 40 % vode izhlapi na nadmorskih višinah 500–1000 m, petina na višinah 1000–1500 m, slaba tretjina v višinah 1500–1800 m, 15 % v višinah 1800–2000 m, desetina pa nad 2000 m, čeprav obsegajo najvišja območja skoraj četrtino vseh površin. Na južni strani Kaninskega pogorja izhlapijo tri četrtine vode v višinah 500–1800 m, slaba polovica pa v višinah 500–1500 m, kar kaže na vpliv vegetacije. Preostanek vode odmakajo kraški izviri.

4. Kraški izviri

Večina večjih izvirov na svetu je kraških. V Sloveniji 125 vodnatih kraških izvirov daje povprečno 35 m^3/s in tudi po daljših sušnih obdobjih je na razpolago kar 27 m^3/s vode. Z vodo iz kraških izvirov se oskrbuje več kot polovica slovenskega prebivalstva. Ker izvirska voda ne zadosti vsem potrebam (38,6 m^3/s), se za pitno vodo črpa tudi podtalnica. Zaledja nekaterih so izpostavljena močnemu onesnaževanju (Plut 2000).

Geološka zgradba Kaninskega pogorja omogoča pojav voda na boku kraškega masiva v Bovški kotlini (Bočič, Boka, Sušec – Mala Boka, Žvika, Vodica, Glijun, Kladenki, Srnica) in na severu (Možnica, Goriuda). Višje na pobočjih so le občasni izviri. Voda je prisiljena priteči na površje zaradi gladine talne vode v kvartarnih sedimentih ali pa jo na dan silijo slabše propustne kamninske plasti. Nekateri manjši izviri na flišu v Bovški kotlini so zajeti za bovški vodovod.

V krasu Kaninskega pogorja so se razvile značilne hidrogeografske (vadozna, freatična, občasno zalita) cone. Freatična in vadozna cona se razlikujeta po smeri in načinu vodnega toka ter količini vode, loči pa ju vsakokratna (navidezna) višina piezometrične gladine, ki niha tudi za več kot 100 metrov. Spremembe so lahko zelo hitre. V freatični coni so vsi prostori zaliti, v njej prevladuje počasno sifonsko, tlačno pretakanje vode, ki ni odvisno od gravitacije, temveč od hidrostatičnega pritiska. V vadozni coni ni stalnih vodnih tokov, voda se pretaka skoraj izključno vertikalno v odvisnosti od strukturnih in litoloških razmer. Količina vode v sistemu je odvisna predvsem od pritoka in odtoka iz sistema, pa tudi od privilegiranih con, ki omogočajo nastanek zalog (Prestor 1992) in prevladujočih kanalov v vodonosniku (razpoklinski, cevni, difuzni).

V spodnjem delu vadozne cone se na stiku s freatično v odvisnosti od vsakokratnih hidrogeografskih razmer oblikuje cona horizontalnega odtoka vode iz kraškega masiva. Iztok se usmerja proti tistemu kanalu, ki najlažje odvaja vodo iz kamnine. Zato nastajajo jame v freatičnem sistemu od spodaj navzgor (Mihevc, 1998: 13).

Razvoj podzemeljskega krasa je odvisen od geomorfnega razvoja površja, velja pa tudi obratno. Večina izvirov v dolini zgornje Soče je danes na vznožju visokogorskih masivov v nivoju lokalne erozijske baze, kraški kanali pa so večinoma nastali globlje s pretakanjem vode v freatični coni. Hitro dviganje ozemlja Julijskih Alp je po ledeni dobi omogočilo hitro in globoko vrezovanje dolin in spremembe rečne mreže. V splošnem je v hladnejših obdobjih pleistocena prevladovalo intenzivno mehanično preperevanje, globinska korozija in ledeniška erozija, ob njihovem koncu pa je potekalo obsežno nasipavanje fluvioglacialnih teras. Kraški sistem se je moral prilagajati vedno novim spremembam lokalne erozijske baze. Med vmesnimi otoplitvami in po zadnjem glacialu se je povečala erozijska moč rek. Prišlo je do vrezovanja, doline so se poglabljale in kraški izviri so v tej fazi spet prešli na nižje lege (Žlebnik 1990).

Prilagajanje kraškega sistema je običajno počasnejše kot spremembe, ki so ga povzročile. Apnenčasti masivi so zaradi podvrženosti koroziji in tektonskega dviganja gora ter hkratnega poglabljanja dolin močno zakraseli. Zato so tudi številni kraški izviri in nekdanje izvirne jame obstali visoko nad dolinskim dnom. Na Kaninskem pogorju je zaradi več-stopenjskega razvoja nastal vodonosnik v več ravneh. Čeprav nadmorske višine posamezne ravni ne moremo natančno določiti zaradi prepletanja jamskih rovov v širokih spletih, lahko na italijanski strani Kaninskega pogorja ločimo tri ravni na višinah 870 m, 1150 m in 1500 m (Muscio in ostali 1983). Ker je pri usmerjanju podzemnih tokov pomembnejše kemično raztapljanje in mehansko širjenje starih rovov kot nastajanje novih, so ponekod verjetno tudi nekaj sto tisoč let stari in višji rovi obdržali aktivno vlogo do danes (Audra 2000).

