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LIFE AND WATER ON KARST

Monitoring of transboundary water resources of Northern Istria

Editors **Nadja Zupan Hajna, Nataša Ravbar, Josip Rubinić, Metka Petrič**

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• Region of Istria
• Karst Research Institute at the Research Centre of the Slovenian Academy of Sciences and Arts
• Faculty of Civil Engineering, University of Rijeka
• Public Institution Natura Histrica
• National Laboratory of Health, Environment and Food

2015

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III. KARST WATER RESOURCES MONITORING

Photo from "Water - Life!" in Istria competition; author: Josip Madračević

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The monograph was done and published in the frame of project ŽIVO! Življenje – voda! (Life – Water!) (IPA CBC SI-HR 2007-2013) as an activity of the project partners Karst Research Institute ZRC SAZU, Faculty of Civil Engineering of Rijeka, and the National Laboratory of Health, Environment and Food, Koper Unit, with the assistance of the lead partner Region of Istria and also the project partner Natura Histrica Public Institution, which merit major thanks for their assistance in its creation. The financing source for the monograph was the IPA Programme of Transboundary Cooperation between Slovenia and Croatia 2007-2013, in the implementation period 01/2014 to 09/2015.

The preparation of the monograph, as well as setting up the observation networks, sampling and analysis of results obtained, involved the collaboration of numerous institutions and individuals that each in their own way contributed to the book. Their work is not reflected in the form of their own published work, but we thank them here for their assistance and cooperation.

In addition to the above-mentioned partner institutions, special recognition is due to the Buje Speleological Society for its willingness to set up and carry out monitoring in selected caves of the project area; the staff of ARSO (Slovenian Environment Agency) in Ljubljana, of the Croatian National Hydrometeorological Institute in Zagreb and of Istramet for meteorological and hydrological data; staff at Istarski vodovod in Buzet (especially Mladen Nežić) and Rižanski vodovod in Koper (especially Melanija Pavšič, David Bembič and all the operators at the Rižana Waterworks) for their help in monitoring; Hrvatske vode (Croatia water management corporation) of Zagreb for data on water quality, VGO of Buzet (Vojmil Prodan) for information on water conditions in the area, POU Buzet (Dijana Kolaković) for help finding archive material and the residents of Northern Istria, who not only collaborated in preparing the monograph, but who for centuries have cared for water and water resources.

The book shows 30 photographs selected in a public photographic competition for best photo on the topic of "Water – Life!" in Istria, which was organised as part of the ŽIVO! project by the Region of Istria. The authors who took the photos selected and reproduced in this book are listed in alphabetical order: Mirna Bartolić, Đani Celija, Julien Duval, Kristian Macinić, Josip Madračević, Doriano Orbanić, Aleksandar Tomulić and Igor Zirojević.

Editors

Photo from "Water - Life!" in Istria competition; author: Josip Madračević

PREFACE

This book is the result of joint work and many years of mutual cooperation between researchers from Slovenia and Croatia. It was made as part of the transboundary project ŽIVO! Življenje – voda! (Life – Water!) (IPA CBC SI-HR 2007-2013), which involved the participation of authors from project partner institutions as well as invited authors who are familiar with the characteristics of the karst area of Northern Istria and the conditions there relating to drinking water supply.

The monograph presents the natural features of Northern Istria, the karst and karst phenomena, karst hydrogeology, ecology and microbiology, and highlights in particular the vulnerability of the karst to various human activities. The main focus of attention is on karst water sources. In assessing their characteristics we used available knowledge of karst water on both sides of the border and supplemented it with new research on the transboundary area in question, which was based on field measurements and sampling, and chemical, microbiological and biological analysis of water. The collected findings form the basis for planning more effective monitoring of the quality of karst water sources, their protection and consequently the improvement of their quality.

The book therefore touches on the area of protecting nature and the environment as the main theme of the project ŽIVO!. During its preparation, publication and, we hope, its path among readers, the general transboundary goals of the project were and will be achieved: preservation of the karst aquifer and natural water sources and sustainable use of the project area through common, sustainable management in the transboundary area; increasing capacities, cooperation in coordinating regional organisations for the protection of nature and the environment; a contribution to improving the quality of life by reducing ecological hazards and through appropriate management of water sources, and linking the environmental protection sector with the tourism sector. The specific transboundary goals of the project were achieved: spreading scientific knowledge of the karst and the state of water sources in the transboundary area of Slovenia and Croatia, and raising the level of awareness among local inhabitants of all age groups, as well as specific interest and professional circles, regarding the biological and environmental value of karst land, with the aim of improving the quality of life. We also fulfilled transboundary aspects such as mobility of researchers and their joint cooperation in field work, analysis of samples, processing the results and writing chapters and the exchange of existing knowledge of the karst in the border area.

The monograph was written for wide professional circles and represents a solid basis for planning life in the karst and managing karst water sources. It is also aimed at people living in Northern Istria whose active relationship with water, adaptation to change and constant concern for maintaining the quality of water contribute to preserving water sources in an area that crosses the national border. The syntagma ŽIVO! Življenje – voda! (Life – Water!) is tied to people and water. An appropriately active relationship between them through history, in the present and in the challenges brought by the future is the best guarantee for preserving sensitive water sources in the karst area of Northern Istria and beyond.

Editors

Photo from "Water - Life!" in Istria competition; author: Julien Duval

INTRODUCTION TO THE KARST AND WATERS OF NORTHERN ISTRIA

Josip Rubinić, Metka Petrič, Nataša Ravbar, Nadja Zupan Hajna, Sonja Diković, Janja Kogovšek, Alenka Koželj

In the monograph produced as part of the ŽIVO! project, we wish to expand the sum of scientific knowledge of the karst, the characteristics of underground water flow and its vulnerability and the state of water sources in the border area shared by Slovenia and Croatia, and in this way to do as much as possible to help preserve natural water resources and their sustainable use.

Slovenia and Croatia are countries that host some of particularly widespread karst landscapes. Carbonate bedrocks on which karst is formed, underlie about half of both states (Slovenia 43% or 8,700 km^2, Croatia 46% or 26,000 km^2). The area of Northern Istria stretches across the border area of Slovenia and Croatia, which is characterised by karst terrain with a developed surface morphology and complex underground water flow (Fig. 1.1).

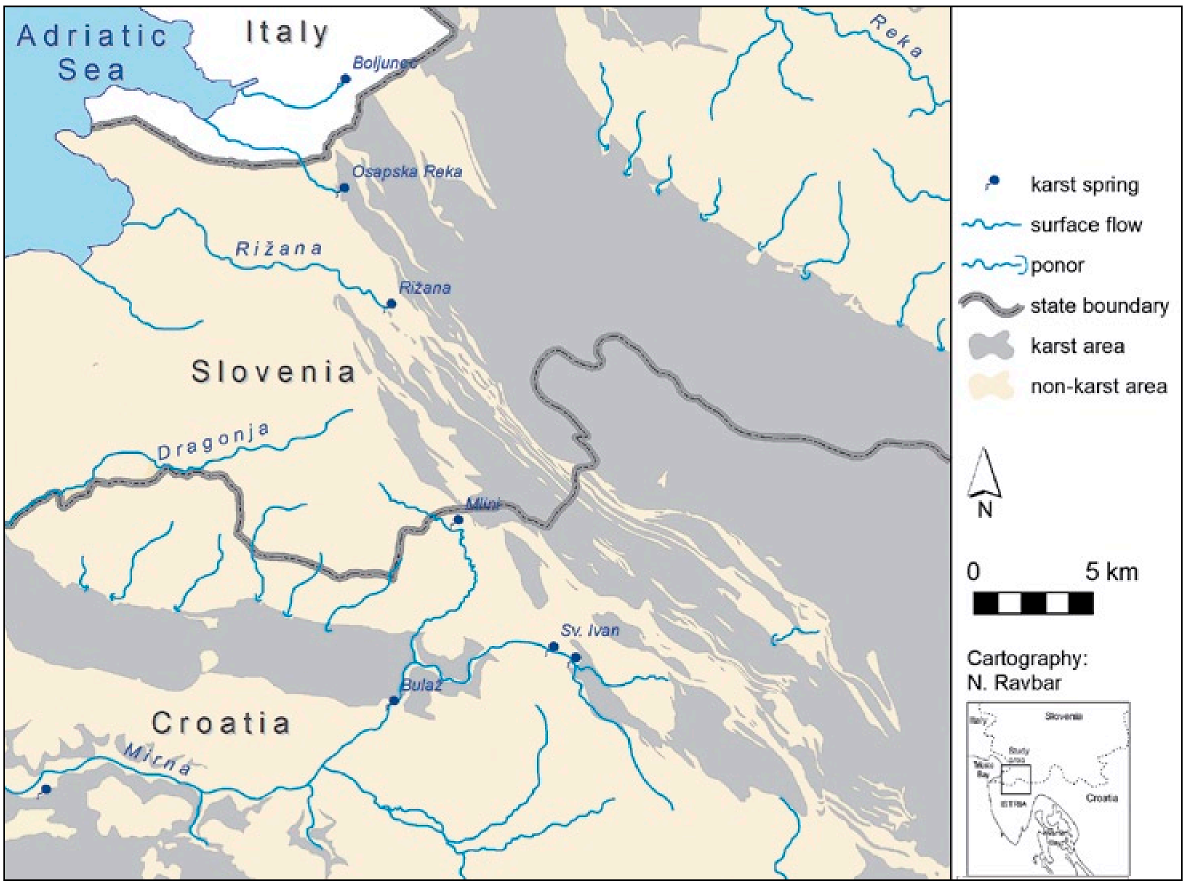


Figure 1.1: Karst and non-karst areas of the Northern Istria.

The project area features alternating karst and non-karst terrain, depending on the rock base, in other words permeable limestone and dolomite and impermeable flysch. The area lies in an extremely dynamic tectonic region, so rock beds are often overthrusted and fractured in various directions. The tectonically deformed and thrusted rock beds the base for varied relief as well as the fragmented surface features and the method of water flow. At the contact between the flysch and limestone are developed typical morphological forms of contact karst, such as blind valleys, ponors where surface water flows into the karst, cave entrances and on the other hand large karst springs.

One of the tasks of the ŽIVO! project was to improve the existing model of managing water sources and protecting their quality in the Northern Istria.

In this karst border area between Slovenia and Croatia, surface and especially subterranean hydrographic networks have evolved. The sources of the Rižana, Sv. Ivan and Bulaž are transboundary water sources of exceptional importance for supplying drinking water to Slovenian and Croatian Istria.. They are fed from a complex aquifer structure which is recharged both through direct infiltration of precipitation and also through sinking streams, which enter into the highly permeable conduits of the karst aquifers. This binary structure renders them extremely vulnerable to various sources of contamination. Their effective protection requires a good knowledge of the processes of water flow and the transport of substances in the system of precipitation – karst aquifer – springs, both in terms of quantity and quality of karst water.

The essential precondition for the quantification and thereby also better understanding of the functioning of complex karst aquifer systems is adequate monitoring, which in current practice is generally limited to monitoring precipitation and the quantity and quality of groundwater at the point of outflow to the surface, i.e. a karst spring, and this with a large discretization in terms of time – once a month or even less frequently. This is insufficient for the modern management of water sources. The basic concept of the ŽIVO! project is therefore to study the functioning of sources and analyse the dynamic of changing water quality at these sources and associated watercourses in the wider impact area. Close monitoring, with sampling performed every few hours, was conducted at times of flood pulses after a long dry period. Preliminary research has shown that at that time changes are most notable, but our understanding of these processes is still very lacking.

We also monitored the state of groundwater both at the points where they flow out through large karst springs used for drinking water supply, as well as on selected surface watercourses in the catchment areas of these springs, at certain other permanent and seasonal springs that are hydrologically linked to these karst springs or their catchments, and in two caves which allow us to monitor the state in the subterranean part of the study area (Fig. 1.2). Given the characteristics, importance and accessibility of the selected sampling points, we opted for a different dynamic of monitoring. On the Slovenian side we focused on the main water source, the source of the Rižana. Numerous studies in the past have yielded solid research into the hydrogeological characteristics of its catchment area, but no detailed analysis of the changing quality of the source in changeable hydrological conditions had been performed. We decided to monitor two sequential flood pulses of differing intensity in June 2015 with a maximum sampling frequency of every two hours during the most pronounced hydrological changes, and with appropriate extension of this interval in periods of smaller changes to the water level.

Figure 1.2: Water sampling at the Butori swallow hole (Photo: Nataša Ravbar).

On the Croatian side we put greater emphasis on the spatial component of the changing quality of karst water. Our main attention was focused on the major water sources, especially the Sv. Ivan and Bulaž springs, while at the same time we monitored events at selected ponors and watercourses in caves in the catchments of the two springs. In order to determine the differences in the functioning of individual sources, to a slightly lesser extent we performed monitoring at selected smaller springs in the observed area. At all these points, with differing frequency of sample taking we monitored the second, more intense flood pulse in June 2015.

Research was focused on monitoring the dynamic of water flow and the solute transport of substances in the karst, so it was important to conduct detailed parallel measurement of precipitation and hydrological conditions. We used publicly accessible measurement data provided by various agencies. At all the locations where there is no such data, we ourselves set up the measurement of levels, electrical conductivity and water temperature. In selecting the parameters for monitoring physical, chemical and microbiological parameters we took into account the results of previous research. In addition to the wide selection of basic physical and chemical parameters, we selected certain specific ones that are typical for the area in question. We performed isotope analysis, and placed special emphasis on analysing various microbiological indicators. All the sample analyses were performed in compliance with the standard procedures and methods in accredited laboratories of the National Laboratory of Health, Environment and Food.

The results of our research are presented in this monograph. The first part sets out the general characteristics of the karst and its vulnerability, and the special features of karst hydrology. It gathers together detailed information on the geographical, geological and hydrogeological characteristics of the observed area of Northern Istria and its impact zone, and on the biological state of subterranean environments in karst caves, while also presenting the culturological aspect of the development of water supply in this area and the attitude of local residents to water. The main section of the monograph is centred around a presentation of the findings of analysis focused on the quantity and quality of water during the observed flood pulses of June 2015. An interpretation of the results of hydrological measurements and of the physical, chemical, isotope and microbiological analyses yielded an assessment of the dynamic of the changing state of the water, and this served to provide guidelines for improving the monitoring of karst sources and aquifers. The existing legislation does not properly address the relevant issue of monitoring the quality of karst water sources, which are characterised by very rapid changes in their quality.

The results obtained point to similarities in terms of the reaction of individual sources to changes in hydrological conditions in their catchment area, and also to variation in the response of the quantitative and qualitative characteristics of the water to these changes. And just as variation is itself the foundation for ensuring stability of the environment, so too is knowledge and timely prediction of changes in the state of karst sources and aquifers the foundation for improved management of karst water sources. In unfavourable climatic and hydrological conditions, the presence of climate change and increasingly complex anthropogenic impacts, which are reflected in a deterioration in water quality and increasingly limited reserves of water for public drinking water supply and preservation of natural ecosystems, the establishing of operational management of karst water sources in real time is urgently needed. In this sense the contribution offered by the results in the study set out in this monograph is especially great.

Photo from "Water - Life!" in Istria competition; author: Josip Madračević

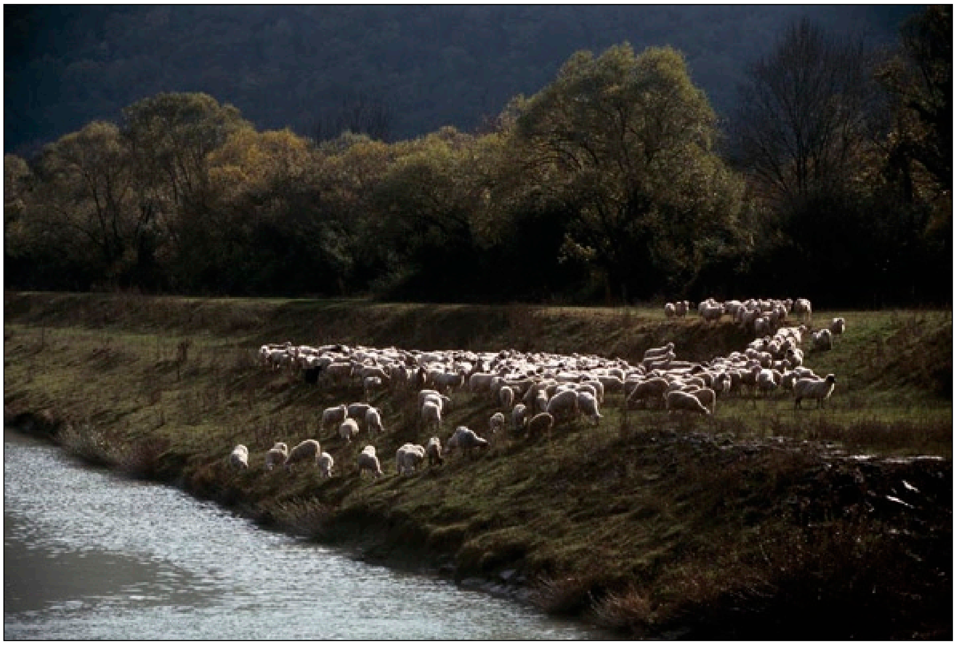


Photo from "Water - Life!" in Istria competition; author: Josip Madračević

I. GENERAL ON KARST

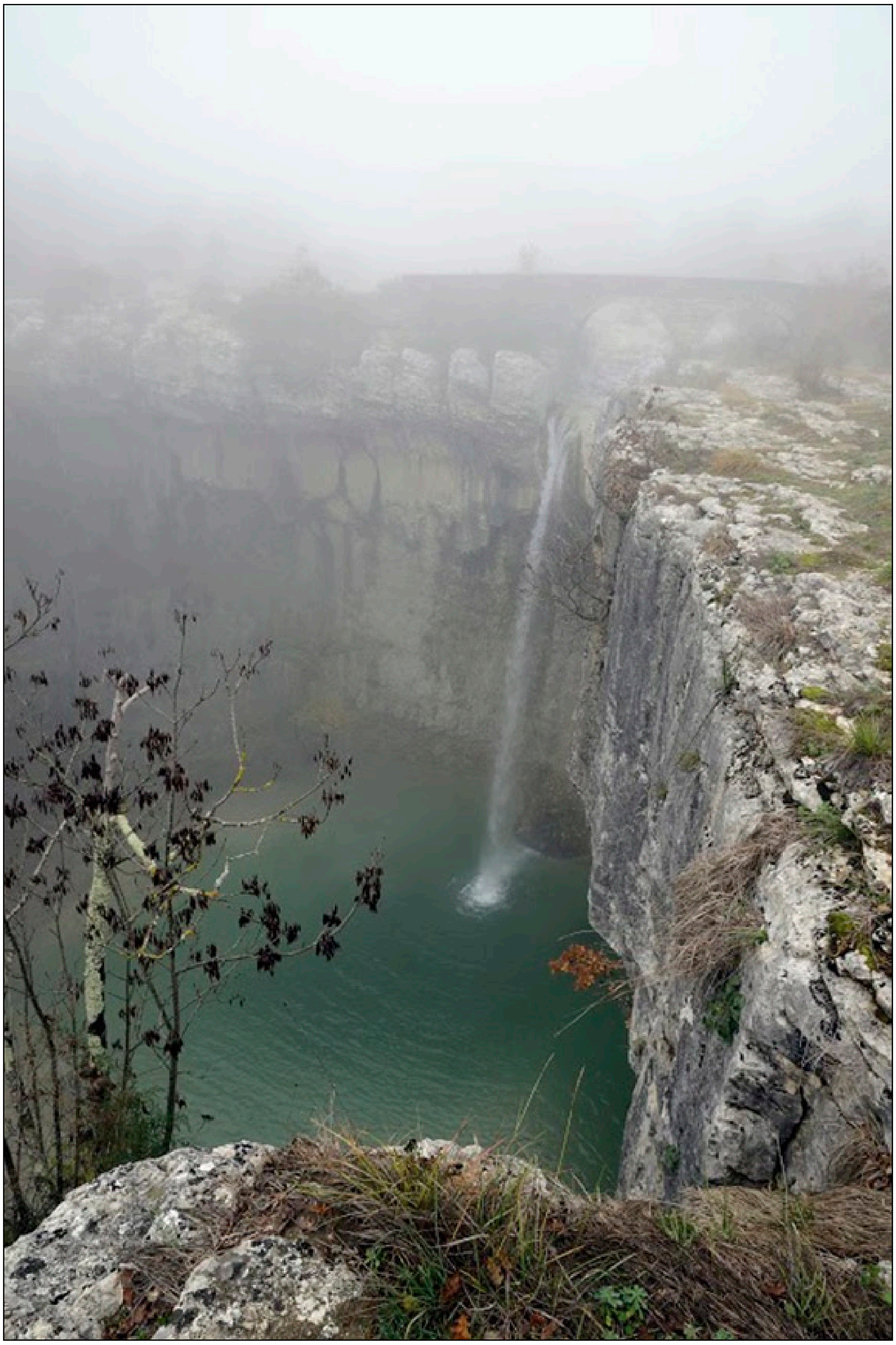


Photo from "Water - Life!" in Istria competition; author: Doriano Orbanić

WHAT IS KARST?