Dokaz za dejstvo, da je vrezovanje površinskih voda v interglacialih in holocenu ponekod potekalo tako hitro, da mu podzemeljski tokovi niso mogli slediti, so kraški izviri visoko v pobočjih nad dnom dolin (Boka) in jame v več etažah (Pološka jama). Posledica opisanega razvoja je dejstvo, da so nižje ležeče jame praviloma vodno aktivne (Glijun), višje ležeče jame pa neaktivne, suhe ali aktivne le občasno (Mačkova jama, Srnica). Zanimivo je opazovati zamik v delovanju Boke v primerjavi z Glijunom. Raziskave namreč kažejo, da ima Boka zaledje v višji nadmorski višini kot Glijun, Bočič ali Sušec (Mala Boka), kar je posledica vodoržnih prelomnih in dolomitnih con.

Poglabljanje dolin je povečalo vlogo litološke in tektonske zgradbe pri oblikovanju kraških masivov glede na položaj izvirov in njihovo zaledje. Jamski sistemi se lažje prilagajajo spremembam erozijske baze v robnih, bolj pretrtih in zakraselih delih karbonatnega masiva, zato so kamnine v notranjosti kraških masivov manj zakrasele kot bližje površju. Bolj kot je kamnina pretrta in zakrasela, lažje voda najde nižjo pot na površje (Kuščer in ostali 1974).

Kjer je kamnina bolj kompaktna, manj prelomljena in razpokana, imata glavno vlogo pri usmerjanju in oblikovanju podzemeljskih rovov litološka zgradba in vpad kamninskih plasti (Gasparo, 1983: 433), sicer pa je pretakanje vode v Kaninskem pogorju bolj prilagojeno sistemu razpok in prelomov kot poteku kamninskih plasti in lezik (Antonini in Squassino 1982, Casagrande in ostali 1999).

Na Kaninskem pogorju tako poznamo dve vrsti jam: tiste, ki so nastale kot del freatičnega sistema in tiste, ki so nastale od zgoraj navzdol z vertikalnim prenikanjem deževnice in snežnice ob robu ledenika ali pa s prenikanjem vode skozi ledeniške in tektonsko predisponirane razpoke. Ker voda v visokogorskem svetu ne odlaga sige, so nekatera brezna nastala tudi z delovanjem prenikajoče vode. Po primerjavi trdote vode, ki prenika v Triglavsko brezno in tiste, ki izvira v dnu doline, se je pokazalo, da voda ni povsem zasičena s karbonatom in bi bila zato sposobna korozije tudi do globine 1000 metrov (Gams1993). V nekaterih jamah na Kaninskem pogorju, kot sta jama Mala Boka in Veliko Črnelsko brezno, so našli tudi sigo, ki je verjetno nastajala v podnebju drugačnem od današnjega.

Na Kaninskem pogorju je odkritih že več kot 800 kraških brezen (jam), od tega jih je enajst globljih od 500 m. Najgloblje doslej odkrito brezno je imenovano Čehi II (1500 m), leta 1996 pa je bila v breznu Vrtiglavica odkrita najgloblja vertikala na svetu v breznih doslej (–643 m). Najgloblja jama na svetu je Veronja v Gruziji, ki sega 1710 m globoko. Doslej je bilo odkritih 6 jam, katerih globina presega 1500 m in kar 70 jam globljih od 1000 m (NSS World Deep Cave List).

4.1. Vodni odtok s Kaninskega pogorja in pretoki v Bovški kotlini

V zadnjih desetletjih so na Kaninskem pogorju izvedli vrsto sledenj voda. Glavni namen raziskav je bila določitev količine, kakovosti in razpoložljivosti pitne vode. Sledenja voda kažejo, da se zaradi specifične geološke zgradbe večina vode s Kaninskega pogorja odteka v izvire med Bovcem in Žago (Glijun, Žvika, Boka, Bočič). Boka odmaka zahodni del pogorja, osrednji del pripada Glijunu, le manjši del vode pa odteka na italijansko stran Kaninskega pogorja in v izvire Možnice. Sledenja voda kažejo, da odteka voda v izvire na Bovškem tudi z italijanske strani Kaninskega pogorja. V Glijunu in Možnici je kakovost vode občasno poslabšana zaradi vsebnosti bakterij (Cucchi in ostali 1997, Novak 1992).

Ob običajnih vodnih razmerah odteka s Kaninskega pogorja povprečno 5,5 m^3/s vode. Posočju pripada približno 50 km^2 ozemlja in večji delež vodnega odtoka (4,76 m^3/s). Na italijansko stran odteka povprečno le 0,76 m^3/s z 8 km^2 ozemlja. Razmerje med pretokom na italijanski in pretokom na slovenski strani je 1 : 5,5, razmerje med pripadajočimi površinami zaledja pa 1 : 6,25 (Novak 1978).