Nadja Zupan Hajna

Karst

When we hear the word “karst” the first things that come to mind are well-known karst phenomena such as the world-famous Postojnska jama (Postojna Cave), stalactites and stalagmites, the curious cave salamander (Proteus anguinus) sometimes known as the “human fish”, and perhaps also the Kras Plateau, Lipizzaner horses, Teran wine and air-dried Karst ham (prosciutto). Well known are also Škocjanske jame (Škocjan Caves) and Plitvička jezera (Plitvice Lakes), both UNESCO World Heritage sites, the intermittent Cerkniško jezero (Lake Cerknica), karst poljes and numerous caves.

Karst represents almost half the land surface of Slovenia and also of Croatia (Gams 2003; Matas 2009). The karst landscape we live in can appear uninteresting and its characteristics can make it seem hostile and uninviting. Karst areas usually have no surface streams or thick soil. The surface is rocky and unsuitable for cultivation. All precipitation quickly sinks beneath the surface, and even rivers disappear through ponors (sinkholes) into the karst, where their waters flow deep underground, out of our sight. For all these reasons karst areas have never been densely populated and the people who have persevered here have eked out a meagre existence and worked hard to survive.

What is the difference between the terms “karst” and “Karst” and what do these almost identically written words mean? In the Slovene language the word kras (karst) means a rocky, barren surface and is frequently used as a toponym. In the scientific sense, “karst” means a landscape with typical karst landforms and underground water flow. As well as a type of landscape, the term “karst” denotes a precisely defined process of dissolution of rock and the characteristic flow of water beneath the surface. “Karst” with a capital K, on the other hand, is the name of the plateau between the Gulf of Trieste and the valley of the river Vipava. It was given this name because of its rocky surface. Because of the precisely defined characteristics of karst topography, the multiplicity of karst landforms and research carried out in the nineteenth century, the word kras, or rather its German form Karst, has also become the international scientific term for karst as a natural phenomenon (Gams 1974 2003; Kranjc 1994).

A characteristic karst process is the dissolution of carbonate rock (limestone and dolomite) by carbonic acid. Viewed more broadly, then, karst is part of the Earth’s crust the characteristics of which are conditioned by the chemical action of water on relatively soluble carbonate rocks. As a result of secondary porosity development through dissolution, the enlargement of fractures by corrosion and the lengthening and widening of conduits, the underground flow system typical of karst areas also develops.

Karst rocks

The rocks most typically subject to karstification – the formation of surface and subterranean karst features – are limestone and dolomite. Limestone and dolomite are the most important sedimentary carbonate rocks and differ in terms of age and formation. Carbonate rocks by definition contain more than 50% of carbonate minerals, mainly represented by calcite and dolomite. Limestone and dolomite also differ in terms of their mineral composition and the mechanical and chemical properties.

The limestone on the Earth’s surface is for the most part of shallow-marine origin (deposited in an environment with a tropical and moderately warm climate) and derives from former platforms. Limestone is still forming today on carbonate platforms and coral reefs (Fig. 2.1); for example in the Bahamas, in the Persian Gulf and off the coast of Australia. Carbonate sediments also form in smaller quantities on the deep sea floor and on continental slopes.

Figure 2.1: Reef growth and the death of organisms that are the basis for the formation of reef limestone; Great Barrier Reef, Queensland, Australia (Photo: Nadja Zupan Hajna).

The geological properties of carbonate rocks are important for the formation of karst. These important properties include both the primary and secondary porosity of carbonate rocks and their mineralogical composition, grain size, texture, bed thickness and degree of tectonic deformation. Water penetrates carbonate rocks through open spaces such as bedding planes (the boundaries between strata), fractures and faults, and at the same time further enlarges them through corrosion. Some interesting facts: the purer the rock, the less insoluble residue it contains; the higher the degree of tectonic deformation, the faster the rock dissolves (Fig. 2.2); sulphur content accelerates dissolution; dolomite dissolves more slowly than limestone and is more subject to mechanical decomposition.

Figure 2.2: Tectonically deformed bedded limestone with karstified fissures (Photo: Nadja Zupan Hajna).

Dissolution

Karst forms in all carbonate rocks provided there is water available to dissolve them. Water causes dissolution through its chemical composition and mechanical properties such as the quantity and manner of flow and the nature and size of its contact with the rock. The intensity of dissolution depends on the quantity of CO_2 available to form carbonic acid.

Karstification of carbonate rocks begins as soon as the rock transitions from the environment in which it formed to a different environment, i.e. from the sea to a freshwater environment. When limestone and dolomite karstify this involves, in principle, the dissolution of the minerals calcite and dolomite, while impurities remain as an insoluble residue.

The most important chemical process for the karst formation in carbonate rocks is dissolution by carbonic acid (Fig. 2.3). Rainwater is enriched with CO_2 in the atmosphere and when percolating through soil, and with it forms a weak carbonic acid:

$$H_2O + CO_2 = H_2CO_3$$

When percolating through carbonate rocks, this weak carbonic acid dissolves them, resulting in the formation of calcium and hydrogen carbonate ions:

$$CaCO_3 + H_2CO_3 = Ca^{2+} + 2(HCO_3)^-$$

When the water enriched with the dissolved ions reaches an open cave environment, the difference in CO_2 partial pressure in the cave results in the degassing of the solution, which causes the precipitation of calcite in various forms of calcareous deposit:

$$Ca^{2+} + 2(HCO_3)^- = CO_2 + CaCO_3 + H_2O$$

Karst thus forms in all carbonate rocks if there is water available to dissolve them.

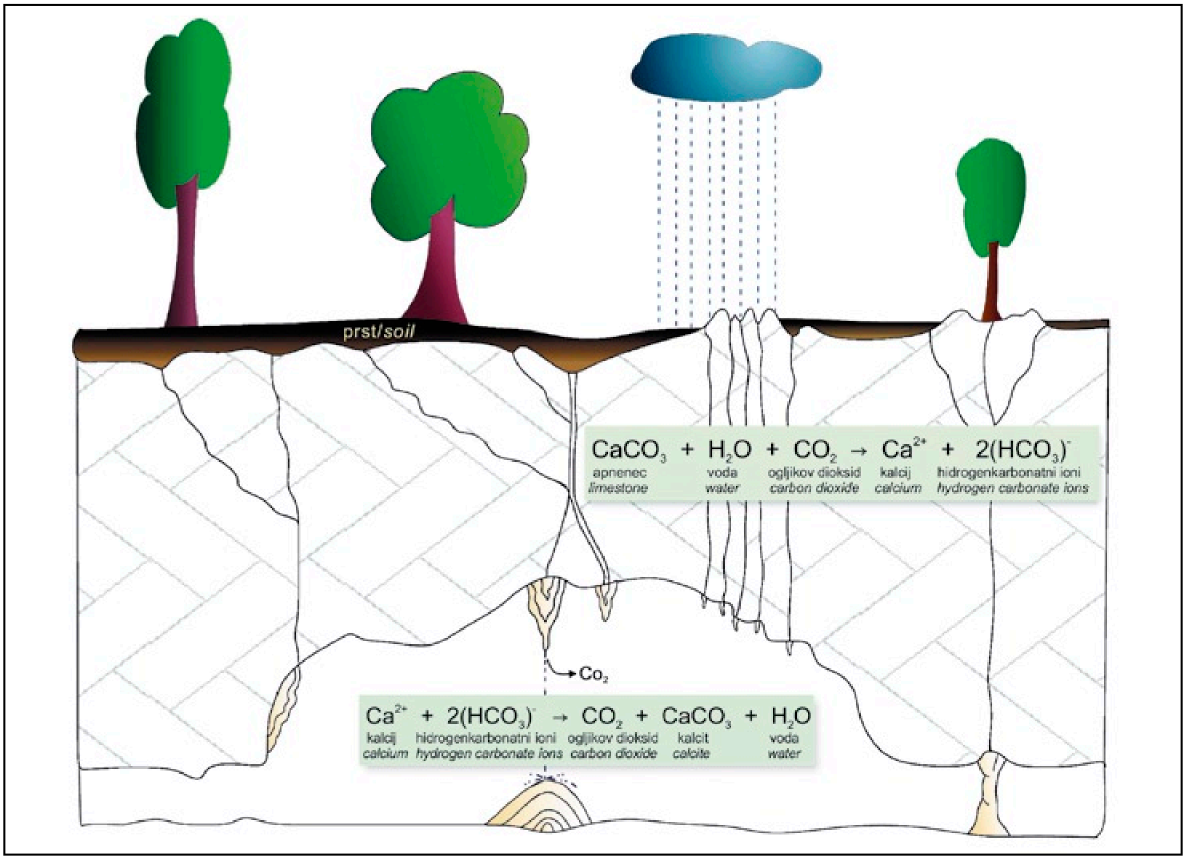


Figure 2.3: Water enriched with CO_2 from the soil and vegetation enlarges fractures through dissolution and penetrates ever deeper. When the water containing the dissolved ions reaches the cave, calcite deposits are precipitated from it in a wide variety of forms.

The intensity of dissolution is influenced above all by the quantity of precipitation, the partial pressure of the available CO_2 and the properties of the rock (Gabrovšek 2000). The key is the amount of precipitation: the more water there is available, the faster the rock will dissolve (rainfall is highest in the tropics – somewhere around 2,500 mm/year). If there is no water (arid areas: deserts, the Arctic, etc.; e.g. just 7 mm/year), there is no dissolution either. Denudation of a karst surface or karst denudation (the uniform lowering of the surface) represents the removal of material from the surface in ionic form. The denudation rate is expressed in m^3/km^2 per year or mm/1000 years. Values are based above all on climate (quantity of precipitation, temperature), evapotranspiration, CO_2 partial pressure and the composition of the rock (minerals, texture, structure, etc.).

Surface relief forms in karst

The dissolution of limestone and dolomite results in the formation of characteristic landforms on the karst surface that are described below (Ford & Williams 1989, 2007; Gams 2003; Mihevc 1997). Various factors dictate what types of karst features will form: the quantity of precipitation, the type of rock, the presence of soil and vegetation and the incline of slopes. Suitable conditions result in the formation of both small solutional features (karren such as flutes, meanders, solution pans, grikes in limestone pavements,) and classic karst features (dolines, conical peaks, poljes, etc.). Karst rock features form through dissolution, which takes place where there is direct contact between precipitation and the bare rock surface. Their formation depends on the quantity of precipitation, the manner of flow and the contact between the water and the surface of the rock. Features directly formed by precipitation on a rocky surface have sharp edges (Fig. 2.4). Rocky features formed beneath the soil or fine-grained sediments are rounded and smooth.

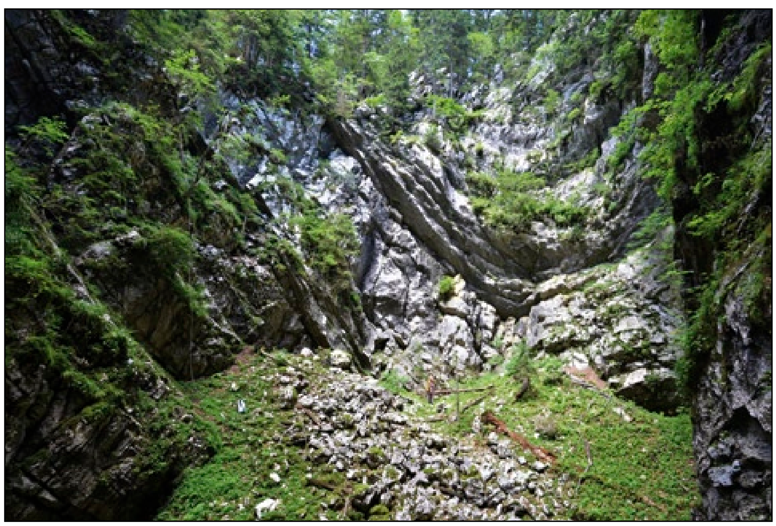
Figure 2.4: Dry solution pans (kamenitzas) with rain flutes (rillenkarren). Solution pans are round or irregular hollows in the rock with a flat bottom and, frequently, overhanging sides. They form as a result of water standing in depressions in which organic matter also accumulates (Photo: Nadja Zupan Hajna).

The doline is the most characteristic karst landform of moderate geographical dimensions. It is a closed funnel- or bowl-shaped depression in karst, whose width is usually greater than its depth (Gams 1974). The same landform can be the result of different processes, for example dissolution, collapse, the washout of fine-grained sediments and the subsidence of strata above more soluble rocks (Ford & Williams 1989). The most common are solution dolines (Fig. 2.5); the water in them dissolves the rock from the surface and carries it underground in the form of a solution. This is how most topographically closed karst depressions of different sizes form. The density of dolines on the surface depends on the type of rock (they are rare on dolomites and very numerous on medium-grained and coarse-grained limestones), on the incline of slopes (dolines are not found on steep slopes) and the degree of fracturing of the rock. Dolines on limestones are rockier than those on dolomites and have less soil on their sides. Soil typically accumulates on the bottom of dolines, which because of the thicker layer of soil are often also cultivated.

Figure 2.5: Dolines on the karst surface near Vodice in Istria (Photo: Nadja Zupan Hajna).

Larger depressions are collapse dolines. A collapse doline is a large karst depression with vertical sides (Fig. 2.6) formed by the collapse of the roof above an underground cave formed by dissolution. Remains of the collapse rubble lie on the floor of the collapse doline. Karst water can be present in it, or it can lead to a lower-lying cave. Larger collapse dolines are between 50 and 200 metres deep and up to a few hundred metres wide. Their volume can reach millions of cubic metres.

Figure 2. 6: Collapse doline with precipice walls and collapse material in its bottom (Photo: Nadja Zupan Hajna).



A karst polje is the largest type of karst depression, with a leveled rocky floor and karst drainage (Fig. 2.7). It has a sheer perimeter and a sinking stream with springs on one side of the polje and ponors on the other. A typical karst polje is formed by dissolution of the rock floor at ground level and at the margins in zones of water table fluctuation. Karst poljes can extend for several tens of kilometres in both length and width. Heavy and long-lasting rainfall causes the underground water level in karst areas to rise and flood the bottoms of karst depressions, both big and small. Because the karst is full of water, the ponors are no longer able to swallow the additional water carried by the sinking stream. This leads to the formation of intermittent karst lakes. In dry periods the karst polje is dry and the water level is deep below the surface. In rainy periods the water level begins to rise and floods the karst polje, resulting in the formation of a karst lake.

Figure 2.7: Typical karst polje is Cerkniško polje (Cerknica Polje) with leveled floor and intermittent lake (Photo: Nadja Zupan Hajna).

The surface of limestone karst is very rocky and rugged and therefore relatively impassable. The soil is thin or accumulates at the bottom of depressions. The surface of dolomite karst is formed through the reciprocal action of denudation processes and fluvio-erosional geomorphic processes. The surface of dolomite karst is smoother and less rocky, and traces of surface water flow are visible. Dells (dolci), a typical surface landform on dolomite, are present (Fig. 2.8). There is more soil than in limestone karst areas and the landscape is therefore inhabited and cultivated.

Figure 2.8: Dells (dolci), a typical surface landform on dolomite (Photo: Nadja Zupan Hajna).

Caves

Karst caves are underground cavities large enough for human entry that are formed as a result of the dissolution of rocks along the route of subsurface water flow in various environments (Ford & Williams 1989). The geological structures and lithological composition of carbonate rocks have a decisive influence on the formation and development of caves. Caves form where water penetrates most easily into rock, in other words through open fissures, faults, bedding planes and the most soluble layers. In the hydrological sense, caves are conduits in a karst massif in which a turbulent water flow is established as a result of dissolution (Gabrovšek 2012). The water, pushed through an initially hairline fracture by constant pressure, dissolves the walls of the fracture. The flow thus increases and the fracture widens further, since the chemically aggressive water penetrates ever deeper. The repetition of this process leads, via the accelerated growth of the fracture, to a breakthrough point in which the rate of flow increases by several orders of magnitude in a very brief period. Caves frequently form below the water table, in the saturated or phreatic zone. Conduits develop around their entire circumference, so typical phreatic passages are round or oval in shape. Epiphreatic passages form in the zone of fluctuation of the karst water table. These passages develop partly in phreatic conditions, i.e. symmetrically under pressure, and partly in vadose conditions, i.e. in a flow with an open surface. The typical shape of passages is usually a combination of the oval (phreatic) shape and the canyon-type (vadose) passage (Fig. 2.9). Vadose caves form between the karst surface and the karst water table. The water in this zone flows gravitationally and only washes a limited part of the cave ceiling. As a result, most of the caves in the vadose zone are shafts.

Figure 2.9: In the epiphreatic zone, the typical shape of passages is most often a combination of an oval (phreatic) shape and a canyon (vadose) shape (Photo: Nadja Zupan Hajna).

Sand and gravel in karst rivers can mechanically grind and significantly transform cave conduits. On the other hand sediments deposited around the circumference of the passage protect the walls against corrosion. If sediments are deposited on the floor, the passage generally grows in an upwards direction, where the walls continue to be exposed to corrosion. This type of passage development is technically known as paragenesis. Since in karst areas the water table (and also the surface) usually lowers over time, caves travel upwards in the hydrological sense, first into the zone of water table fluctuation (the epiphreatic zone) and then higher into the unsaturated or vadose zone (see also Fig. 3.1). Here they intersect with vadose shafts created by water percolating from the surface. The term speleogenesis is used to describe the entire life cycle of caves, from their formation to their collapse.

Age of karst

Karst is an important land-based source of information about past conditions in an environment. The most important carriers of this information are sediments on the karst surface and in caves. Sediments are classified in terms of their formation into clastic, chemical and organic, and in terms of their origin into autochthonous and allochthonous. Cave sediments (speleothems, alluvium, collapse rubble, etc.) reflect climate and processes in caves and on the surface.

Cave mineral deposits are chemical deposits precipitated from a saturated water solution. The quantity of cave mineral deposits is usually greater in lower positions, warmer climates and in the presence of higher rainfall, because dissolution of the rock is more intensive and more ions are available. Speleothems vary in form, mineral composition, colour and age (Lacković 2003; Zupan Hajna 2006). Their form depends on the type of water inflow. Different shapes grow from dripping, running, trickling, trapped, capillary or condensate water and through evaporation. The mineral composition and colour of speleothems depends on the composition of the rock above the cave which is dissolved by percolating water. The vast majority of speleothems are composed of calcite ($CaCO_3$), aragonite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$).

The formation of speleothems is an indicator of climatic conditions in the environment, since cave minerals are not as a rule precipitated in dry and cool climatic conditions. The intensity of dissolution of limestone is dependent on climate, in other words on geographical breadth, surface relief, the quantity of rainfall, temperature, soil cover, the quantity of biogenic CO_2 in the soil and the properties of the carbonate rock itself. The more rock is dissolved in a given period/environment, the more concretionary material can consequently be precipitated in caves. Thus the quantity of cave mineral deposits is usually greater in lower positions and warmer climates and in the presence of higher rainfall.

Allochthonous cave sediments are above all sediments carried underground from an impermeable zone by sinking streams (gravel, sand, silt, clay). These provide important information about the environment in which they formed before being transported and deposited in the cave. The same rocks on the surface weather differently under different environmental conditions (temperature, quantity of precipitation, pH, Eh). Various minerals accumulate in the weathered residues. Some derive from the original rock, while others formed during the weathering process. In the case of Eocene flysch, which is a relatively common rock in contact with carbonate rocks in south-west Slovenia and Istria, the most common final products of weathering are quartz, feldspar residues and various clayey and ferrous minerals, which reflect the weathering environment (Zupan Hajna 1998).

In the last 20 years knowledge of the age of cave sediments in Slovenia has advanced considerably, above all thanks to the use of various dating methods (Mihevc 2001, 2007; Zupan Hajna et al. 2008; Zupan Hajna et al. 2010). In the study of cave sediments, past researchers have mainly linked sediments to events in the late Pleistocene and Holocene, above all because of a lack of suitable dating methods. Sediments are believed to have been influenced in particular by alternations of warm and cool Pleistocene periods. Thus the deposition of clastic sediments is assumed to be tied above all to cool periods and the deposition of concretionary material to warm periods of the Quaternary. Datings of cave mineral deposits using the carbon method have not had a significant influence on these interpretations, because of the relatively short range of this method. A new view of sedimentation in caves has been opened up by palaeomagnetic and magnetostratigraphic research supported by numerical datings and by mineralogical, petrological, geochemical and geomorphological analyses.

The rate of denudation also helps us calculate the theoretical resistance of caves in an erosion environment. Within the erosion cycle caves can endure for up to 10 million years, if the rate of denudation is somewhere between 20 and 60 m of dissolved limestone on the karst surface in a million years (Gams 2003; Mihevc 2001). Geomorphological interpretations and analyses of roofless caves (Fig. 2.10) have clearly shown that some sediments in caves accessible to humans are Pliocene or even older.

Figure 2.10: Part of roofless cave named Ulica outside the entrance to the Ulica Pečina cave in the Podgradgrajsko podolje near Račice (Photo: Nadja Zupan Hajna).

The age of sediments in caves can be determined using absolute (numerical) methods – those that tell us when they formed – and relative/comparative methods that tell us which sediments are younger and which are older. We can use results regarding the age of sediments to reconstruct Cenozoic tectonic and karst processes in Slovenia. With the help of palaeomagnetic research of sediments and other dating methods, in particular biostratigraphy, we have in several cases determined cave sediments to be of enormous age and found that many cave sediments in caves in Slovenia were already deposited in the Miocene, meaning that the caves must already have existed then. The oldest cave sediments in karst areas of Slovenia are more than 5 million years old (Zupan Hajna et al. 2008, 2010). Two ages of cave sediments stand out in the research: between 1.8 and 3.6 million years old and around 4.1 to 5.4 million years old. In Račiška Pečina, a cave in the Podgrajsko podolje, for example, a profile just 3 m high has been found to contain recent mineral deposits, older Holocene mineral deposits with strata of Palaeolithic charcoal, cave bear bones from the Pleistocene, strata of sandy loam containing the bones of small mammals – believed to be around 2 million years old, and, in the lower part, mineral deposits up to 3.2 million years old. On the western edge of the Podgorski kras two different ages were determined in two profiles of sediments in roofless caves in the Črnotiči quarry. Recrystallised mineral deposits with intermediate strata of red clay are all more than 1.77 million years old. Meanwhile the strata containing sediments carried into the cave by a former sinking stream are between 2.6 and 4.5 million years old.

The most important result concerns the age is that cave fills, caves and karst are substantially older than expected earlier in general.

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Photo from "Water - Life!" in Istria competition; author: Kristian Macinić

SPECIFICS OF KARST HYDROLOGY

Metka Petrič, Josip Rubinić

Introduction

Karst areas with permanent surface water flow are rare. Precipitation quickly disappears underground through karstified terrain, where it flows – for the most part hidden from our view – through karst conduits, fissures and pores of different sizes towards karst springs, where it again flows out onto the surface, usually at a point where a karst area meets a non-karst area. Together with the water, pollution – the consequence of various human activities in the sensitive karst environment – can also spread quickly and represents an increasing threat to the quality of karst waters. The latter are an extremely important source of drinking water and according to some estimates supply almost a quarter of the world's population. This percentage is even greater in Slovenia and Croatia (approximately 50% and 35% respectively), while karst water sources represents practically the only source of drinking water (80–90%) in the area under study within the ŽIVO! project.

Good knowledge of the characteristics of karst water flow and contaminant transport is essential for the successful safeguarding of the quality of water sources. Thanks to the use of a variety of research methods, some of which are specially adapted to the characteristics of karst, understanding of these processes is constantly improving (White 1988; Bakalowicz 2005; Ford & Williams 2007; Goldscheider & Drew 2007; Kogovšek 2010). The main characteristics and features of the presence and flow of water in karst are presented below.

Water in karst

Because of fracturing of karst rocks (for the most part limestone and dolomite), rainwater percolates rapidly through the barren karst surface or scant soil cover and passes underground, and together with surface watercourses from non-karst zones (e.g. flysch areas) that sink underground on contact with karst, recharges a karst aquifer. This is a rock formation containing voids in which water flows or is stored for periods of a longer or shorter duration. These voids can be intergranular pores in the bedrock, fissures of different sizes and karst conduits. Karst aquifers are thus characterised by great diversity in the flow and storage of water. Their structure and functioning differ greatly from those of non-karst aquifers (e.g. intergranular aquifers). Permeability is extremely high, the rate of flow is high and the usually unknown directions of underground water flow can reach sections that can be several tens of kilometres distant.

Aquifers can be divided into several parts in terms of flow characteristics and underground water storage processes (Fig. 3.1). The upper section, in which rapid vertical flow through primary drainage conduits combines with slow percolation through less fractured bedrock, represents the unsaturated or vadose zone. This section, in which the pores are only periodically filled with water, can be several hundred metres thick. The top section, which is more heavily fractured, is known as the epikarst zone and plays an important role in shaping the rapid and slow flow of infiltrated water (Mangin 1975; Williams 1983; Kiraly et al. 1995; Klimchouk 2000; Trček 2003). Karstification within this section reduces with depth and vertical percolation is impeded, except via the enlarged principal fractures. As a result, temporary storage occurs, particularly after heavy rainfall, and some of the water runs off laterally towards the main fractures and quickly flows vertically down them towards the saturated zone. The remaining water percolates slowly through the unsaturated zone and continues to recharge the aquifer even in periods without rainfall.

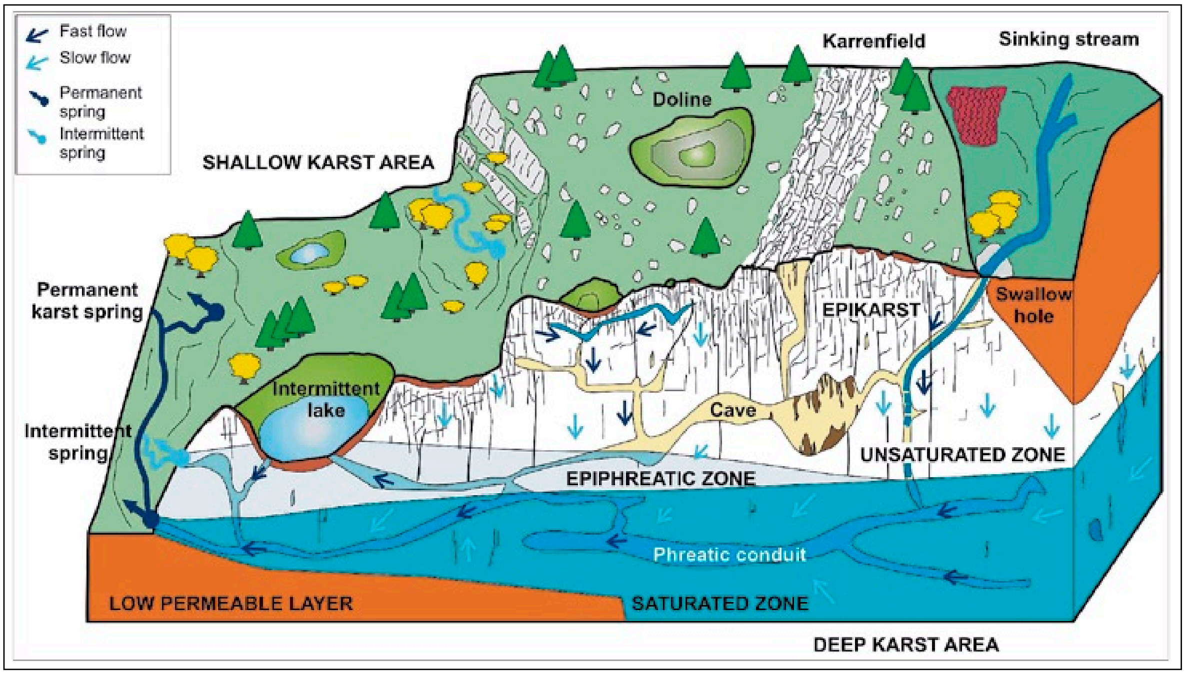

Figure 3.1: Schematic model of a karst aquifer (Ravbar 2007).

The lower part of an aquifer consists of the saturated or phreatic zone, in which all pores are filled with water. The transitional region between the unsaturated and saturated zones is known as the flood zone or epiphreatic zone. Here the pores are full of water when the water level is high and dry when it is low. It is limited by the range of fluctuation of the water table, which is defined as the level below which all pores are full of water. This is often unconnected and its position is very hard to determine, since it is constantly changing and very dependent on hydrological states. We can only observe it in individual flooded caves and boreholes, and therefore the level of karst groundwater is frequently unknown.

Water flow in the saturated zone is through conduits, fractures and porous bedrock. Flow is frequently turbulent and is usually sub-horizontal in the direction of springs. As a result of the rapid solutional enlargement of fractures, during the process of karstification the hydraulic conductivity of the system of underground karst conduits increases and the level of groundwater gradually falls (Gabrovšek 2000; White 2002; Ford & Williams 2007). In the same geological timescale, these processes are paralleled by global climate changes. These are reflected in global changes to the sea level, which represents the lowest erosional base of the free discharge of groundwater. With the rise in sea level at the time of the last glaciation, the sea flooded the lower sections of karstified walls (Surić & Juračić 2010), which slowed discharge from previously formed karst drainage systems. The velocity fell in the lower sections of karst aquifers, which also changed conditions for the depositing of sediments in karst aquifers and their coastal zones. At the same time, a dynamic freshwater-saltwater balance was created in the coastal parts of karst aquifers.

Groundwater usually discharges on the surface in large karst springs, while more dispersed discharge is also possible on a smaller scale. Springs are extremely important points for the study of karst groundwater, since they can be directly observed and their characteristics reflect the characteristics of the karst aquifer by which they are fed (Kresic & Stevanovic 2010). They are also extremely important as sources of drinking water, something to which we devote particular attention in this monograph.

In karst areas, then, we observe water at the points where it disappears underground, in some karst caves through which water flows, and in karst springs. By using a variety of research methods we attempt to establish where and how water flows through the underground. In the first place we are interested in the directions and velocities of this flow. Owing to the already mentioned heterogeneous nature of karst, differences in speeds can be very great, ranging from an order of magnitude of km/h through the most permeable karst conduits to an order of magnitude of cm/h through zones of very low permeability (Milanović 1979; Petrič 2009). The directions and characteristics of underground water flow and the transport of contaminants in it are also significantly affected by hydrological conditions, which are above all the consequence of the distribution and quantity of rainfall.

The amount of time that precipitation water will need to flow from the surface to the outflow therefore depends on the permeability of underground conduits and on precipitation and hydrological conditions. Water passing through main conduits, where it flows very quickly, can reach a spring in just a few hours or days. Water that percolates more slowly through the system and can remain inside the less permeable zones of an aquifer for a longer period, can stagnate and accumulate underground for several weeks, months or even years. Only sufficiently intense rainfall that establishes water flow through even the smallest fractures can drive this water out onto the surface.

Karst springs

Karst springs represent the natural outflow of groundwater onto the surface. An aquifer can empty through a single spring or through a system of several springs, some of which can be so-called overflow springs, which are only active periodically when the water level is high.

The rate of flow, which gives the volume of discharged water per unit time, changes very rapidly in karst springs. During dry periods the rate of flow can fall to just a few litres per second or springs can dry up entirely; after long periods of plentiful rain, rates of flow can increase to several tens of cubic metres per second. A diagram of changing discharges over time, known as a hydrograph, shows the considerable rapid changeability of flow rates in karst springs and their dependence on the distribution and quantity of rainfall in the catchment area of the spring (Fig. 3.2).

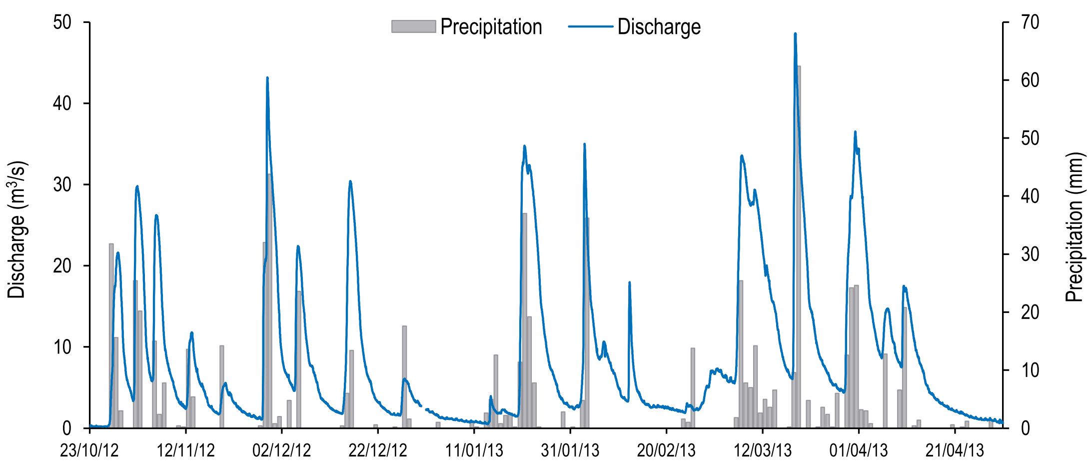

Figure 3.2: Example of changing daily precipitation in the catchment area and discharges of the Rižana karst spring.

Changes in precipitation and hydrological conditions result in changes in the physical and chemical properties of the water, and thus also of its quality. It is therefore necessary to take these dynamics duly into account when planning monitoring of the quality of karst water sources.

The catchment area of a spring includes the entire area from which surface water and groundwater flow towards the spring. Areas that mark the divergence of water flows towards different springs or into different river basins or drainage areas are called watersheds. In porous aquifers these correspond to orographic boundaries (surface watershed), while in karst it is extremely difficult or impossible to determine them precisely (Fig. 3.3). Watersheds are typically influenced by the geometry of the aquifer, while a special feature of karst is that their position can change, which consequently changes the size of the catchment area in different hydrological conditions. Another phenomenon that may be observed is that of karst bifurcation, which describes the drainage of water from a specific point towards different springs, in other words an overlapping of the catchments of different springs. Sometimes changing hydrological conditions can change the direction of underground water flow in karst aquifers.

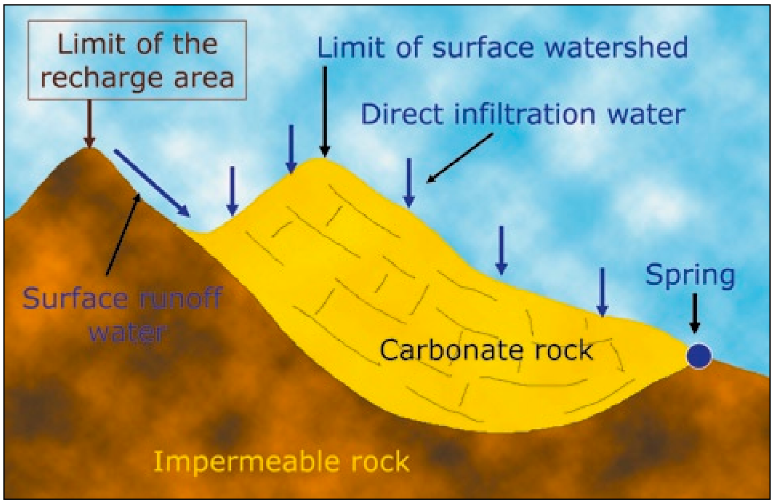

Figure 3.3: Sketch of the catchment area of a karst spring (from Vigna & Banzato 2009).

Defining the catchment area of a karst spring is an extremely important part of hydrological research. Knowing the size of the catchment area helps us estimate the yield of the spring, and is particularly useful when planning how to protect it from pollution. The best results are obtained through a combination of different research methods (geological and hydrogeological mapping, hydrological balance, tracer tests, etc.).

Importance of hydrological and hydrogeological research

In order to undertake comprehensive study of water in karst areas, we use basic hydrological and hydrogeological research methods, which however often need to be adapted to the special characteristics of karst aquifers (Goldscheider & Drew 2007). Basic information about the boundaries and structure of an aquifer is provided by geological research, which can be effectively complemented by the use of geophysical methods. Geomorphological analyses provide us with information about karst landforms, which significantly influence the characteristics of infiltration and underground flow. Speleological research is a special feature of the study of karst areas. This type of research, carried out in karst caves, enables the direct study of water percolating through the unsaturated zone and of water flow in karst conduits. With the help of hydrological research we analyse and compare the recharge and discharge of an aquifer and link these two processes with an estimate of the hydrological balance. Methods to determine the hydraulic parameters of underground water flow and storage are specially adapted because of the significant heterogeneity of karst, and considerable caution is necessary when interpreting the results of borehole tests. Tracer methods using natural and artificial tracers have proved to be very suitable for the research of karst waters. When tracing with natural tracers over a longer period, we monitor in detail the changes in various natural parameters of karst waters (e.g. temperature, electrical conductivity, Ca and Mg ions, isotopic composition, microorganisms, etc.), and by comparing the collected data we reach conclusions about the characteristics of karst aquifers. When tracing with artificial tracers (e.g. fluorescent tracers, salts), environmentally harmless substances are injected into the aquifer system, after which we are able to monitor flow direction and characteristics through observation at various points within this system (in flooded caves, boreholes or springs). Increasing use is being made of numerical modelling in the simulation of water flow and the transport of substances in karst, although when modelling it is necessary to take into account the special characteristics of karst and, because of these, to be aware of the limitations of models and to use extreme caution when applying their results in practice.

Good knowledge of the characteristics of karst aquifers is also a precondition for their adequate protection and optimisation of their use. Where and how quickly pollution from the karst surface spreads in the karst interior and in what springs we can expect to see it can only be successfully predicted if we have sufficient knowledge of the characteristics of the geological structure and hydrogeological and hydrological conditions in the area under consideration. Rapid and appropriate action is therefore only possible if adequate research has already been carried out (Knez et al. 2011).

Karst water sources and climate change

It is also necessary to highlight the importance of protecting karst water sources with a view to climate change processes, which are particularly present in the Mediterranean area (Bolle 2003) and which are expected to intensify in the future (IPCC 2007). Unfavourable air temperature and precipitation trends across the wider region are reflected in clearer trends of flow reduction and decreasing water reserves (Bonacci & Gereš 2001; Švonja et al. 2003). Such unfavourable trends are also present in the research area of the ŽIVO! project and have been illustrated in the case of the Rižana spring. Fig. 3.4 shows the modular values of the mean annual discharge of the Rižana at the Kubed station downstream of the source and mean annual air temperatures and precipitation at the Postojna climate station, which although it is located outside the boundaries of the spring's catchment area nevertheless offers a good reflection of climate conditions on the regional scale. The figures are taken from the website of the Environmental Agency of the Republic of Slovenia. Analysis was carried out at the level of hydrological years, which correspond better than calendar years to the hydrological cycle of filling and emptying of water reserves. In the analysed period of 52 years, an upwards trend was identified for air temperature (an increase of 4.5% over 10 years), while downwards trends were identified for precipitation (2% over 10 years) and discharges, where with an increase in drinking water needs discharges of the Rižana fell by as much as 10.3% over 10 years.

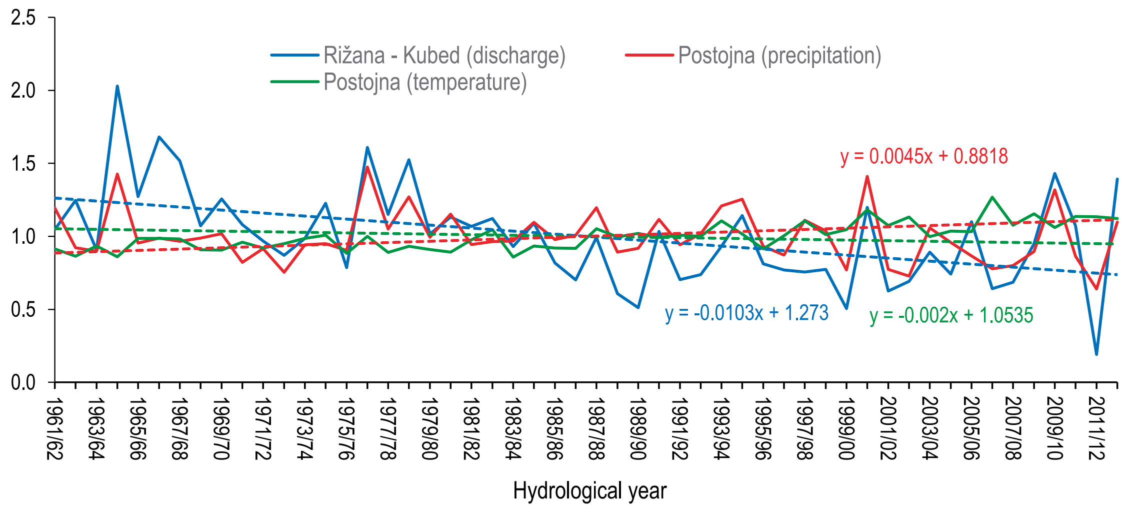

Figure 3.4: Modular values of annual precipitation and mean annual air temperatures at the Postojna station and mean annual discharges of the Rižana at the Kubed station (for hydrological years from 1961/62 to 2012/13).