Za izvir Glijuna je značilen pretok okrog 1 m^3/s, ki lahko po navedbah iz literature niha od 0,15 m^3/s do 15 m^3/s. Izvir Boke daje povprečno 0,2 m^3/s vode z maksimumom okrog 50 kubičnih metrov na sekundo, lahko pa se tudi izsuši. Žvika daje povprečno 0,1 m^3/s. minimalni pretok znaša komaj 10–15 l/s, maksimalni pa lahko preseže 1 m^3/s. Pretok Sušca lahko naraste vse do 10 m^3/s medtem ko je večino leta suh, Goriuda na italijanski strani pa ima povprečni pretok 0,15 m^3/s (0,03–10 m^3/s) (Gasparo 1991, Kunaver 1978, Novak 1979, Cucchi in ostali 1997).

Razmerje med odtokom, evapotranspiracijo in padavinami imenujemo odtočni količnik. Jenko (1959) ga je za visokogorski kras ocenil na 80–90 %. Kunaver (1978) navaja za Kaninsko pogorje vrednost 90 %, za porečje Soče nad Kobaridom pa 85 %. Kolbezen in Pristov (1998) navajata za Sočo pri Kršovcu 79,3 %, za Sočo pri Logu Čezsoškem pa 81,5 %. Na podlagi nam znanih podatkov je vrednost odtočnega količnika na Kaninskem pogorju nekoliko višja in znaša 90,6–93,5 %. Domnevamo, da poteka razvodnica med porečji Reklanice, Tilmenta in Soče čez Oslovo glavo (2025 m) na Belo Peč (2149 m) na severna pobočja Kuntarja (2124 m) in Hudega Vršiča (2344 m) (Novak 1978). Zaledje Glijuna tako sega onstran mejnega grebena Črnel. Izmerjene vrednosti povprečnih maksimalnih, srednjih in minimalnih pretokov rek se razlikujejo od tistih, ki so bile izračunanne s pomočjo podatkov o padavinah in evapotranspiraciji med drugim tudi zaradi odstopanj med potekom reliefne in dejanske, kraške razvodnice. Na Kaninskem pogorju znaša specifični odtok 94,83 l/s/km^2 (Komac 2000).

Dolgoročna opazovanja rečnih pretokov kažejo, da so v Bovški kotlini kar močni izviri. Večinoma so to desni pritoki Soče, manj pa jih je na levi. Med Kršovcem in Logom Čezsoškim priteka povprečno 6,15 m^3/s vode z nižkom februarja (2,7 m^3/s) in viškom maja (10,4 m^3/s). Povprečni maksimalni pretok znaša 102,89 m^3/s, povprečni minimalni pa 0,65 m^3/s. Podzemeljskemu pritoku Soče v Bovški kotlini pripada približno polovica (40–60 %) vode. K površinskemu pritoku prispeva deževnica neposredno 30–35 % vode, v obliki snega pa obleži in nazadnje v reko odteče približno 20–25 % vode. Ocenjujemo, da s Kaninskega pogorja pritekajo tri četrtine (4,76 m^3/s), z južnega dela Bovške kotline pa četrtina vode (1,39 m^3/s). Severni del Bovške kotline daje približno 3,42 krat več vode kot južni, na podzemni dotok v Sočo v Bovški kotlini pa odpade približno 52 % vode (Radinja 1978).

4.2. Oskrba naselij s pitno vodo

Kljub veliki količini vode v kraških izvirih pod Kaninom je le dobra desetina na razpolago za vodno oskrbo naselij v Bovški kotlini. Minimalni razpoložljivi specifični odtok znaša najverjetneje okrog 10 l/s/km^2

(Čar in Janež 1996). V običajnih razmerah Bovec potrebuje 65 l/s vode, poraba pa je predvsem poleti in pozimi močno povečana zaradi turistične dejavnosti. Bovec se danes z vodo oskrbuje pretežno iz vrtin na Čezsoškem polju. Prebivalci nekaterih starejših delov Bovca so se do nedavna oskrbovali z vodo iz majhnih lokalnih izvirov, ki so za bovški vodovod zajeti V Bisnah, na Praprotnici, Na Skali in pri Tomažéku in dajejo ob nizkem pretoku skupaj 2–2,3 l/s. Pred časom se je Bovec oskrboval tudi iz črpališča pri mostu čez reko Koritnico, ki je bilo kasneje opuščeno. Da bi zagotovili stalnejšo vodno oskrbo so v rečno teraso pri Čezsoči izkopali dve vrtini, kjer danes črpajo vodo za Bovec in Čezsočo. Tudi vrtini sta ogroženi zaradi bližine reke in odvisnosti od električne energije, čeprav se voda nikoli ne skali. Okoliška naselja (Plužna, Podklopca, Žaga) in zaselki (Zavrzelno) se še danes oskrbujejo z lokalnimi izviri. Večji kraški izviri pod Kaninskim pogorjem kot je na primer Glijun, pa za vodovod niso zajeti, saj sledenja voda kažejo, da voda s Prestreljeniških podov, kjer je smučišče, odteka v izvire med Žago in Bovcem. Visokogorski kras je zaradi hitrega pretakanja in pomanjkanja pokrova prsti še posebej občutljiv za onesnaževanje in ob višku sezone preobremenjen. Glijun, Žvika ter Možnica in Boka so občasno onesnaženi z organskimi polutanti (Novak 1992).