Since the problems of water quantity and quality are becoming increasingly serious, accuracy of forecasting and effectiveness of water source management will become more and more important (Coppola et al. 2003). Karst aquifers are usually treated as static systems with the characteristics they had in the past and still have in the present. However, in order to understand the functioning and protection of water sources and predict their behaviour under extraordinary conditions, it is necessary to analyse them at the conceptual level as dynamic systems in a constant evolution of climatic and hydrological conditions and related changes. The hydrological component of real-time operational water source management using mathematical models that enable us to estimate water flow in karst, and also changes to its quality, is becoming increasingly important. Here it is essential that in our analysis we use good-quality data obtained through the well-planned and accurately implemented monitoring of climatic and hydrological processes in karst springs and their catchments.

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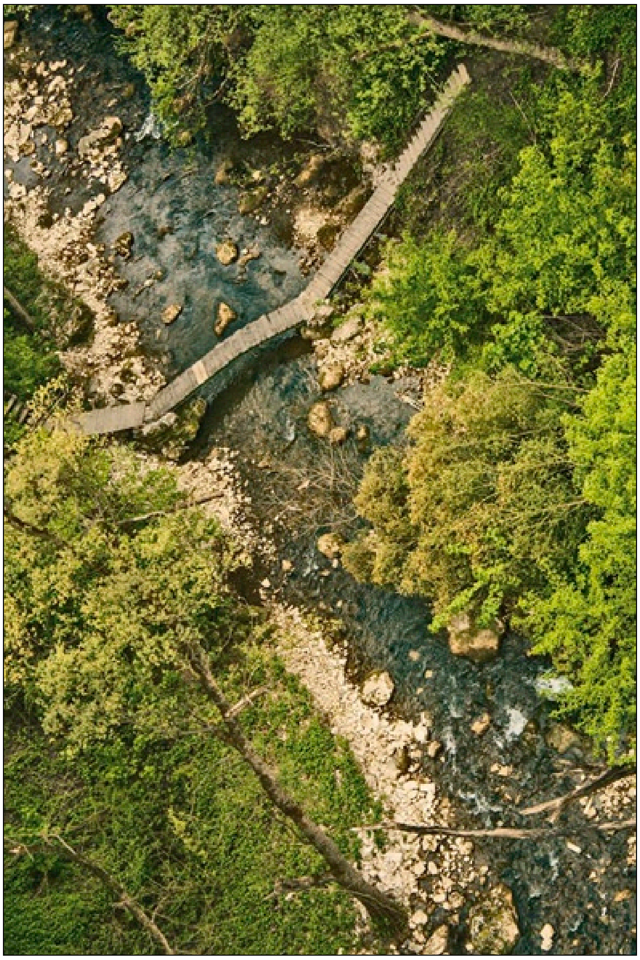

Photo from "Water - Life!" in Istria competition; author: Mirna Bartolić

ENVIRONMENTAL VALUE AND VULNERABILITY OF KARST RESOURCES

Nataša Ravbar, Janja Kogovšek, Tanja Pipan

Introduction

Karst terrains are one of the landscape types that provide humans with numerous and multiple benefits, which are derived from ecological services and aesthetic attractiveness. Due to the special intrinsic characteristics of karst, climate change effects on recharge, together with the increasing pressures on karst groundwater quality, the exploitation of karst natural resources and accompanying urbanization at various karst regions, has already caused landscape and ecosystem deterioration. Their protection thus poses many scientific and practical challenges, which requires a specific approach (Drew & Hötzl 1999; Ravbar & Šebela 2015).

Slovenia and Croatia are countries that host some of particularly widespread karst landscapes. Carbonate bedrocks on which karst is formed, underlie about half of both countries. Among various types of karst, Dinaric karst is the most widespread and ranks among largest contiguous karst areas in the world (Gams 2004; Mihevc & Prelovšek 2010). The extensive Dinaric karst landscapes are unique to both countries, considered the locus typicus for karst landscapes around the world. These territories have created unique environments with values related to natural and cultural heritage having relevant natural and environmental significance.

In the present chapter environmental values of the Dinaric karst are considered. Reasons for karst being an extremely vulnerable environment are presented and the importance of enhancing its conservation is stressed.

Environmental value of karst

In both countries, karst aquifers cover about half of the needs and are of exceptional importance for drinking water supply (Fig. 4.1). In many regions karst aquifers often afford the only exploitable reserves, which therefore present invaluable sources for human health, food security, and the economic sector. Moreover, many karst springs contribute to surface waters and play a major role in maintaining numerous aquatic ecosystems and wetlands (Bonacci et al. 2009; Kresic & Stevanovic 2010; Ravbar & Kovačič 2015).

Figure 4.1: The Rižana karst spring is a drinking water source for about 86,000 inhabitants of the Slovenian coastal region, but supplies more than 120,000 people in the peak tourist season (Photo: Nataša Ravbar).

Particular karst landforms, such as caves, poljes, springs and other geomorphologically remarkable phenomena contribute significantly to geodiversity and are fundamental to the retention of biodiversity and other ecosystem services. These landforms are also historically a focus of human attention for recreation and well-being. Many have become tourist attractions and prompted the development of tourism (Hamilton-Smith 2007; Williams 2008). In the predominantly mountainous areas of practically untouched Dinaric karst nature, several national parks, such as for example Risnjak, Plitvice lakes, Paklenica, Krka, Kornati, and protected natural reserves (e.g., Snežnik, Velebit, Biokovo) have been established (Fig. 4.2). Caves also offer opportunities for scientific study and education by providing an insight into past environmental, geomorphological, ecological and anthropogenic conditions. These can potentially include undisturbed archaeological sites and well-preserved animal and human remains.

Figure 4.2: The Notranjska Regional Park with its 22,810 ha of land is the second largest natural park in Slovenia. It includes sights such as: the Snežnik mountain, the intermittent Cerkniško jezero, the Rakov Škocjan, the Križna jama, etc. (Photo: Nataša Ravbar).

Figure 4.3: The raw materials from the quarries are useful as construction material, stone aggregate for preparation of concrete, mortar, bituminous mixtures and surface treatments for roads, airfields and other trafficked areas, as bulk material for railways and jetties (Photo: Stanka Šebela).

Karst terrains are also important for mineral resources (Fig. 4.3). Most common mineral resources are carbonate rocks, such as limestones, dolomites, gypsum. They are used for a wider range of purposes than any other rocks. While this activity is of undoubted importance economically and commercially, it poses demanding environmental and restoration challenges (Gunn & Bailey 1993).

Due to specific geomorphological and hydrological characteristics karst areas provide the physical habitat for particular communities that are characterized by high biodiversity. A great variety of species are present both on the surface and in the underground. Unusual fauna that develop in the light-deficient subsurface environment range from bacteria to crustaceans, spiders, fish and small mammals. Many species are rare or even endemic, strictly tied to the local habitat (Culver & Pipan 2013).

Microbial organisms are important in karst as well. The organisms and their role in karst has just recently been studied more intensively and appeared to be important in biological and geological processes in karst environment. They may accelerate dissolution, contribute to the deposition of flowstone or may be indicators of contamination sources (Barton 2006; Mulec 2014).

Vulnerability and degradation of karst

Karst systems are generally stable environments that have developed over thousands of years. Air and water are the media connecting surface with the underground. Aeration and rapid infiltration conditioned by heterogeneous permeability of fissures and voids have the main effects on consequent corrosion processes and complex surface – underground air and water exchange. These particular structural and hydrological characteristics rank karst landscapes and related habitats among the highly vulnerable ones. Therefore any maladjusted land use practices may cause serious and irreparable alteration of the natural processes and pose environmental concerns.

Human impacts and encroachments may result in different types of contamination, natural hazards, ecosystem degradation and loss of biodiversity. They may also cause alteration of other natural karst processes, such as corrosion and carbon cycle. The underground is particularly susceptible to these changes, as it is characterised by relatively constant temperatures and humidity all year round. Once damaged, karst surface and underground environments often take a long time to recover. The process of recovery may be very difficult or even impossible (Ford & Williams 2007).

In the past few decades an increased pressure on karst landscapes, i.e. by intensive and unsustainable spread of settlement, infrastructure and industry, the development of tourism, and intensive agrarian land use have occurred. Exhaustive reshaping and degradation of the landscape have greatly expanded, largely as a result of technological development and mechanization. Modifying the natural conditions may intensify the natural susceptibility to contamination and degradation (Drew & Hötzl 1999; Parise & Pascali 2003; Kovačič & Ravbar 2013).

Quarrying and engineering activities, excessive filling of dolines have become a major encroachment on the surface (Fig. 4.4). Many dolines are filled with construction waste, sometimes also with other waste, for levelling purposes. These issues are closely related to deforestation and consequently to soil destruction or erosion which alters surface – underground transmission of air and water. Thin or even absent soil, sediment and vegetation coverage provides minimal absorption or other natural cleaning processes. The absence of these protective layers prevents pollutants from degrading chemically, biologically, or physically and further accelerates infiltration into subsurface.

Diverse types of hazards, coming from different human activities, threaten karst landscapes. The greatest contamination mainly derives from urban wastewaters, where sewage is not well regulated or not regulated at all, contamination from unsuitable transport systems, hazardous spills of dangerous substances and dumping. Some serious hazards can derive also from industrial, agricultural, tourist, sport and construction activities (Fig. 4.5).

Figure 4.4: A) Doline filling and B) landscape levelling (Photo: Gregor Kovačič).

Figure 4.5: Illegal waste disposal in caves and shafts present high risk of groundwater to contamination due to direct linkage of surface with the underground (Photo: Karst Research Institute Archive).

Water transport is the easiest and the most rapid way for contaminants to enter the karst system. Underground solution conduits and voids very rapidly convey most of the flow. In areas of localized recharge (e.g. swallow holes, shafts), surface water is directly linked to groundwater. Transport mechanisms in the underground are several orders of magnitude greater than in non-karst systems reaching velocities up to several hundred meters per hour. Due to the complexity of connections and extreme changes in different hydrological conditions, the courses of underground water in karst are often unknown. Connections and intersections of water paths over large distances (up to many tens of kilometers) are common. A greater distance does not necessarily mean less danger from pollution (Ford & Williams 2007; Kresic & Stevanovic 2010).

In the underground, water flow is often turbulent, in limited conditions of aeration and reduced biological activity. Turbulent flow often means the mobilization of insoluble pollutants and prevention of their retention (Fig. 4.6). In anaerobic conditions the rapid flow reduces the possibility of biodegradation. As a result, the self-cleaning capacities of underground waters in karst are very low and limited to a considerable degree.

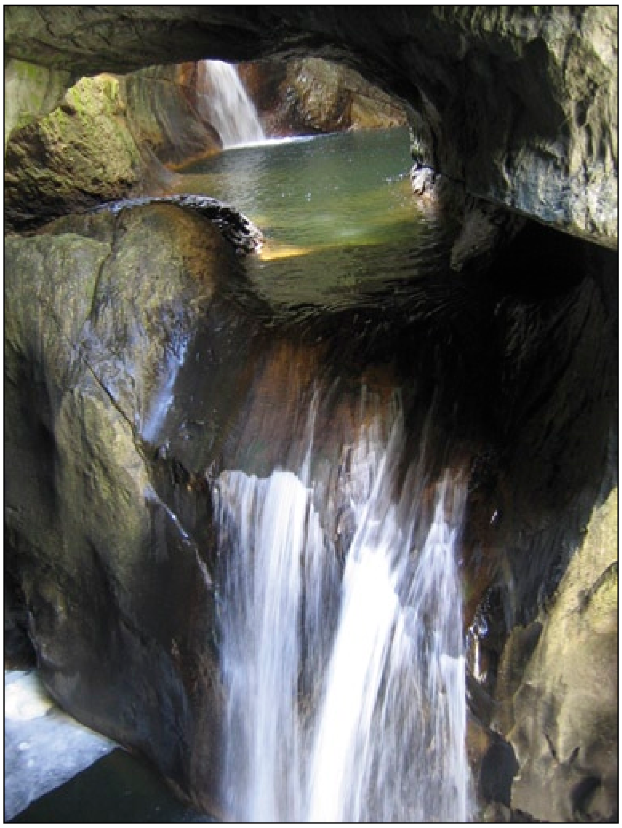

Figure 4.6: A consolidated cave stream, the Reka River of Škocjanske caves in southwestern Slovenia (Photo: Nataša Ravbar).

Vulnerability of karst water

Self-cleaning processes of karst waters are often less effective due to the rapid infiltration, reduced filtration, high-speed flow and transfer away from the entry point. Fracturing and karstification degree of underground pathways and respective hydrological conditions are determining underground transport processes (White 1988; Király 2002). Groundwater flow in karst aquifers is often characterized by strong variability of flow dynamics in response to different hydrologic conditions within a short time period (Kogovšek & Petrič 2012; Ravbar 2013). Consequently, water table fluctuations are often in the order of tens of meters, differences in flow velocities between low- and high-flow conditions can reach ten or even more times. Dependence on hydrologic conditions also results in variation of flow directions, and thus in contribution of different parts of the aquifer to a particular spring (Fig. 4.7).

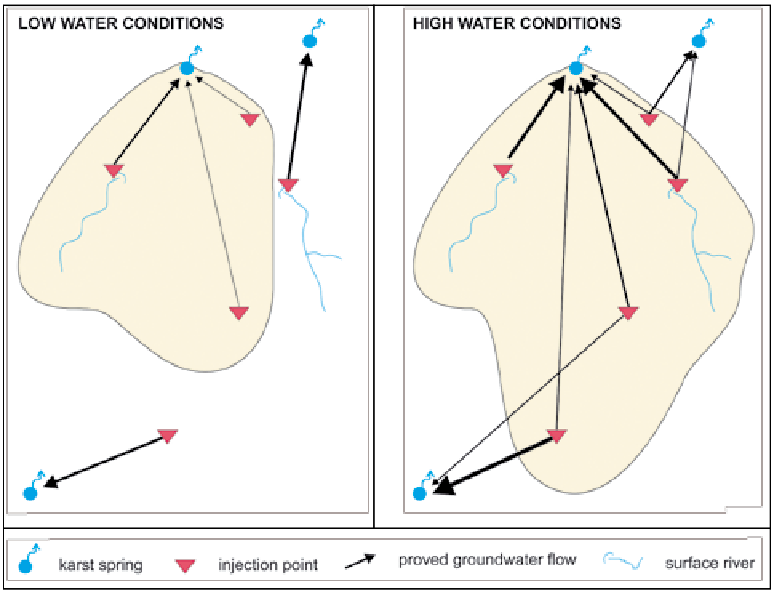

Figure 4.7: A conceptual model of a karst aquifer system functioning during low- and high-water conditions with wider arrows indicating proportionately great flow volume.

Hydrological variability has many implications for contaminant transport, groundwater availability and vulnerability. Rising groundwater level reduces the thickness of the unsaturated zone and decreases protectiveness of the overlying layers. Higher water flow velocities reduce underground retention. During high-flow conditions there is usually more surface flow and hence more concentrated infiltration underground. Change from laminar to turbulent flow may occur resulting in higher transport velocities, shorter transit times, more effective transport of sediments and bacteria, mobilisation of DNAPL's (Dense Non-Aqueous Phase Liquid). Raising water table above the conduit ceiling induces change from open-channel to pressurised flow.

During low flow conditions contaminants may thus be temporarily stored in the overlying unsaturated zone or accumulated in the adjacent non-karst areas that drain into karst. After enough substantial and intense precipitation accumulated contaminants are directly transported through preferential routes towards the springs. If dilution is not sufficient, the springs may be characterised by increased levels of contaminants (e.g. nitrates, phosphates, sulphates, chlorides, bacteria and other). Such contamination conditions have been observed in a very dry year 2012 in Slovenia, when numerous karst water resources were heavily microbiologically contaminated and not suitable for potable use before proper treatment (Kogovšek 2012).

Results of similar studies reveal that after an intense recharge, spring discharge often increase rapidly, while there are no or very minor changes in electrical conductivity and temperature. This is explained by hydraulic pressure-transfer in the aquifer, i.e., the water discharging at the spring during this phase is displaced conduit water (old water). A turbidity signal that sometimes occurs during this phase is due to the remobilization of sediments from karst conduits. A temporary electrical conductivity increase that is often observed before or during peak discharge can be explained by the arrival of water from other zones of the aquifer due to changing pressure relations and flow fields, such as water from the epikarst or from fissured rock volumes adjacent to the conduits (Shuster & White 1971; Worthington 1991; Fournier et al. 2007; Ravbar et al. 2011; Kogovšek 2013). Subsequent decrease in electrical conductivity that often coincides with turbidity increase and increase of other contaminants, often accompanied with changing temperature, indicates arrival of new (i.e. surface) water (Fig. 4.8).

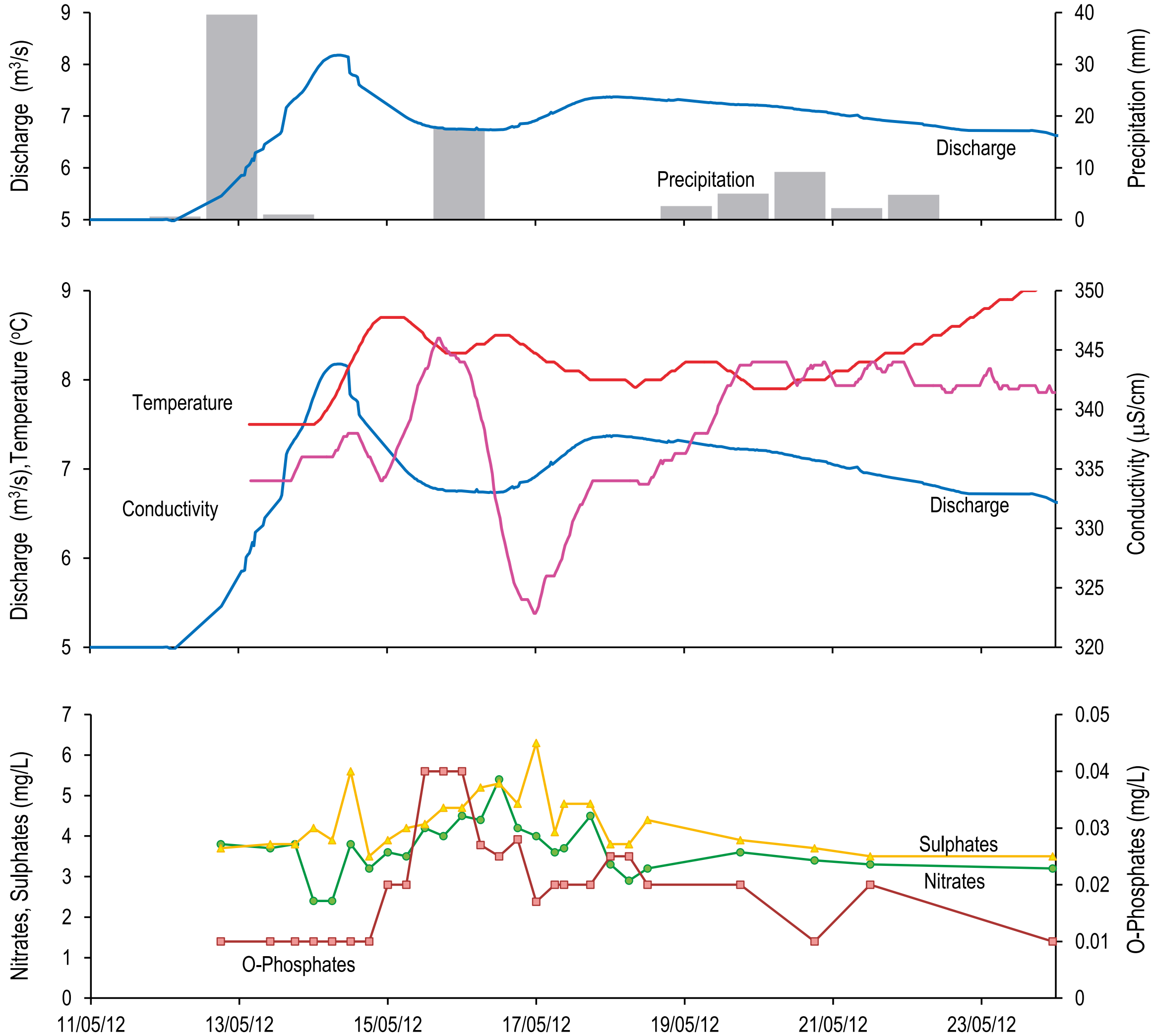

Figure 4.8: Storm response of the Malenščica spring showing dynamics of natural parameters (discharge, temperature, electrical conductivity, chlorides, nitrates, sulphates and phosphates), and precipitation in spring 2012. Precipitation values represent daily time intervals.

Besides groundwater quality problems, the biggest actual concerns especially from the karst water management perspectives, are changes in the large-scale hydrological cycle induced by global warming. As it is expected, climate stresses may have implications for water quantity and quality in many areas and affect freshwater dependant ecosystems and several socio-economic activities (Kundzewicz et al. 2008). Because karst aquifer systems are highly controlled by heterogeneous permeability, they have very low retention capacity (but still higher than for example surface flow), limited to low-permeability matrix. These aquifers are highly dependent on respective hydrological conditions and have the potential to be strongly impacted by freshwater shortfalls and floods.

Karst subterranean habitats and their vulnerability

Karst underground creates highly specialized ecosystems with a permanent absence of light and hence an absence of photosynthesis. Due to low-energy and aphotic conditions, primary productivity is extremely limited or even absent. With the exception of a few caves and possibly most deep-groundwater habitats with significant chemoautotrophy, all subsurface food webs rely on the import of surface organic matter. Thus, subterranean organisms must contend with complete darkness, limited food, and at least a reduction in seasonal cues which makes subterranean ecosystems extremely vulnerable to any changes and disturbance (Humphreys 2006; Culver & Pipan 2009).

Subterranean environments include aquatic and terrestrial habitats. A variety of subterranean habitats originate in many small solution pockets and cavities with complex horizontal and vertical pathways that are either dry, temporarily or permanently watered. Aquatic subterranean habitats occur in cave streams and seeps, and may show greater temporal variability in chemical and physical parameters. Phreatic water habitats occur in water-filled underground voids, often tens to hundreds of meters deep. It is characterized by very slow flow rates and consequently long residence times (decades or even centuries). An intermediate between an aquatic and terrestrial habitat is the cave hygropetric – a thin layer of water flowing over (sub)vertical surfaces. The flow is well oxygenated and often relatively rich in organic matter.

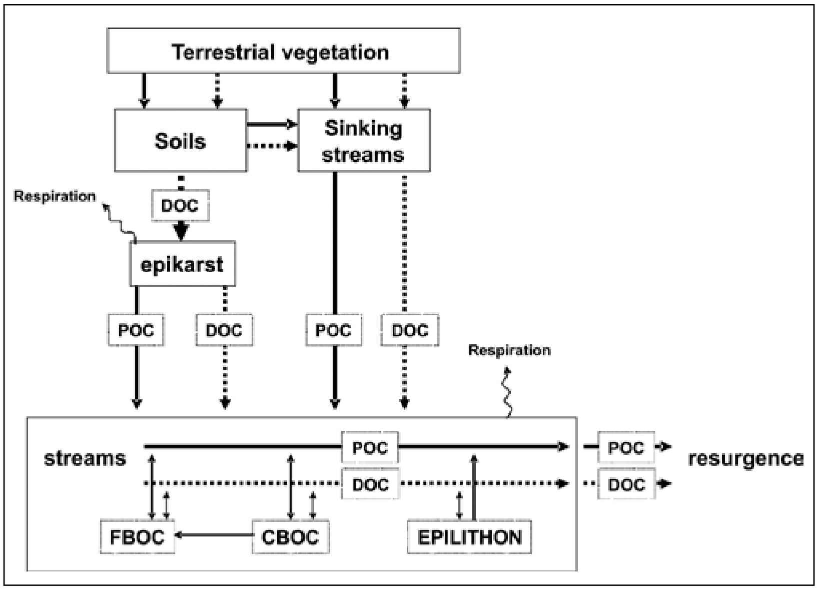

Figure 4.9: A conceptual model of energy flux and distribution (as organic carbon) in a karst basin. Solid and dashed arrows represent the flux of particulate (POM) and dissolved (DOM) organic matter. Standing stocks of organic carbon in cave streams include fine (FBOM) and coarse (CBOM) benthic organic matter and biofilms on rocks (Simon et al. 2007).

Energy and food sources (Fig. 4.9) enter subterranean habitats in a variety of ways (Culver & Pipan 2009, 2014). Percolating water carries with it dissolved organic matter, some suspended particles of organic matter, and a variety of microbes and minute invertebrates. This seemingly unimportant source of nutrients is actually the most important one in many situations. Flowing water, especially streams entering caves, carries with it not only dissolved organic material, but also particulate organic material, in some cases up to the size of logs (Simon et al. 2003). Flowing water provides nutrients not only to aquatic communities in caves but also to terrestrial communities that live alongside cave streams (riparian communities). Wind and gravity bring nutrients into caves when organic material comes into an entrance. Examples include falling leaves as well as animals that fall or wander into a cave, cannot exit, and die. The hallmark of this food source is its unpredictability. Active movement of animals is, in some caves, a major source of nutrients, especially in terrestrial cave habitats. The most notable examples of this food source are bats, and in fact distinct communities of organisms specialize on the bat guano of caves. Finally, roots penetrate into some shallow caves, and species utilize the roots as a food source.

Figure 4.10: Caves provide a kind of shelter for bats to have their maternity colonies (Photo: Jurij Hajna).

Many organisms spend some or all of their life cycle in caves, particularly cave entrances. The entrance and twilight zone of a cave are refuges from temperature extremes of the surface. Some species, such as the spider *Meta menardi*, are specialized for the surface–subsurface ecotone at cave entrances. The entrance and twilight zones of caves are relatively predator-free, at least for vertebrate predators. Some birds nest in caves on a more or less regular basis. The best-known visitors to caves are bats. Depending on the species, bats use caves as maternity colonies, as hibernacula, and as temporary roosts during the warmer months of the year (Fig. 4.10).

Many species spend their entire life cycle in caves. In the case of terrestrial species, troglobionts have an obligate dependence on caves and must complete their entire life cycle in caves (Fig. 4.11). Troglophiles can complete their life cycle in caves, but they can also complete their life cycle in surface habitats. The equivalent terms for aquatic species are stygobionts (Fig. 4.12) and stygophiles. These species are adapted to spend their entire lives in these extreme environments. Most of them have no eyes, often lack pigment, and have elongated legs and antennae. Some have specialized organs that detect smell and movement to help them navigate in a totally dark environment and find food, avoid predator or find a mating partner. Currently, more than 4,000 troglobionts and 2,000 stygobionts have been formally named, and at least several times that number probably exists (Culver & Pipan 2013).

Figure 4.11: The first troglobiont, the cave beetle Leptodirus hochenwartii *found in Postojnska jama was described by Schmidt in 1832 (Photo: Slavko Polak).*

Figure 4.12: The remarkable cave amphibian, Proteus anguinus anguinus*, was the first stygobiont to be mentioned in scientific writing, described by Laurenti in 1768 (Photo: Jurij Hajna).*

Karst resources and ecosystem services conservation

Karst landscapes are important for natural resources, ecosystem services and biodiversity yet are increasingly threatened by urbanization and development activities. Unfortunately karst and cave protection is rarely considered in landscape planning. Because karst areas are extremely vulnerable to anthropogenic and other environmental impacts, their particular structural and hydrological characteristics must be understood and considered when carrying out investigations, confronting with specific environmental and engineering problems or when planning management of resources.

Management planning must consider all of the natural resources found within the region, as well as interaction between various components. Any interference with this relationship is likely to have undesirable and irreversible impacts, while disturbance in the natural balance of any of these components may have implications for all the others.

Laws and regulations that are effective in other terrains may not be as effective or may even fail in karst settings. Therefore, proper regulations may be needed to satisfactorily protect karst resources, particularly as related to the location of landfills, underground storage tanks, oil and gas wells and pipelines, and facilities that manufacture and/or store hazardous materials. Additional necessary actions are certainly identification and protection of highly vulnerable karst features, monitoring of cave climate and groundwater quality and public education about cave and karst conservation.

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Photo from "Water - Life!" in Istria competition; author: Kristian Macinić

II. STUDY AREA: NORTHERN ISTRIA

Photo from "Water - Life!" in Istria competition; author: Igor Zirojević

LOCATION, TOPOGRAPHY, CLIMATE

Andrej Mihevc

Northern Istria

The territory that is the subject of research in this project is small but with considerable diversity of landscape. There are two reasons for this. The first is the transition from warm, coastal Istria to the hilly interior and the related differences in climate features. The second is the geological structure. Two types of rocks alternate here: limestones and flysch sandstones and marls. Because limestones predominate, these set the character of the landscape: an absence of continuous soil cover and subsurface water flow. Soil thick enough to allow agriculture, and thus also settlement, is only found here and there, in karst depressions, but above all on flysch bedrock. Water flow is also dependent on the rocks. At the point of contact between flysch and limestone we find numerous ponors in the hilly part of the landscape and a large number of karst springs in the lowland part. This landscape can be characterised by the name "Northern Istria".

The central part of Northern Istria lies at a latitude of 45° 27' N and a longitude of 14° 5' E, at the transition from the Istrian Peninsula, the largest peninsula in the northern Adriatic, to the interior.

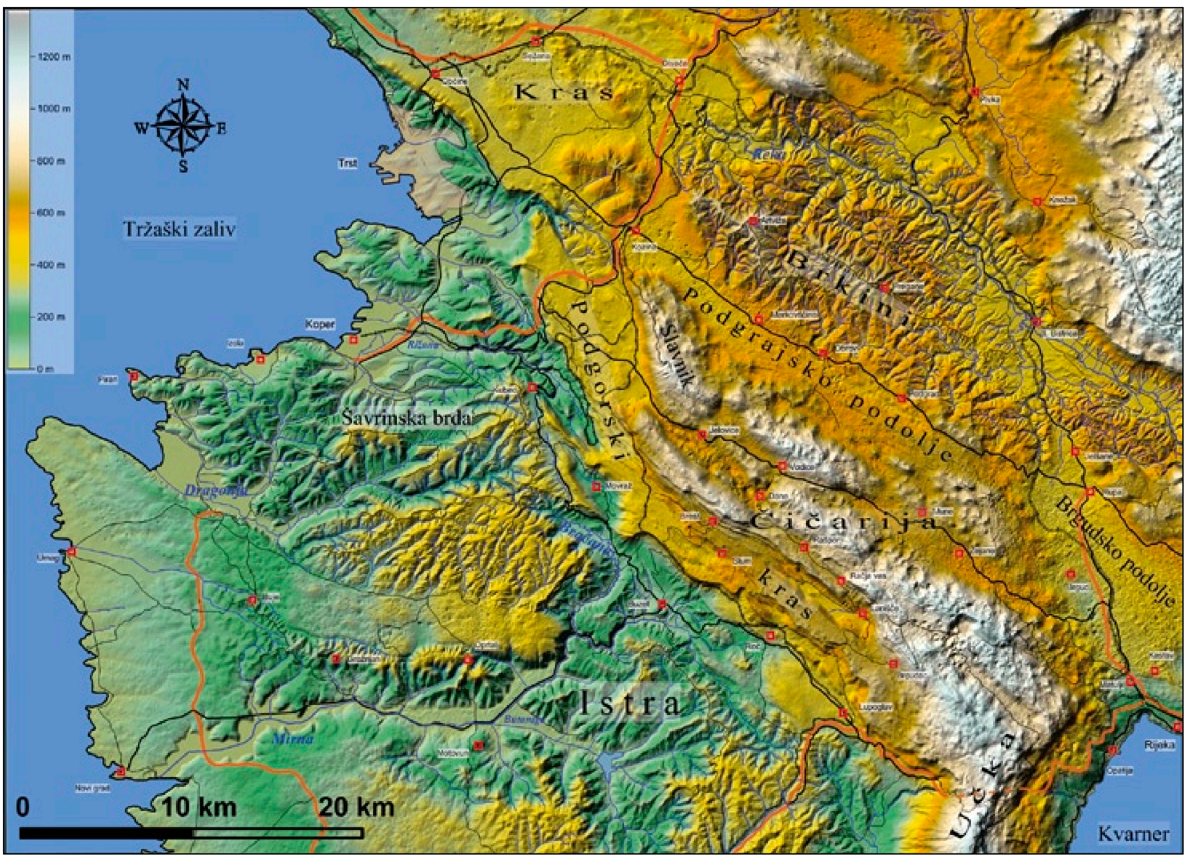

Figure 5.1: Morphology of Northern Istria. The clearly demarcated relief units and different types of surface are plainly visible. A ridge-and-valley relief on flysch and flat, plateau-like limestone areas broken up by dolines and other karst depressions can be clearly distinguished. LiDAR data: Geodetski oddelek ARSO and SRTM NASA.

Northern Istria is composed of several prominent units of relief (Fig. 5.1). The central, widest, highest and most prominent section is Čičarija/Ćićarija, a chain of hills that extends in the Dinaric direction, from northwest to southeast. It begins near Kozina with a narrow crest that rises up to Slavnik, then expands in several parallel ridges separated by elongated uvalas, dolines and other karst depressions. It reaches its highest point on Učka and then descends steeply towards the Kvarner Gulf.

In the interior, the highland section descends in steps to an extensive, already somewhat disconnected karst plain (Gams 2004). Its northern part, the Podgrajsko podolje (Podgrad karst lowland), lies above the Gulf of Trieste, while on the southern side the Brgudsko podolje (Brgudac karst lowland) lies above the Kvarner Gulf. Above them rise the Brkini and Jelšane hills, from where a series of sinking streams flow into the valley.

On the seaward side of Čičarija/Ćićarija the land descends in step-like fashion in a series of elongated strips of alternating flysch and limestone, into the so-called flysch-grey Istria (Fig. 6.28).

Overview of the different units of the landscape

Brkini

The Brkini are hills composed of impermeable flysch rocks. They reach their highest point in their northwestern section on the ridge between Ajdovščina (804 m) and Artviže (817 m). The Brkini become lower towards the southeast and then continue without a visible transition into the Jelšane and Novokračine hills. The alternation of deeply incised valleys and rounded ridges is a basic characteristic of the Brkini. Since the valleys are narrow and steep and covered with forest, settlement and also the main routes stick to the ridges.

Waters flow from the Brkini towards the Reka River on the north side, while towards the south each stream sinks underground separately at the margin of the Podgrad valley system in blind valleys.

Figure 5.2: Northwestern part of the Podgrajsko podolje. In the foreground is the Brezovica blind valley; behind it, on the edge of the erosional surface, is Kozina; on the horizon is the Gulf of Trieste (Photo: Andrej Mihevc).

Podgrajsko in Brgudsko podolje

A series of streams flow towards the south from the slopes of the Brkini and Jelšane hills. When streams from impermeable rocks flow onto limestones, they flow over them for a time and then sink underground. In doing so, and of course in contact with precipitation, they help form karst, which is therefore known as contact karst (Fig. 5.2).

The first landforms to appear at the edge of the karst, when the water level in the karst was still high and the streams could not therefore sink underground, were marginal corrosional surfaces, plains and karst lowlands. These include the Podgrajsko podolje and the Brgudsko podolje.

The Podgrajsko podolje is 2–4 km wide and rises gently from around 500 m at Kozina to around 670 m at Starod, at the national border. Towards the SE the lowland descends in a gentle but distinct curve into the Brgudsko podolje. This lowland lies at height of around 450 m near Rupa but descends to around 300 m and then drops steeply towards the sea between Opatija and Rijeka. The Brgudsko podolje is up to 7 km wide.

Both of the lowlands are composed entirely of limestone and feature many dolines (Fig. 5.3), collapse dolines, blind valleys and caves. These landforms could only develop after the land had lifted as a result of tectonic forces and karstified, and the rivers could begin to sink underground, in the process forming valleys that end as blind valleys in ponors.

Blind valleys formed in limestone and usually have a broad floor covered with alluvial deposits (Fig. 5.4). Alluvium is deposited outside ponors from flood water that stagnates outside ponors because underground routes to distant springs are full of obstacles.

Figure 5.3: Dolines in the Podgrajsko podolje (Photo: Andrej Mihevc).

Figure 5.4: Brezovica is a typical blind valley with a broad sediment-covered floor. Above the village is the flysch catchment area of the sinking stream. Floods are of short duration (Photo: Andrej Mihevc).

On the southwestern edge of the Brkini and Jelšane hills, 24 sinking streams collect water and sink into the karst. These waters have carved deep ravines in the flysch, while in limestone areas their valleys have widened into blind valleys. The valleys extend in a series from Rodik to Šapjane or Rupa. The largest blind valleys are Brezovica, Odolina, Velike and Male Loče, Jezerina and Račiška, Brdanska in the Podgrad valley system, and the Šapjane and Novokračine blind valleys on the edge of the Brgudsko podolje system near Rupa (Fig. 5.5).

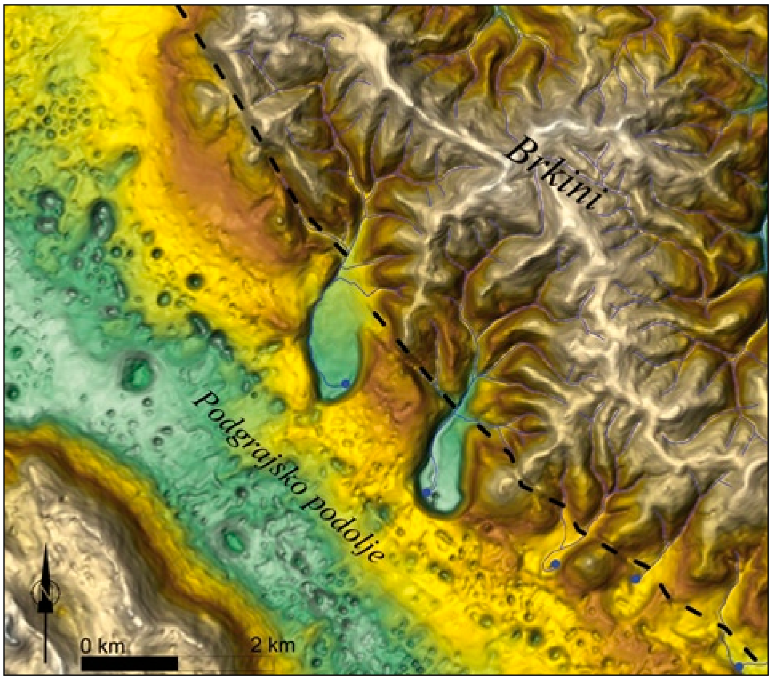

Figure 5.5: Digital model of the relief of the Podgrajsko podolje along the southern margin of the Brkini hills. The dotted line indicates the contact between limestone and the flysch of which the Brkini and Brda are composed. Sinking streams are marked as blue lines with blue circles at the points where they disappear underground. The blind valleys are, running from west to east: Brezovica, Odolina, Hotična, Slivje and Male Loče.

Čičarija/Ćićarija and Učka

The central, morphologically most important part of the Northern Istria is Čičarija/Ćićarija. This is the common name for the predominantly karst area or series of hills and peaks rising above the karst erosional surfaces between the Gulf of Trieste and the Kvarner Gulf. Čičarija/Ćićarija formed as a result of the underthrusting of Istria towards the northeast. This process saw the formation of the characteristic geological structure, the alternation of limestone and narrow bands of flysch, and a raising of the entire territory.

In its northern section Čičarija/Ćićarija begins as a narrow ridge of Slavnik. This widens towards the southeast and is joined by parallel ridges, with the result that above the Kvarner Gulf it already forms a range of hills more than 10 km wide with numerous peaks above 1,000 m. The relief reaches its highest point on Učka (1,400 m), which is just 6 km from the shore of the Kvarner Gulf. The rocky slopes of the karst elevations, doline-rich erosional surfaces and other karst depressions are littered with hundreds of dolines that are clearly visible in grassland but hidden in the extensive forest areas.