4.3. Fizikalne in kemične značilnosti kraških izvirov

V času od novembra 1999 do junija 2000 sem nekatere od kraških izvirov pod Kaninskim pogorjem podrobno opazoval (Komac 2000). Enkrat mesečno sem jemal vzorce vode in jih analiziral. Zbrani podatki so omogočili natančnejši opis značilnosti izvirov. S podatkov lahko tudi sklepamo na splošne značilnosti. Kot kažejo dolgoročna opazovanja, obstaja povezava med pretočnimi režimi, vrsto kraškega pretakanja in variabilnostjo fizikalnih in kemičnih lastnosti vode (Tyc 1997). Analize so potekale od 21. 11. 1999 do 15. 5. 2000. Podrobneje je bila analizirana voda naslednjih izvirov:

Skupina I – izviri na flišu Bovške kotline:
- Izvir pri Tomažéku vzhodno od Bovca,
- Geršpotok nad in pod Bovcem,
- Ubivnica nad Bovcem.

Skupina II – izviri na apnencu Bovške kotline:
- Izvir Glijuna pri vasi Plužna,
- Kladenki blizu vasi Plužna,
- Izvir Vodice,
- Izvir Žvike,
- Izvir Boke,
- Izvir Bočiča (jama),
- Izvir v kvartarnih sedimentih pri Bočiču.

Za lažjo primerjavo podatkov sem vzorčil tudi reko Sočo pri Logu Čezsoškem. Izvir Boke sem opazoval le enkrat. Opis hidrogeografskih razmer temelji na opažanjih, meritvah na terenu in na rezultatih kemičnih in fizikalnih analiz vode. Opravljene so bile analize naslednjih parametrov:
- vsebnost kisika v vodi (mg/l) in zasičenost vode s kisikom (%),
- temperatura vode (° C),
- delež ogljikovega dioksida (%),
- specifična elektroprevodnost vode (μS/cm),
- vrednost pH,
- vsebnost fosfatov, nitratov in sulfatov (mg/l),
- kalcijeva, skupna, karbonatna in magnezijeva trdota (° NT).

Kemične in fizikalne analize sem opravljal deloma na terenu, v večji meri pa v fizičnogeografskem laboratoriju Oddelka za geografijo Filozofske fakultete Univerze v Ljubljani. Na terenu sem s prenosnim merilnikom kisika meril vsebnost kisika v vodi, nasičenost vode s kisikom in temperaturo. Vsebnost nitratov sem določal s pripomočkom »Visocolor Nitrate 50«, delež prostega CO_2 v vodi pa s postopkom titracije. Vredost pH sem v laboratoriju določal z merilnikom, prav tako tudi elektroprevodnost. S postopkom titracije sem določal količino fosfatov, nitratov, sulfatov ter kalcijevo, skupno, karbonatno in magnezijevo trdoto. Pridobljeni rezultati so pripomogli k dopolnitvi tipologije izvirov, izdelavi preproste bilančne sheme za Kaninsko pogorje in opisu splošnih hidrogeografskih značilnosti. Rezultati so tudi osnova za opis glavnih kemičnih in fizikalnih lastnosti izvirov. Dolgoročna opazovanja namreč kažejo, da obstaja pozitivna povezanost med pretočnimi režimi, tipi pretakanja v vodonosniku in kemičnimi ter fizikalnimi lastnostmi izvirske vode (Tyc 1997).

V glavnem nismo zasledili večjih razlik med izviri na flišu in izviri na apnencu. Če omenimo zgolj bistvene, moramo povedati, da imajo izviri na flišu običajno nižje pretoke kot izviri na apnencu in tudi amplituda pretokov je manjša. To je predvsem posledica manjših zaledij izvirov. Pozimi so tudi pogosteje pokriti z ledom in se lahko tako pozimi kot poleti izsušijo.

Zaradi nižjih pretokov in drugačnega pretočnega režima imajo izviri na flišu drugačen temperaturni režim kot izviri na apnencu. Izviri na flišu imajo običajno nižje temperature pozimi in višje poleti, temperatura izvirov na apnencu pa je običajno najnižja poleti.

Izviri na flišu imajo višjo skupno, kalcijevo in magnezijevo trdoto kot izviri na apnencu, karbonatna trdota pa je običajno nižja. Menimo, da je to posledica pretakanja vode skozi prst, kjer se nasiči z ogljikovim dioksidom in korozijo mešanice, ki je posledica mešanja kraške vode iz apnenca s tisto v flišu in na površini. V vodi izvirov na apnencu je tudi več kloridov, vendar pa manj sulfatov kot v izvirih na flišu. Izviri na flišu imajo tudi nižje vrednosti nitratov, nižje razmerje Mg/Ca in večjo vsebnost prostega ogljikovega dioksida in višjo elektroprevodnost. Nekateri osnovni podatki fizikalnih in kemičnih analiz so prikazani v preglednici št. 5.