A basic characteristic of the landscape is karst formed into high ridges and, between them, elongated strips of lower relief. These can be erosional surfaces, as at Golc, Vodice, Vele Mune and Brgudac, or doline-rich lowland in the Dinaric direction, such as Podkruh between Golubovac (1,013 m) and Mahen Vrh (1,144 m), or large uninhabited uvalas such as Vodički Dolac south of Vodička Griža (1,142 m). In this relief, small elongated karst poljes connected to the flysch belts have also formed near Lanišće, Račja Vas and Praproče. These are the only areas with surface water flow in Čičarija/Ćićarija. Streams emerge on the edges of these poljes, flow across them and disappear into the karst on the other side. Because of the flysch bedrock there is also more arable land here.

Podgorski kras

On the seaward side of Čičarija/Ćićarija is a slightly lower flat relief zone which is geologically conditioned by the alternations of bands of thrust lenses of flysch and limestone. This is no longer a uniform shelf and we may probably see in it the extreme edge of the great Istrian erosional surface that is tectonically and erosionally badly damaged and disconnected at the foot of Čičarija/Ćićarija and Učka. The limestone sections of the shelves are doline-rich erosional surfaces, while the flysch parts are elongated depressions. The best-preserved and widest section is the Podgorski kras, a broad erosional surface about 5 km wide between the edge of karst plateau and Slavnik at a height of around 450 m. It continues at a similar height above sea level in a southeastern direction past Rakitovec, Slum, Krkuž, Kompanj and Semič to Brest.

A common characteristic of this landscape is the plateau-like area which extends on the north side to the slopes of the Čičarija/Ćićarija hills or plateaux, and on the seaward side ends with a prominent steep margin. Below them are numerous karst springs, where the water from Čičarija/Ćićarija emerges, and also the water from the sinking streams of the Podgrajsko podolje.

Figure 5.6: The Podgorjski kras – old cultivated dolines surrounded by dry-stone walls are visible after a fire (Photo: Andrej Mihevc).

Istria

Below the edge of the Karst, which is defined by the contact of limestone and flysch, the tributaries of the Rižana, Bračana, Mirna and Boljunščica emerge in numerous karst springs. These rivers formed a ridge-and-valley relief in the flysch, which strongly disconnected and lowered the originally flattened surface. The doline-rich erosional surface on limestones near Buzet, which is cut through by the gorges of the Bračana and the Mirna, is better preserved.

Owing to its lower height above sea level, the prevailing flysch rocks and the abundance of water, this landscape is much more densely populated.

Climate characteristics

Northern Istria is also very diverse in terms of its climate. Various types of climate exist in this region, from moderate Mediterranean to moderate continental and Alpine, depending on the height above sea level and the distance from the sea. A common characteristic is the cold continental wind, the Bora wind, which is particularly pronounced in winter, when it brings snow, low temperatures and frost right up to the coast. A good description of climate conditions can be provided by the data measured at weather stations in Koper, Buzet and Kozina and on Učka (Perko 1998, Riđanović 1975).

The average annual temperature by the sea in nearby Koper is around 14 °C (Koper 13.5 ˚C). The average July temperature in the same period is 24 ˚C and the average January temperature is 4 °C. Annual rainfall is around 1,000 mm and is highest in October and November. In the summer months droughts are frequent because of the high temperatures and heavy evaporation. Temperatures are similar in the area around Buzet. In Kozina (500 m) the average July temperature is 19 °C and the average January temperature is 0.2 °C. Average annual rainfall is around 1,300 mm. Most rain falls in the autumn months and the total annual quantity increases further east. In Čičarija/Ćićarija and on Učka rainfall is as high as around 3,000 mm. Behind these hills, in the lower Podgrajsko podolje and the Brkini hills, precipitation is significantly less (around 1,500 mm a year). Average July temperatures are below 20 °C because of the greater height above sea level, while January temperatures are around 0 °C. Snow is rare in the coastal region but the thickness and duration of snow cover grow rapidly in the hilly interior.

Climate features, particularly the summer drought characteristic of the Mediterranean coastal area, are more marked in limestone areas. Because of the very thin soil cover and deep karst water flow, the effects of drought are much greater than on thicker soils developed on flysch marls or sandstones.

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Photo from "Water - Life!" in Istria competition; author: Josip Madračević

Photo from "Water - Life!" in Istria competition; author: Igor Zirojević

OVERVIEW OF THE GEOLOGY

Bojan Otoničar

Lithostratigraphic data

The oldest rocks of the area in question crop out in the central part of the Podgrad corrosional surface (Podgrajsko podolje). They are represented by Lower Cretaceous limestones and dolomites (Šikić et al. 1972), which sedimentation ended in the wider area with regional emersion at the Aptian/Albian boundary (Velić et al. 1989; Jurkovšek et al. 1996; Durn et al. 2003).

Emersion, which is defined above all by carbonate breccia, was followed by deposition of the Upper Albian to Upper Campanian sequence of shallow marine carbonate rocks of the penultimate megasequence of the Adriatic Carbonate Platform (AdCP; sensu Vlahović et al. 2005). In the central part of the Podgrajsko podolje, the oldest rocks of this megasequence are predominantly represented by grey limestones and dolomites of Albian–Lower Cenomanian age, in which a significant proportion of coarse-grained calcareous and dolomitic breccias occur (Šikić et al. 1972) (Fig. 6.1). Similar rocks also appear in Čičarija/Ćićarija, and elsewhere in Istria (Stache 1889; Polšak 1965; Blašković 1969; Biondić et al. 1995; Vlahović et al. 1995; Velić et al. 2003) and in the Kras plateau, where they are defined as the Povir Formation (Jurkovšek et al. 1996, 2013).

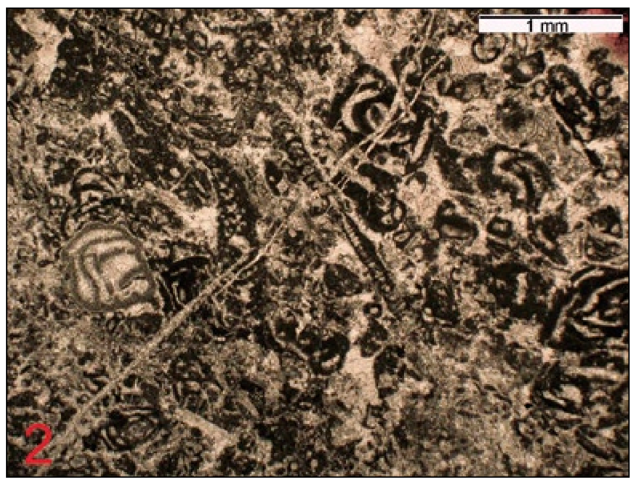


Figure 6.1: Coarse-grained dolomitic breccia was presumably formed through dissolution of intermediate strata of gypsum/anhydrite (Lower Cenomanian) (width of image: approx. 1 m) (Photo: Bojan Otoničar); Figure 6.2: Bioclastic foraminiferous packstone with the foraminifera Broeckina (Pastrikella) balcanica (Upper Cenomanian) (Photo: Jernej Jež).

In the area of the Buje Anticline between Savudrija and Buzet (Placer et al. 2010) the oldest rocks are represented by peritidal Lower Cenomanian limestones of the stable carbonate platform. In the upper part of the Lower Cenomanian and in the Middle Cenomanian carbonate successions the lithofacies of which indicate deposition in different depositional environments of the disintegrated carbonate platform follow (Vlahović et al. 1994; Tišljar et al. 1998; Velić et al. 2003; Durn et al. 2003). Thus in a relatively short distance we can observe simultaneous lateral transitions from peritidal limestones to those deposited in various parts of the slightly inclined slope (ramp) of the intraplatform basin or deep lagoon. In such slightly deeper marine environments, finer-grained micritic limestones were mainly deposited, in which cherts are sometimes present (Vlahović et al. 1994). The intraplatform basins were gradually filled by prograding sandy bioclastic bodies advancing towards the open sea. Until the end of the Cenomanian relatively uniform shallow-marine carbonate environments were again established on a more or less leveled carbonate platform, where light-grey micritic limestones of the mudstone structural type and bioclastic (rudist) floatstones were deposited (Vlahović et al. 1994; Durn et al. 2003).

The Albian and Lower/Middle Cenomanian are not precisely distinguished in the Podgrajsko podolje, and only the Upper Cenomanian can be treated separately on the basis of the Chrysalinina gradata-Broeckina (Pastrikella) balcanica biozone. Here grey and brownish-grey bedded bioclastic foraminifera limestones (Fig. 6.2), for the most part deposited in the subtidal environments of the internal parts of an open lagoon, predominate over light brownish-grey dolomites. At the Cenomanian/Turonian boundary a tectonically controled deepening of the internal parts of the platform occurred in a large part of the AdCP, the scale of which was also significantly influenced by a simultaneous global eustatic second-order sea-level rise (sensu Haq et al. 1987) (Fig. 6.3) and the related oceanic anoxic event (OAE2) (Jež et al. 2011). A consequence of this was the partial drowning of the platform and the gradual deposition of a succession of hemipelagic calcispheric micritic limestones at least around 50 m thick, in which pelagic foraminifera and bioclasts also appear (Šribar 1995; Jež et al. 2011). The equivalent of these limestones in the Kras is represented by the calcispheric and bioclastic limestones of the Repen Formation (Jurkovšek et al. 1996), and in Čičarija/Ćićarija by grey bituminous limestones (Blašković 1969), the central part of which is also composed of calcispheric limestones (Biondić et al. 1995) or a sequence around 100 m thick of grey to grey-brown poorly bedded to massive calcispheric wackestones of the drowned carbonate platform (Sveti Duh Formation) (Brčić et al. in press).

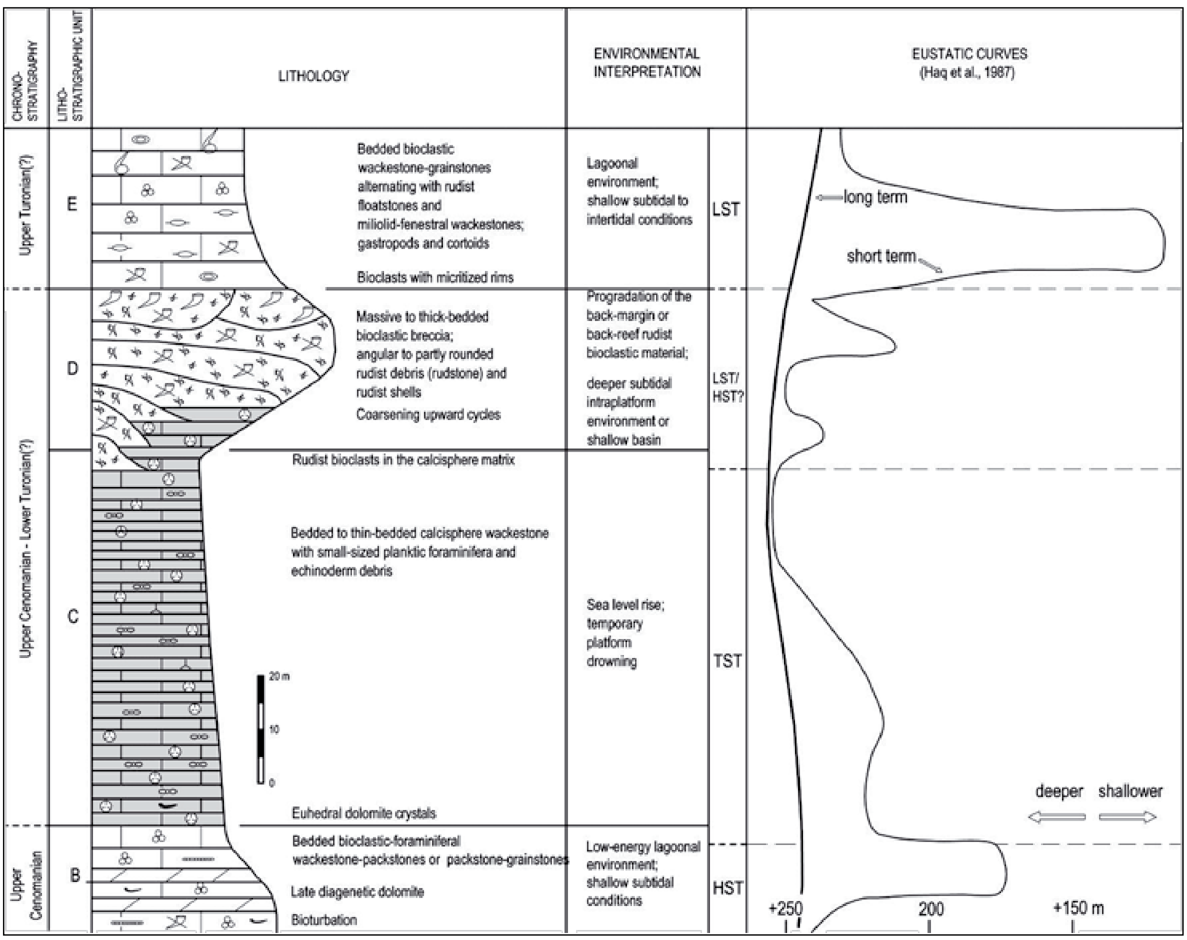


Figure 6.3: Upper Cenomanian/Turonian section of the lithostratigraphic column of the Hrušica geological profile in the Podgrajsko podolje with interpretation of sedimentary environments and the eustatic curve (from Jež et al. 2011).

This sunken marine area was gradually filled with relatively coarse grained rudist bioclastic material. Thus around 90 million years ago shallow-marine depositional environments were re-established in the area of the Kras and the Podgrajsko podolje (Fig. 6.3). Although a relatively stable or slowly rising sea level and stable tectonic conditions can be sufficient for the filling of a basin, in our case we cannot entirely exclude the influence of a marked Upper Turonian global third-order sea level fall (sensu Haq et al. 1987) on the establishing of shallow-marine sedimentation conditions (Jež & Otoničar 2009, 2010).

Micritic limestones with desiccation pores and limestones of the oncolite horizon that comprise the lower part of the Sežana Formation in the Kras (Šribar 1995; Jurkovšek et al. 1996) were deposited over rudist bioclastic limestones. Limestones with a micritic matrix in which algae, rudists, miliolids and cyanobacteria(?) of the Aeolisacus genus alternate are also characteristic of higher parts of the formation. "Peritidal" limestones with desiccation pores are also present here (Šribar 1995; Jurkovšek et al. 1996). In the Kras, researchers place the Sežana Formation in the period between the Upper Turonian and the Lower Santonian (Jurkovšek et al. 1996).

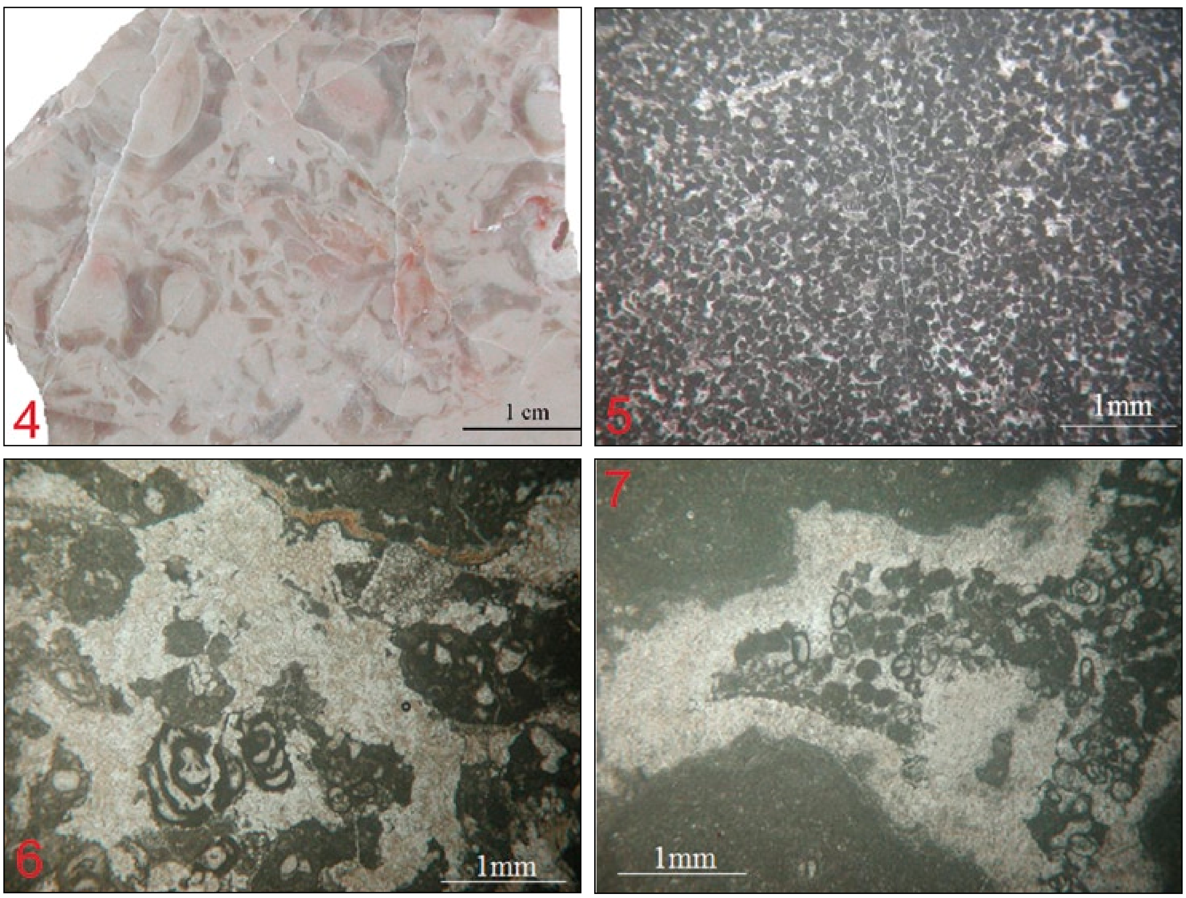


Figure 6.4: Rudist floatstone (Velika Gobovica; Coniacian–Santonian) (Photo: Bojan Otoničar); Figure 6.5: Well-sorted fine-grained peloidal (pelletal) packstone/grainstone (Podgrad; Coniacian–Santonian) (Photo: Bojan Otoničar); Figure 6.6: Bio-peloidal packstone with little channels formed through non-selective dissolution of the bedrock, fossils and allochems (Podgrad; Coniacian–Santonian) (Photo: Bojan Otoničar); Figure 6.7: Bioturbation [?(bio) erosion] burrows are in places surrounded by sparite displaying the characteristics of marine cements. Marine conditions are also indicated by the peloidal foraminiferal packstone/grainstone that fills the burrows (Podgrad; Coniacian–Santonian) (Photo: Bojan Otoničar).

In the Podgrajsko podolje, lagoonal micritic limestones predominate in Sežana Formation for the most part, with rudist bioclasts only appearing frequently in the lower part. On Slavnik, beds with rudist bioclasts are also slightly more frequent in the highest part of the formation, directly below the palaeokarst surface (see below; Otoničar 2006) (Fig. 6.4). Both in the southeastern part of the Podgrajsko podolje and on Slavnik, a distinctive horizon of partly pedogenically modified peloidal limestones appears in the upper section, respectively approximately 75 m and 50 m below the palaeokarst surface (Otoničar 2006; Jež et al. 2011) (Figs. 6.5 and 6.6). Above this horizon, limestones (in particular) in the Podgrajsko podolje (in the area around Podgrad itself) show frequent sedimentary-diagenetic forms linked to repeated short-term exposure of carbonate sediments on land and/or the sea floor (Otoničar 2006) (Fig. 6.7).

In the southeastern part of the Podgrajsko podolje the bedrock below the palaeokarst surface is composed of Coniacian–Santonian limestones (Jež et al. 2011); in Čičarija/Ćićarija it is composed of massive Upper Turonian to Coniacian recrystallised micritic limestones (Biondić et al. 1995); and in parts of the Slavnik area it is composed of grey limestones of Santonian or even Upper Santonian age (Otoničar 2006). In the Podgrajsko podolje, limestones of this age were deposited on a slightly inclined carbonate ramp that was generally inclined in a northeastern direction (in today's position) and which is represented here by the various lithofacies of open and closed lagoons and the peloidal shoals between them (Otoničar 2006) (Fig. 6.8).

Between the Upper Santonian and the Upper Campanian, limestones of the Lipica Formation were deposited in the Kras (Jurkovšek et al. 1996). The thickly bedded to massive light-grey to medium-grey limestones with rudists in the Kozina area are also believed to belong to this formation (Jurkovšek et al. 1997), although in places directly below the palaeokarst surface they contain foraminifera of the Coniacian-Santonian Scandonea samnitica-Murgella lata biozone (Otoničar 2006).