Podrobnejše meritve so bile opravljene na izvirih Glijun in Žvika v času od 12. novembra 1999 do 12. januarja 2000. S samodejnim merilnikom so potekale meritve temperature in specifične elektroprevodnosti. Merilna naprava je last Inštituta za geologijo in paleontologijo Univerze v Trstu, s katerim smo sodelovali. Podatki so omogočili izračun obsega zaledja izvira Glijuna, medtem ko podatki za izvir Žvike niso bili uporabni zaradi nepravilne postavitve naprave oziroma vpliva sončnega obsevanja.

V nadaljnjem besedilu so predstavljene osnovne kemične in fizikalne značilnosti izvira Glijuna. Primerjali smo podatke Novaka (1979), Kunaverja (2000) in naše terenske ter laboratorijske meritve.

Temperatura vode izkazuje izrazito sezonskost. Nanjo vpliva topljenje snega, zato je najnižja julija, ko v povprečju znaša 5,41° C. Temperature so nadpovprečne v obdobju januar–april in oktobra (7,16° C) ter novembra, kar kaže na vpliv jesenskih padavin. Temperaturna viška opazimo marca, in oktobra, sekundarni nižek pa nastopi decembra. Letni potek temperature je obratno sorazmeren s pretokom in magnezijevo trdoto ter premo sorazmeren s kalcijevo, skupno in karbonatno trdoto in količino suhega ostanka v vodi. Povprečna letna temperatura Glijuna znaša 6,47° C. Povprečna temperatura izvirske vode je običajno blizu povprečni temperaturi zraka nekega kraja, vendar je pod Kaniniskim pogorjem temperatura izvirske vode običajno znižana zaradi vpliva snežnice. Razlika med minimalno in maksimalno vrednostjo znaša 26,7 % povprečne letne vrednosti.

Povprečna letna vrednost skupne trdote znaša 4,95° NT. Odvisna je od pretoka in temperature vode, zato ima najnižje vrednosti poleti. Primarni nižek nastopi med junijem in julijem, nekaj dni pred temperaturnim. Sekundarni nižek je novembra. Višek skupne trdote je februarja (5,56° NT), sekundarni pa oktobra (5,34° NT). Razlika med minimalno in maksimalno vrednostjo znaša 21,4 % povprečne letne vrednosti.

Minimum karbonatne trdote nastopi junija ali julija (4,14° NT) in pozimi, maksimum pa oktobra (5,1° NT) in januarja. Povprečna vrednost karbonatne trdote je 4,4° NT. Karbonatna trdota ima podoben letni potek kot skupna in se med letom bolj spreminja. Razlika med minimalno in maksimalno vrednostjo znaša 27,0 % povprečne letne vrednosti. Karbonatna trdota je bolj kot druge trdote odvisna od padavin. Več kot je v vodi deževnice, manjša je karbonatna trdota.

Kalcijeva trdota se med letom bolj spreminja kot skupna ali magnezijeva trdota. Povprečna letna vrednost znaša 3,89° NT. Maksimum nastopi ob nižku pretokov februarja (4,35° NT), minimum pa junija (3,36° NT). Razlika med minimalno in maksimalno vrednostjo znaša 36,2 % povprečne letne vrednosti.

Magnezijeva trdota se med vsemi trdotami med letom najbolj spreminja. Razlika med minimalno in maksimalno vrednostjo znaša 58,9 % povprečne letne vrednosti (1,29° NT). Maksimum nastopi poleti, sekundarni maksimum pa pozimi. Poletni maksimum je odvisen od junijskega viška pretokov, saj nastopi 1 mesec za njim, julija (1,66° NT). Minimum magnezijeve trdote nastopi maja (0,9° NT), sekundarni minimum pa ob jesenskih padavinah (1,08° NT). Poletni maksimum je odvisen od maksimuma pretokov. Po navedbah iz literature kaže vsebnost Mg^{2+} ionov v vodi, ki je ob visokih vodah nižja od 1 mg/l na pretakanje kraške vode pretežno skozi velike kanale v dachsteinskem apnencu. Ker se manjši delež vode pretaka skozi dolomitna območja, je tudi magnezijeva trdota ustrezno nižja (Cucchi in ostali 1997). Trditev se ujema s časovnim potekom magnezijeve trdote v izviru Glijuna, saj je magnezijeva trdota tem višja, čim višji so pretoki. Višji kot so pretoki, več vode se pretaka po velikih kraških kanalih. Tudi velika variabilnost magnezijeve trdote kaže na odvisnost od pretočnih razmer.