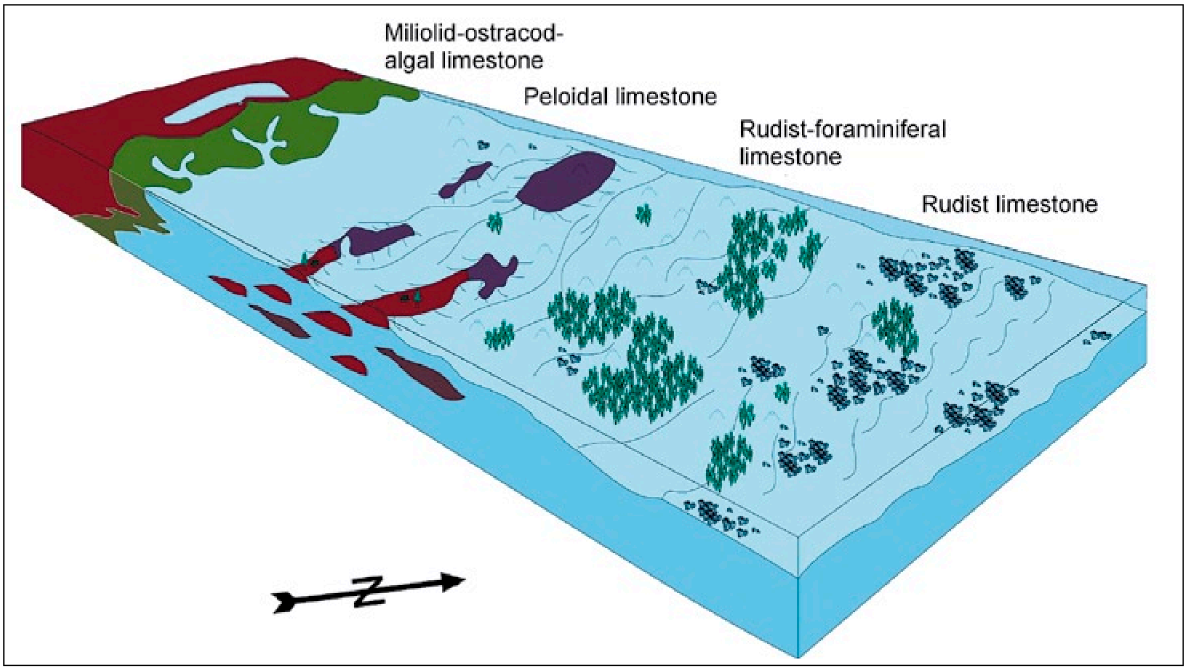


Figure 6.8: Idealised depositional model of the AdCP in the area of present-day Istria, the Podgrajsko podolje and the Kras (Coniacian–Santonian).

In southwest Slovenia and the Croatian and Slovenian parts of Istria, the passive-margin Cretaceous shallow-marine carbonate successions of the AdCP are separate from the Upper Cretaceous and/or Palaeogene shallow-marine sequences of the synorogenic carbonate platform with irregular palaeokarst surface (Otoničar 2006, 2007, 2008, 2009) (Fig. 6.9).

Surface palaeokarst landforms are in places covered and filled by bauxite (Fig. 6.10), while below the surface there are horizons of intertwining conduits ranging from centimetres to tens of centimetres in size (Fig. 6.11) and both vadose and phreatic caves (Fig. 6.12). All karst cavities were later filled with several generations of sediments and cements/flowstones. In the epikarst zone, carbonate and non-carbonate rocks were frequently pedogenically altered, while dissolution-widened root channels (so-called root karst sensu Viles 1988) are also typical (Fig. 6.13). Vadose channels, small shafts and pockets can extent up to several tens of metres below the palaeokarst surface, where in places they reach originally horizontally oriented phreatic caves. The latter show characteristics of halocline caves formed at the interface between salt water and fresh or brackish water (Otoničar 2006).

Although in places small fluctuations of sea level can be recognised from karst landforms and their fillings, systematic trends in the isochrones of the carbonate rocks that immediately overlie and underlie the palaeokarst surface and, consequently, the extent of the chronostratigraphic gap (Fig. 6.14) can mainly be explained by the evolution and topography of the peripheral foreland bulge (forebulge) (Otoničar 2007, 2008) (Fig. 6.15).

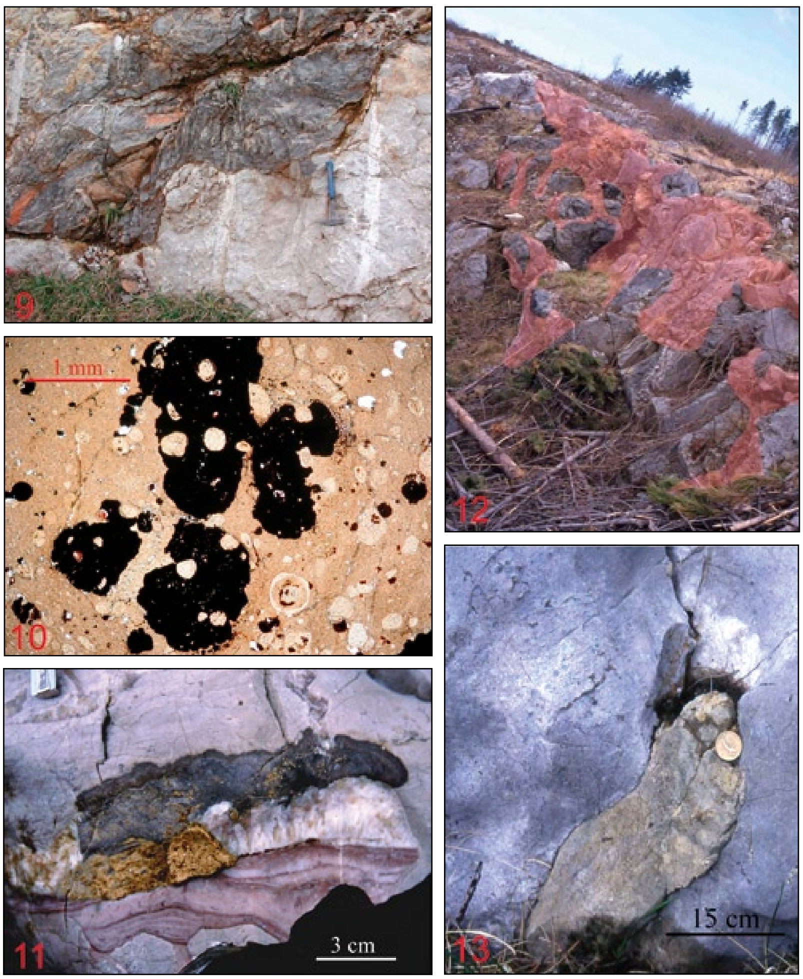


Figure 6.9: Undulated palaeokarst surface separates the Upper Santonian limestones of the Lipica Formation from the Maastrichtian limestones of the Liburnian Formation (Kozina) (Photo: Bojan Otoničar); Figure 6.10: Bauxite peloids and ooids in pelitomorphic bauxite (bauxitic wackestone), partly replaced by hematite (Kozina; Maastrichtian) (Photo: Bojan Otoničar); Figure 6.11: Smaller cavities filled with several generations of various sediments and cements (flowstones) branching away from larger karst caves (Podgrad; Palaeocene) (Photo: Bojan Otoničar); Figure 6.12: Large irregular originally generally horizontally oriented filled halocline cave (Podgrad; Palaeocene); (the cave is coloured in red for better visibility) (Photo: Bojan Otoničar); Figure 6.13: The dissolution-enlarged root channel is filled with pedogenically modified carbonate (root karst; Podgrad; Palaeocene) (Photo: Bojan Otoničar).

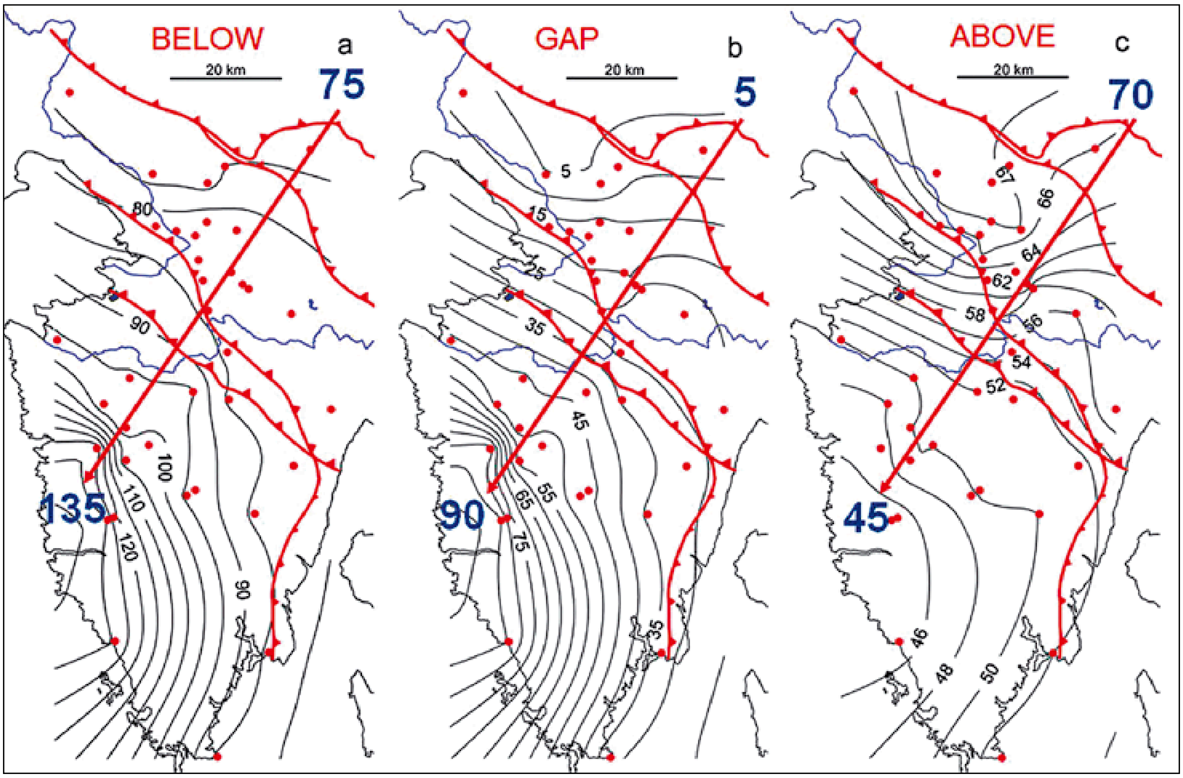


Figure 6.14: Isochrones (in millions of years) of the carbonate rocks directly underlying the paleaokarst surface (a), the extent of the chronostratigraphic gap (b), and the carbonate rocks directly overlying paleaokarst surface (c). The Figures also show the main structural characteristics of the area and the locations of the geological profiles considered.

The Maastrichtian and Palaeocene–Eocene shallow-marine carbonate rocks of the Adriatic-Dinaric region, which lie between thick Mesozoic carbonate sequences and palaeogenic clastites, comprise the youngest (terminal) carbonate megasequence in the area of the former AdCP (Košir & Otoničar 1997). It is made up of three higher-order lithostratigraphic units that combine to form the Kras Group (Košir 2003) (Fig. 6.16): The Liburnian Formation, the Trstelj Beds and Alveolina-Nummulites Limestone (ANL). The carbonates of this megasequence were deposited at a time of strong tectonic activity in the Upper Cretaceous and Palaeogene and may be defined as sedimentary sequences of synorogenic carbonate platforms (Košir & Otoničar 2001, 2002) (Fig. 6.15).

In southwest Slovenia and Istria, and also elsewhere on the AdCP, sediments of different ages of various lithofacies, members and formations are deposited on the palaeokarst surface (Fig. 6.14). This discrepancy is the result of sedimentation over the uneven palaeokarst surface and the specific tectonically conditioned uplift and later subsidence of the platform, where an important role was also played by local or regional structural-tectonic conditions (Otoničar 2006, 2007, 2008) (Fig. 6.15).

In the whole of the northern part of the AdCP (SW Slovenia and Istria), the palaeokarst surface is only covered with carbonate rocks of the Liburnian Formation, which are of Upper Maastrichtian age, in the Kras and in the area around Kozina (Drobne 1977; Jurkovšek et al. 1996; Otoničar, 2006; 2007) (Fig. 6.17). Facies of directly overlying limestones change rapidly both laterally and vertically (Figs. 6.18 to 6.22). They are frequently very limited in spatial terms and represent sediments of fillings of karst depressions during oscillating transgression [the so-called blue hole phase of transgression (see Durn et al. 2003)] (Fig. 6.21). During the initial phase of transgression, some palaeokarst pockets and shafts were filled with breccia containing remains of fossilised vertebrates, for the most part pulverised dinosaur and crocodile bones and teeth (Debeljak et al. 1999, 2002) (Fig. 6.22). Otherwise, the lower sections of the Liburnian Formation predominantly comprise dark-grey bedded (and, locally, laminated) micritic limestones containing ostracods, gastropods, foraminifera and, in places, rudists (Fig. 6.18). The limestones are pedogenically altered in places (Figs. 6.19 and 6.20) and thin inclusions of coal also occur (Otoničar & Košir 1998; Ogorelec et al. 2001). The sedimentological and palaeontological characteristics reveal that the sediments of the lower part of the Liburnian Formation were deposited in marginal salt water to brackish environments. Towards the Cretaceous–Tertiary boundary, pedogenic and pseudomicrokarst forms (breccias) are increasingly frequent, while the limestone bedrock shows characteristics of closed-lagoonal sedimentation (Jurkovšek et al. 1997).

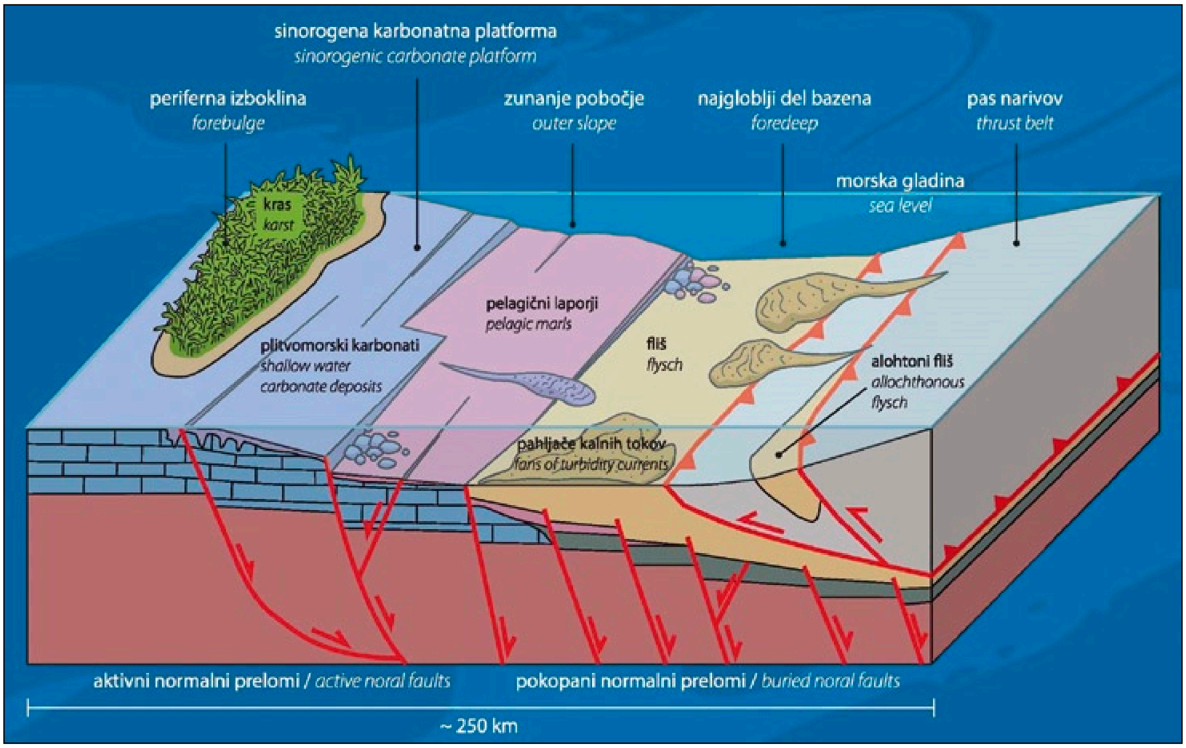


Figure 6.15: The schematic block diagram of the foreland basin system shows the position of the orogenic wedge, the deep-marine section of the foreland basin (the foredeep) and the peripheral bulge (the forebulge). The model also shows the distribution of macrofacies before the completion of tectonic plate convergence (adapted from Bradley & Kidd 1991).

Palustrine limestones of the "Kozina type" are followed by only rarely pedogenically modified foraminifera (miliolid) limestones of the Slivje Formation (Delvalle & Buser 1990) (Fig. 6.23), or Slivje Limestones (Jurkovšek et al. 1996), which Pavlovec (1963) combined with Operculina Limestones as a separate subdivision of ANL in the Trstelj Beds (Fig. 6.16).

In the Kras and the Brkini hills and on Slavnik, the upper levels of Slivje Limestone are of Middle Palaeocene age (Hottinger & Drobne 1980). In the upper section, operculinas begin to appear increasingly frequently in limestones with large miliolids and encrusting red algae, while discocyclinas and the first small nummulites appearing slightly further up.

At Kozina and Divača, on the basis of the fossil inventory and sedimentological characteristics, Zamagni et al. (2008) divided Thanetian and Ilerdian mainly foraminiferous limestones into the different facies and foraminifera assemblages characteristic of the depositional environments of a carbonate ramp.

Although individual red algae, Dasycladaceae and corals can already appear in the upper section of the limestones of the "Kozina facies", a special feature, particularly in the lower section of Operculina limestones, is represented by microbialite-coral mounds. The alternation of the main mound-formers (microbes and corals) points to relatively rapid changes in physical and chemical conditions in the environment, which is a consequence of a seasonality and the accelerated inflow of terrigenous nutrient-rich fresh water from subaerially exposed parts of the platform to the area of the inner ramp in the period of the warm, humid, subtropical climate of the Upper Thanetian (Zamagni et al. 2009). At the same time, the appearance of microbial mounds also predicts wider, even global changes in climate, from a seasonal and drier climate in the Lower Palaeocene to the extremely humid and warm climate at the Palaeocene–Eocene boundary, which corresponds to the so-called Palaeocene–Eocene Thermal Maximum event (PETM) (Zamagni et al. 2009, 2012).

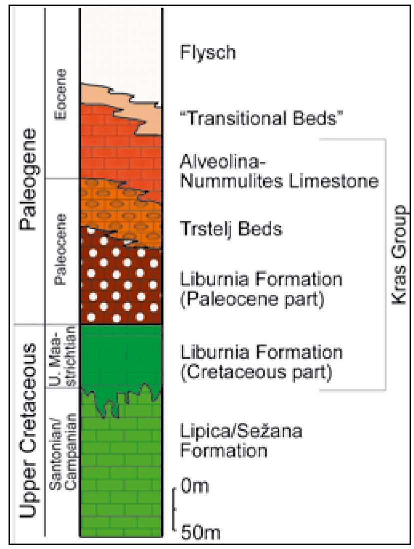


Figure 6.16: Generalised lithostratigraphic column of the Upper Cretaceous to Eocene succession of rocks in the Kras and the Podgrajsko podolje (after Košir 2004).