Glijunu prinese največ suhega ostanka ob nizkih pretokih, ko prevladuje odcedna voda. Suhi ostanek znaša povprečno 89,76 mg/l z maksimumom ob minimumu pretokov februarja (102 mg/l) in minimumom junija (93,5 mg/l). Razlika med minimalno in maksimalno vrednostjo kaže na relativno veliko variabilnost, kar potrjuje odvisnost od pretočnih razmer v velikih prevodnikih.

Pretok je najbolj variabilen dejavnik kraških izvirov. Variabilnost je povezana s klimatskimi spremembami (padavine, temperature), topljenjem snega v gorah, s količino vode v kraškem sistemu in njegovo prevodnostjo, kot tudi lego izvirov glede na bližnje kraške izvire (Tyc 1997). Na podlagi Novakovih (1979) meritev znaša povprečni minimalni pretok 0,53 m^3/s (januarja), povprečni maksimalni pretok 20 m^3/s (junija) in srednji pretok 4,57 m^3/s. Večina drugih raziskav kaže, da znaša povprečni pretok približno 1 m^3/s (Audra 2000). Nesorazmerje med podatki je verjetno posledica različnih meritev in velikega razpona med minimalnimi in maksimalnimi pretoki, ki je sicer podobno razmerju med minimalnimi in maksimalnimi pretoki izvirov Vipave (Janež in ostali 1997). V obdobju 1987–1991 je bilo v enem letu 70–120 dni, ko je imel Glijun pretok višji od 3,3 m^3/s. Podatki kažejo, da je neposredni vpliv padavin bolj očiten v topli polovici leta, saj v visokogorju pozimi večina padavin obleži kot sneg.

4.4. Analiza krivulje praznjenja

V obdobju med 11. 12. 1999 in 26. 12. 1999 so bile na izviru Glijuna postavljene naprave, s pomočjo katerih smo med drugim pridobili tudi podatke o višini vode oziroma pretoku. Opazovano obdobje je bilo s hidrološkega vidika zanimivo, saj je v Plužnah v dveh mesecih deževalo le 13 dni. V tem času je v treh padavinskih sunkih padlo komaj 190,3 mm dežja (snežne padavine v izračun niso vštete), v Bovcu pa le 150,6 mm, kar je dobra petina povprečnih padavin v tem času. Na Plužnah je deževalo v obdobju 15. 11.–22. 11. 1999, 6.12., v obdobju 11. 12.–14. 12. ter v obdobju 26. 12.–29. 12. 1999. Januar 2000 je bil na Plužnah in v Bovcu povsem brez padavin. Z zbranimi podatki smo lahko opisali pretočne razmere in analizirali krivuljo praznjenja. Na podlagi zbranih podatkov o višini vode in meritvijo pretočnega profila, smo izračunali pretok izvira za posamezne vrednosti višine vode po enačbi:

$$Q = 3{,}8197 \times h_{vode} + 29{,}508.$$

Padavine na začetku in v sredini decembra so povzročile nagel porast pretoka Glijuna od 0,3 m^3/s (10. 12. 1999) do viška 2,1 m^3/s (11. 12. 1999). Pretok je nato upadal do 24. 12., ko smo ob 21^h izmerili 0,03 m^3/s, torej manj, kot pred deževjem.

Na podlagi vrednosti pretoka v določenem času lahko določimo osnovne parametre kraškega izvira. Izračuni, ki jih navajamo, so zaradi analize enega niza podatkov in kratkega opazovalnega obdobja le bolj ali manj natančen približek, imajo informativno naravo in prinašajo okvirne vrednosti.

Pri analizi hidrograma, opisu njegovih osnovnih lastnosti in izračunih smo se naslonili na ugotovitve B. F. Mijatovića (1968: 43–81), po katerem lahko s pomočjo hidrograma nekega izvira določimo delež vode v nekem porečju, ki pripada podzemeljskemu odtoku. Krivulja praznjenja ima podobo hiperbole, ki je najvišja na levi strani grafa in sprva strmo, nato pa vedno bolj položno upada. Ravna se po enačbi:

$$y = e^{-\alpha(t-t_o)},$$

kjer koeficient α označuje vrsto odtoka glede na značilnosti kraškega prevodnika, vrednost »e« pomeni naravni logaritem, vrednost t pa čas na začetku praznjenja (t_o) in kasneje (t). E. Maillet je l. 1903 postavil splošno obliko enačbe za krivuljo praznjenja, ki se glasi takole:

$$Q_t = Q_o \times e^{-\alpha(t-t_o)}$$

»Q_t« označuje pretok v danem času »t« [dan], »Q_o« pa pretok ob začetku praznjenja izvira. S to enačbo označimo pretočne razmere v delu hidrograma, ki je označen z »BC« (glej sliko 7). Položaj daljice BC na hidrogramu je odvisen od koeficienta α. Višja kot je vrednost koeficienta, bolj je krivulja strma in obratno. Velja enačba:

$$V_t = \frac{Q_t}{\alpha}$$

Q_t pomeni pretok v določenem času, V_t prostornino vodnonosnika oziroma skupno prostornino, ki jo je v kraškem masivu zapolnjevala voda, preden je pritekla na površje.

Iz zgornje enačbe sledi, da je vrednost koeficienta praznjenja enaka ulomku med pretokom v danem času in prostornino zaledja. Vrednost koeficienta α je ena osnovnih značilnosti posameznega izvira, saj opisuje način praznjenja:

$$\alpha = \frac{[\log Q_o - \log Q_t]}{[0{,}4343 \times (t - t_o)]}$$

Krivulja praznjenja, ki jo nanesemo na koordinatni sistem, ima obliko hiperbole, če pa vrednosti pretoka nanesemo na logaritemsko skalo, dobimo diagram, ki je sestavljen iz ravnih črt. Na logaritemski skali vidimo, da koeficient praznjenja α predstavlja tangens kota, ki ga krivulja praznjenja oklepa z absciso (glej sliko 8).

Vrednost α je nižja, ko se prazni vodonosnik, v katerem prevladuje vodni tok skozi mrežo lasnic, razpok, višja pa, ko se prazni kraški vodonosnik, v katerem prevladujejo večji kanali. Ločimo več načinov praznjenja kraškega sistema glede na vrsto prevladujočih kraških prevodnikov. Višja kot je vrednost koeficienta praznjenja, večja je prevodnost kanalov in hitreje se vodonosnik prazni. Na hitrost praznjenja vplivajo prosta, nepovezana poroznost kamnine in dotok oziroma količina vode v sistemu. Hitre spremembe pretoka po padavinah so posledica dejstva, da padavinska voda izrine vodo iz kraških razpok. Izvir najprej večinoma napaja voda, ki se je zadrževala v krasu (Tyc 1997). Tudi Glijun napaja difuzna voda.

Praznjenje kraškega sistema je najhitrejše, če voda teče skozi cevne prevodnike velikostnega reda meter[7]. Voda v tej coni teče v turbulentnem režimu, koeficient praznjenja α je velikostnega reda $n \times 10^{-1}$. Ob praznjenju kraškega sistema skozi kanale in špranje velikostnega reda m^{-1} voda teče v prehodnem režimu med turbulentnim in laminarnim. Koeficient praznjenja α je v tej coni velikostnega reda $n \times 10^{-2}$. Ko poteka praznjenje kraškega sistema skozi najmanjše prevodnike velikostnega reda m^{-2} do m^{-3}, je tok laminaren, koeficient praznjenja pa je velikostnega reda $n \times 10^{-3}$. Takšno vodo imenujemo tudi odcedna voda. Na pretok v določenem času vpliva tudi hidrostatični tlak, ki je v visokem krasu občuten zaradi velikega in hitrega nihanja piezometrične gladine.

Na začetku poteka praznjenje skozi vse prevodnike istočasno. Veliki kanali in razpoke se praznijo sorazmerno hitro, toda kaj kmalu količina vode iz malih prevodnikov preseže tisto iz velikih. Količina vode iz

[7] Z oznakami m^1, m^{-1}, m^{-2} prikazujem velikostni red. Oznaka m^{-1} tako pomeni decimeter, oznaka m^{-2} centimeter, oznaka m^{-3} pa milimeter itd.

malih prevodnikov se ob praznjenju zelo počasi znižuje. Različni režimi praznjenja se odražajo na krivulji praznjenja, zato je ta ponavadi sestavljena iz treh ali štirih vedno položnejših delov (A, B, C, D na sliki 8). Izračunamo lahko razmerje med pretokom skozi cevne prevodnike in odcedno vodo. Pretok določa obseg zaledja in podzemeljske ožine, ki kontrolirajo pretočne maksimume. Glede na razmerje med odcedno vodo in pretokom skozi cevne prevodnike se lahko kraško podzemlje izprazni že v nekaj dnevih (izvir Aliou) ali več mesecih (izvir Torcal) (Pulina 1999).

Na krivulji praznjenja smo z grafično metodo določili karakteristične točke. Začetek praznjenja označuje pretočni višek. Nato smo na krivulji praznjenja določili tri karakteristične točke. Prva nastopi dan po pretočnem višku (0,69 m^3/s), druga pa devet dni po pretočnem višku (0,2 m^3/s).

Izračuni kažejo, da je bilo pred začetkom praznjenja kar 82,6 % vode v zaledju Glijuna shranjene v prevodnikih najmanjšega velikostnega reda. Ta delež nam tudi pove kolikšen je delež odcedne vode. Prevodniki srednjega velikostnega reda so prispevali 13,9 % prostornine, največji prevodniki pa komaj 3,5 % prostornine. Razmerje med prostorninami znaša 1 : 4 : 20, kar je podobno razmerju med pretoki na začetku, sredini in ob koncu praznjenja (1 : 3 : 9).

V vodonosniku je bilo ob začetku praznjenja približno 2,5 milijona (2.535.710 m^3), ob koncu praznjenja pa približno 2 milijona (2.094.122 m^3). Iz sistema je odteklo približno 500.000 m^3 vode.

Primerjava podatkov o pretoku Glijuna in padavinah na Plužnah kaže, da dobiva izvir Glijuna vodo z okrog 8,5 km^2 ozemlja. Zelo verjetno je zaledje izvira nekoliko večje, saj je del padavin padel v obliki snega in obležal v gorah. Domnevamo, da kraško zaledje izvira Glijuna obsega okrog 10 km^2, kar je približno petina površine Kaninskega pogorja. Kot smo omenili zgoraj, se lahko tudi fizikalne in kemične lastnosti vode spreminjajo v odvisnosti od sprememb piezometrične gladine in količine vode v sistemu. Raziskave na izviru Lintvern pri Vrhniki kažejo, da je lahko kraško zaledje izvira tudi dva krat večje kot kažejo morfološke in reliefne razmere (Habič 1970).

5. Sklep

Hidrogeografski pomen izvirov v Bovški kotlini je odvisen od lege v sinklinalno zasnovani Bovški kotlini v zahodnih Julijskih Alpah. Kaninsko pogorje pripada Južnim Alpam in krnskemu pokrovu. Gradi severno krilo bovške sinklinale, v kateri so nagubane kamnine triasne, jurske in kredne starosti, njena os pa je usmerjena od zahoda proti vzhodu. Karbonatne kamnine so skupaj debele 2600 m, fliš 600 m, kvartarni sedimenti pa do 320 m.

Vode s Kaninskega pogorja se stekajo v tri porečja in pripadajo dvema povodjema. Kraška razvodnica na Kaninskem pogorju se ne ujema z reliefno. Na slovensko stran Kaninskega pogorja odteka voda z območja, ki meri 50 km^2, na italijansko stran pa z območja, ki meri le 8 km^2. Tudi odtok na slovensko stran je šest krat večji kot odtok na italijansko stran. Za območje sta značilna visok odtočni količnik (90,6–93,5 %), ki je povezan z obilnimi padavinami, nizko evapotranspiracijo in hitrim odtokom v podzemlje in visok specifični odtok (94,8 $l/s/km^2$).

Med kraškimi izviri na apnencu in izviri na flišu v Bovški kotlini ni bistvenih razlik v osnovnih fizikalnih in kemičnih značilnostih, saj tudi fliš vsebuje karbonatne kamnine in je trdota voda relativno visoka (Komac 2000).

Natančen obseg zaledij izvirov pod Kaninskim pogorjem ni natančno znan. Raziskave kažejo, da Glijun odmaka približno petino Kaninskega pogorja (10 km^2), vendar tudi, da prihaja do horizontalnega prepletanja zaledij kraških izvirov, ki so sicer ločena z litografskimi, tektonskimi ali drugimi mehanskimi pregradami.

Izviri, ki odvajajo vode z različnih nivojev imajo tudi različne pretočne režime. Izviri, ki so odvodniki višjih kraških con, hitreje reagirajo na padavine. Zanje je značilno, da pozimi presahnejo, spomladi se pretoki povečajo zaradi topljenja snega v visokogorskem svetu. Nižje ležeči izviri odvajajo odcedne vode v obdobju nizkih pretokov. Boka in Glijun na južni ter Goriuda na severni strani Kaninskega pogorja odvajajo visoke vode zgornje kraške cone, Žvika, Bočič, Vodica in nekateri drugi manjši izviri pa vode globljih – po nadmorski višini nižjih con in odcedne vode. Dokaz za trditev je dejstvo, da so meritve ob sledenju v breznu Led Zeppelin ob visoki vodi 14. 11. 1997 pokazale v izvirih Boke, Glijuna in Goriude nižjo vsebnost Mg^{2+} iona kot v drugih izvirih. To kaže na odvisnost teh izvirov od pretakanja visokih voda po velikih kanalih v dachsteinskem apnencu. Na hiter tok in odvajanje vode iz zgornjih kraških con kaže tudi večja vsebnost organskih snovi v izvirih Goriuda, Sušec in Glijun v primerjavi z drugimi izviri (Cucchi in ostali 1997).

Izviri pod Kaninskim pogorjem so zajeti za lokalne vodovode, obenem pa je območje zaradi kraškega značaja zelo občutljivo za onesnaževanje voda. Kakovost nekaterih izvirov ne dopušča uporabe za pitno vodo zaradi občasne organske onesnaženosti, ki je predvsem posledica turistične dejavnosti na Prestreljeniških podih. Središča odločanja bi morala ponovno preučiti vlogo in pomen visokogorskega krasa v Sloveniji danes in v prihodnosti. Zato bi morali izvesti natančnejše raziskave, ki bi nam dale natančnejši vpogled v dogajanja v visokogorskem krasu. Zelo verjetno bo vloga Kaninskega pogorja vedno večja zaradi mednarodnega položaja in bližine območij, kjer je na razpolago malo dobre pitne vode. Ob dejstvu, da bo v prihodnjih desetletjih pomen zalog pitne vode vedno večji, bi današnje varovanje vodnih virov na Kaninskem pogorju pomenilo naložbo za prihodnost.