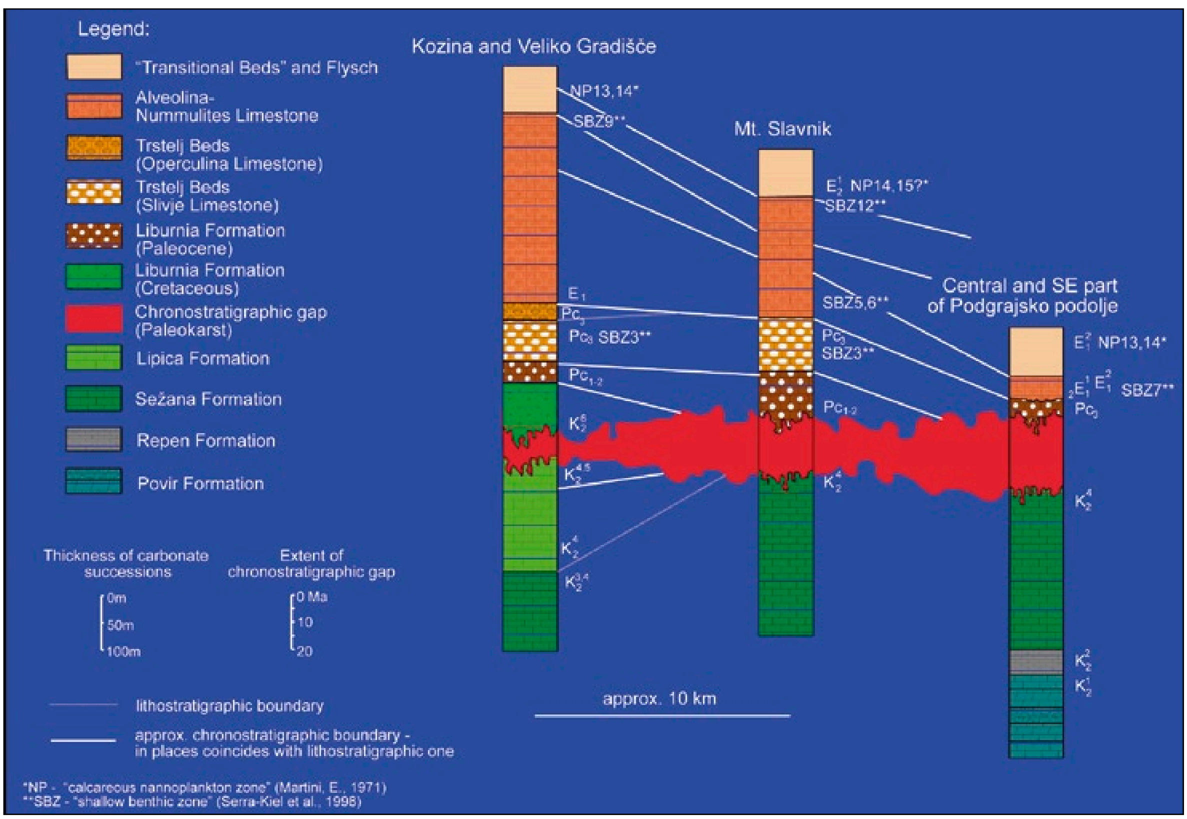
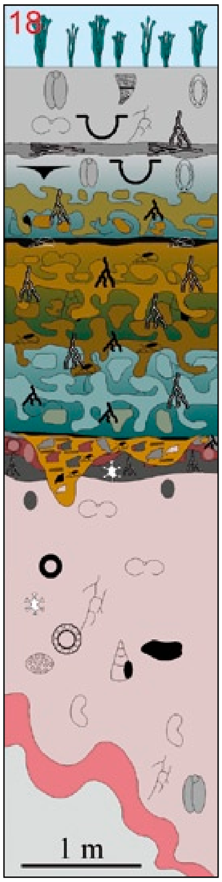
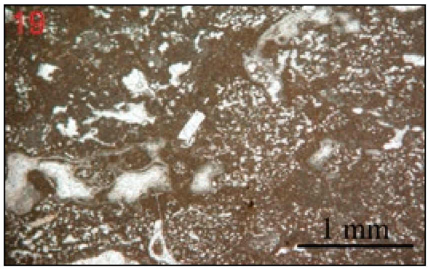


Figure 6.17: Lithostratigraphic columns of three locations in the Podgrajsko podolje and on Slavnik. Despite the proximity of the locations, we can observe considerable differences in the thickness of the lithostratigraphic units and the range of stratigraphic gaps (from Otoničar 2006).





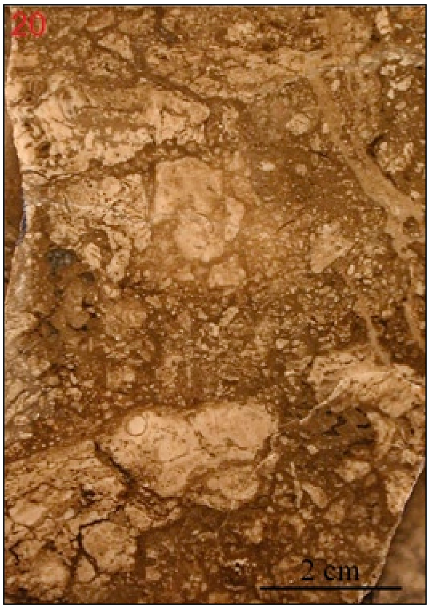


Figure 6. 18: The lithological column of the strata directly overlying the palaeokarst surface (red edge) near Kozina (Liburnian Formation) shows marine sediments of the "blue hole" phase of transgression, which in the upper section are pedogenically modified in several phases (Photo: Bojan Otoničar); Figure 6.19: Micrite with fenestrae, which represent root channels filled with sparite and surrounded by pedogenic micrite formed into a fine alveolar-septal texture (rhizosphere) (Kozina; Maastrichtian) (Photo: Bojan Otoničar); Figure 6.20: Breccia or pseudobreccia texture of pedogenically (root-related) strongly modified primary marine or brackish paralic micrite (Kozina; Maastrichtian) (Photo: Bojan Otoničar); Figure 6.21: Spatially limited thin-bedded dark micritic limestones fill a palaeokarst depression – the "blue hole" phase of transgression (Minjera, Palaeocene) (Photo: Bojan Otoničar); Figure 6.22: Limestone breccia with the remains of bones and teeth of fossilised vertebrates (dinosaurs, crocodiles) fills a palaeokarst shaft (Kozina; Maastrichtian) (Photo: Bojan Otoničar).

The first alveolines, which reach their greatest diversity in the Middle and Upper Ilerdian, appear in the lower section of the last unit of the Kras Group or Alveolina-Nummulites Limestone (Jurkovšek et al. 1996) (Fig. 6.24), while nummulitids are much more frequent in the upper sections of the ANL.

In the area under consideration, basin carbonate, mixed carbonate-clastic (Fig. 6.25) and siliciclastic rocks (flysch) (Fig. 6.26) of Eocene age lie above the ANL. Because the transitions of shallow-marine to deeper-marine carbonates are gradual, glauconite and phosphate minerals can occur in the horizon that characterises the termination of shallow-marine carbonate sedimentation and the start of deposition of pelagic and hemipelagic sediments (Košir & Otoničar 1997).

The described rock succession represents the more or less basic pattern of the succession of the Kras Group and flysch in the wider area of SW Slovenia and Istria. There are clear deviations in places, in particular in the age of the first rocks covering the palaeokarst surface (Figs. 6.14 and 6.17), the thickness of individual lithostratigraphic units and the period of the beginnings of flysch sedimentation (Fig. 6.27).

In the northeast-southwest direction the palaeokarst surface is covered by progressively younger carbonates, for the most part of the Liburnian Formation (Fig. 6.14). In this direction the basin rocks are also progressively younger

(Fig. 6.27), which indicates the retreat or retrogradation of the carbonate platform and the progradation of the foreland basin in a NE–SW direction (in today's position) (Košir & Otoničar 1997; Otoničar 2007) (Fig. 6.15). Here it is necessary to point out the frequent deviations from the general trend and the major differences in the thicknesses of the same chronostratigraphic units, which is the consequence of regional and local tectonic activity during their sedimentation (Otoničar 2006, 2007).

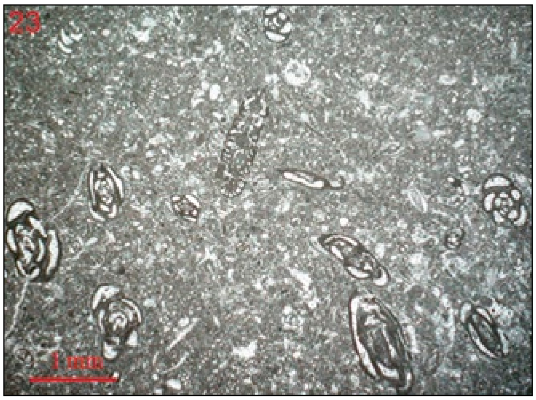
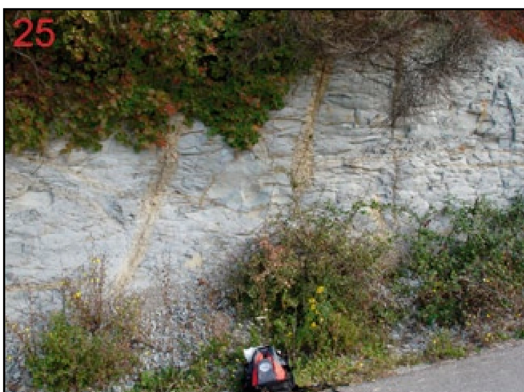


Figure 6.23: Peloidal foraminiferal packstone with the foraminifera Rhapidionina liburnica (Kozina; Liburnian Formation; Maastrichtian) (photo: Bojan Otoničar); Figure 6.24: Alveolina-Nummulites Limestone (Eocene) (Photo: Bojan Otoničar).



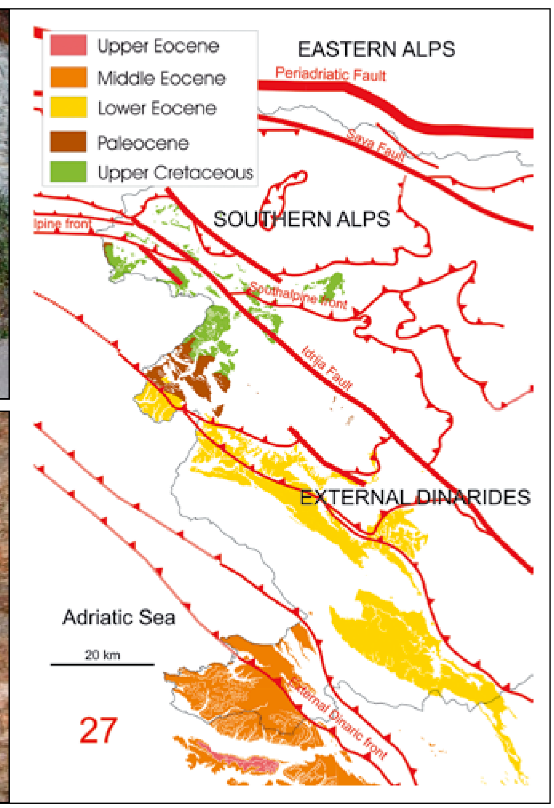


Figure 6.25: "Transitional" marls with crabs (Middle Eocene, Kubed) (Photo: Bojan Otoničar); Figure 6.26: flysch: alternation of thin-bedded marls and sandstones. The lower part of the structure of the duplex is clearly visible (Middle Eocene; Simonov zaliv near Izola) (Photo: Bojan Otoničar); Figure 6.27: Geological map of the extension of flysch and the main structural elements of W Slovenia. The map is mainly based on data from various Basic Geological Maps of Yugoslavia, 1:100,000 (Buser 1986; Buser et al. 1967, 1968; Grad & Ferjančič 1974; Jurkovšek 1986; Pleničar et al. 1969; Šikić et al. 1972).

In Istria the age and, to a large extent, the lithofacies of the directly overlying strata of the paleokarst surface change relatively rapidly and, with some deviations, relatively systematically (Fig. 6.14). Towards the SW or the central section of the west coast of Istria, the limestones of the directly overlying strata are progressively younger – from the Maastrichtian and Palaeocene limestones of the Liburnian Formation in southwest Slovenia, via the Lower Eocene limestones in northwest Istria to the Upper Eocene limestones along the central part of the west coast of Istria. Generally speaking, the thickness of the Kras Group, which can only be represented by the ANL, is also thinner in this direction. In the Metković-Mečari profile near Pazin the thickness of the ANL and the "Transitional Beds" between the palaeokarst surface and the flysch is just 20 to 25 m (Tarlao et al. 1995). In the area of the Buje Anticline, the lower sections of the palaeokarst surface developed in Cenomanian limestones are covered by Lower Eocene freshwater-to-brackish thin-bedded micritic limestones of the Liburnian Formation of a thickness of up to some tens of metres (Hamrla 1959; Šinkovec et al. 1994; Velič et al. 1995; Gabrić et al. 1995; Durn et al. 2003). More distinct karst depressions (karst pockets, shafts, etc.) are frequently filled with pyritised bauxite, which was excavated in the valley of the Mirna in several small underground and opencast mines (Šinkovec et al. 1994). In the limestones of the Liburnian Formation we frequently find relatively thin inclusions of black coal, which has also been mined in Sečovlje (Hamrla 1959, 1986).

Tectonic regionalisation

The present geological and topographic picture of the area of research is to a large extent a result of the geodynamics of the marginal parts of the fold and thrust belt of the Dinaric Orogen (External Dinarides) or the underthrusting of the Istrian Peninsula below the Dinaric Range, especially from the Middle Miocene on (Placer 2008; Placer et al. 2010). These processes involved, in particular, sedimentary sequences of the Mesozoic passive margin of the Adria-Apulian Microplate (sensu Stampfli & Mosar 1999) and Upper Cretaceous and Palaeogene synorogenic depositional areas. The underthrusting of Istria is a consequence of the anticlockwise rotation of the Adria Microplate ("Adria" sensu Stampfli et al. 1998) and the related, generally north – south oriented pressures (Marton et al. 1995; Bressan et al. 1998; Placer et al. 2010), which also caused reactivation of and horizontal movements along "Dinaric" (northwest – southeast) oriented faults (Jurkovšek et al. 1996; Bressan et al. 1998). The underthrusting of Istria below Čičarija/Ćićarija (Placer 2002) is reflected in the uneven uplifting of the terrain in its hinterland and in the recent seismic activity of the area.

The area under consideration lies in the tectonically very affected transition between the External Dinarids and its foreland. The greater part of it belongs to the External Dinaric Imbricate Belt, of which the Istrian-Friulian Underthrust Zone or the Northern Istrian Structural Wedge and the Kras-Notranjska Folded Structure are part (sensu Placer et al. 2010). Only a small section in the southwest of the area under consideration belongs to the stable part of the Adria Microplate ("solid core of Adria") or the Southern Istrian Structural Wedge (sensu Placer et al. 2010) (Fig. 6.28).In the narrower sense of geotectonic regionalisation, the Kras and the Podgrajsko podolje are part of the Čičarija/Ćićarija Anticlinorium (Placer 2005; Placer et al. 2010), which as part of the Komen Thrust Sheet (Placer 1981, 1998) belongs to the Kras-Notranjska Folded Structure (Placer et al. 2010). The area delimited by the Petrinje Thrust Fault (the most important thrust fault, along which movement is also greatest, even up to 10 km, is the otherwise slightly lower-lying Palmanova Fault) in the northeast and the Buje Thrust Fault in the southwest (the Kraški rob; i.e. " the Kras edge"), the whole of the Slovenian and Italian part of Istria and the area between Savudrija and Buzet) belongs to the Northern Istrian Structural Wedge (Placer 2007; Placer et al. 2010) (Fig. 6.28). The Buje Fault also represents a relict front of the thrusts of the External Dinarids (Placer et al. 2010). In the northeast section the Northern Istrian Structural Wedge is strongly imbricated, where flysch and carbonate rocks alternate in the area of the Kraški rob. The central section, which with the exception of the Strunjan Structure is not so tectonically affected, builds flysch on the surface, while the southwest section is represented by the carbonate Buje Anticline (Fig. 6.28).

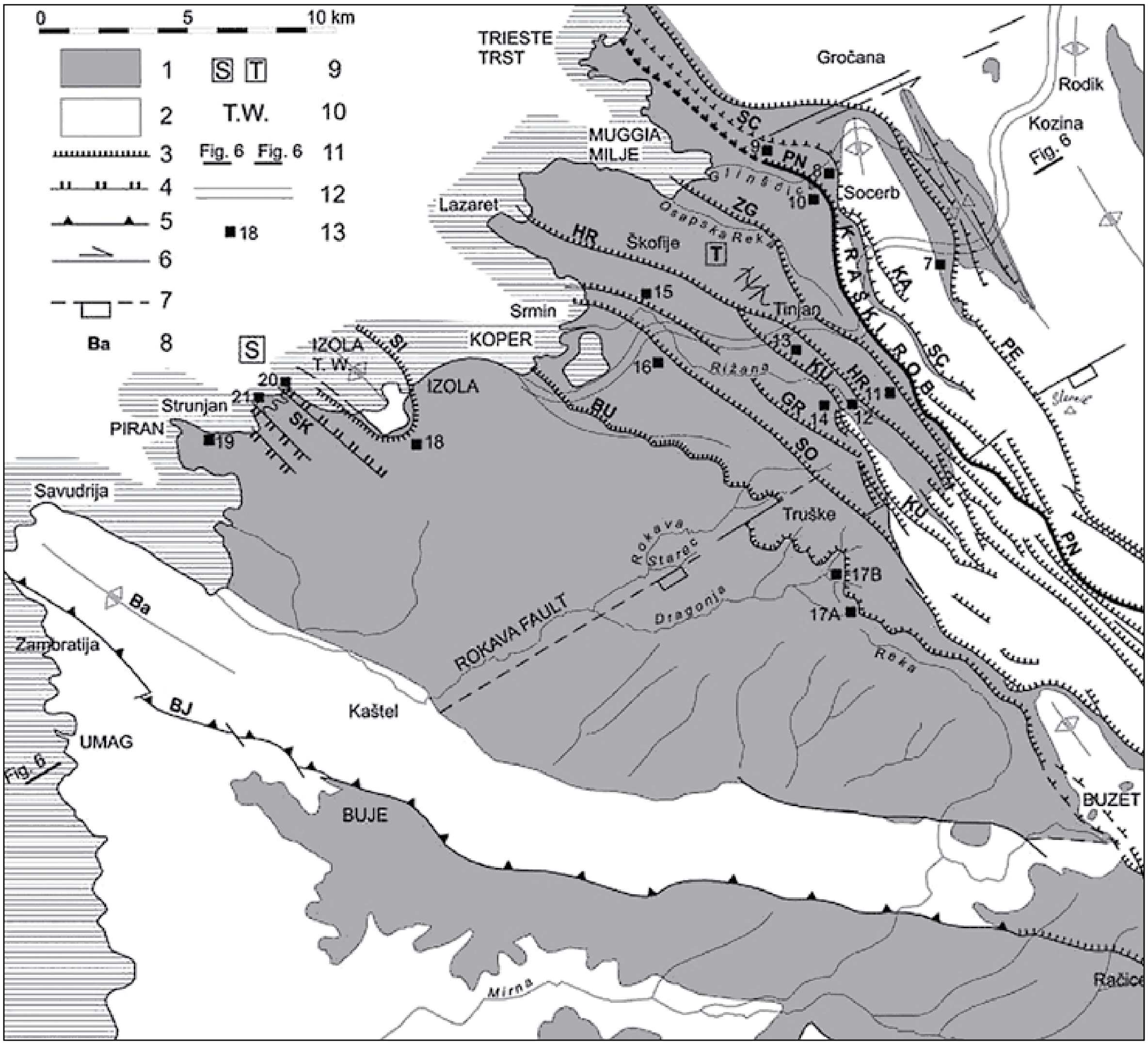


Figure 6.28: Istria-Friuli Underthrust Zone (Placer 2007, Placer et al. 2010). 1. Upper ductile horizon: flysch; 2.Platform carbonates;3.Thrust faults: PE – Petrinje Thrust Fault, KA – Kastelec Thrust Fault, SC – Socerb Thrust Fault, PN – Palmanova Thrust Fault (local Črni Kal Thrust Fault), ZG – Zanigrad Thrust Fault, HR – Hrastovlje Thrust Fault, KU – Kubed Thrust Fault, GR – Gračišče Thrust Fault, SO – Sočerga Thrust Fault, BU – Buzet Thrust Fault, SI – Simon Thrust Fault; 4. Secondary thrust faults of the Strunjan Structure: SK – Sv. Križ Thrust Fault; 5. Thrust Front of External Dinarides: BJ – Buje Fault; 6. Strike-slipe fault; 7. Normal fault; 8. Ba – Buje Anticline; 9. S – Strunjan Structure, T – Tinjan Structure; 10. Izola Tectonic Window; 11. Synthetic profile Umag-Kozina on Fig. 6 (in Placer et al. 2010); 12. Motorway.

The wider area of the Podgrajsko podolje has the character of an anticlinorium (Placer 1981) but the region is disected by numerous Dinaric and transverse Dinaric faults and faults running in an east – west direction (Placer 1981; Jurkovšek et al. 1996). The folds and some faults reflect the multi-phase kinematic evolution of the region, which is the result of different tension states in periods from the Cretaceous to the present (Jurkovšek et al. 1996). A similar multi-phase kinematic evolution of the region is also apparent in Istria, the tectonically least affected part of the former Adriatic Carbonate Platform. The orientation of Cretaceous tectonic structures in fact typically differs from those of the Jurassic and Eocene (Marinčić & Matičec 1991; Velić et al. 1995).

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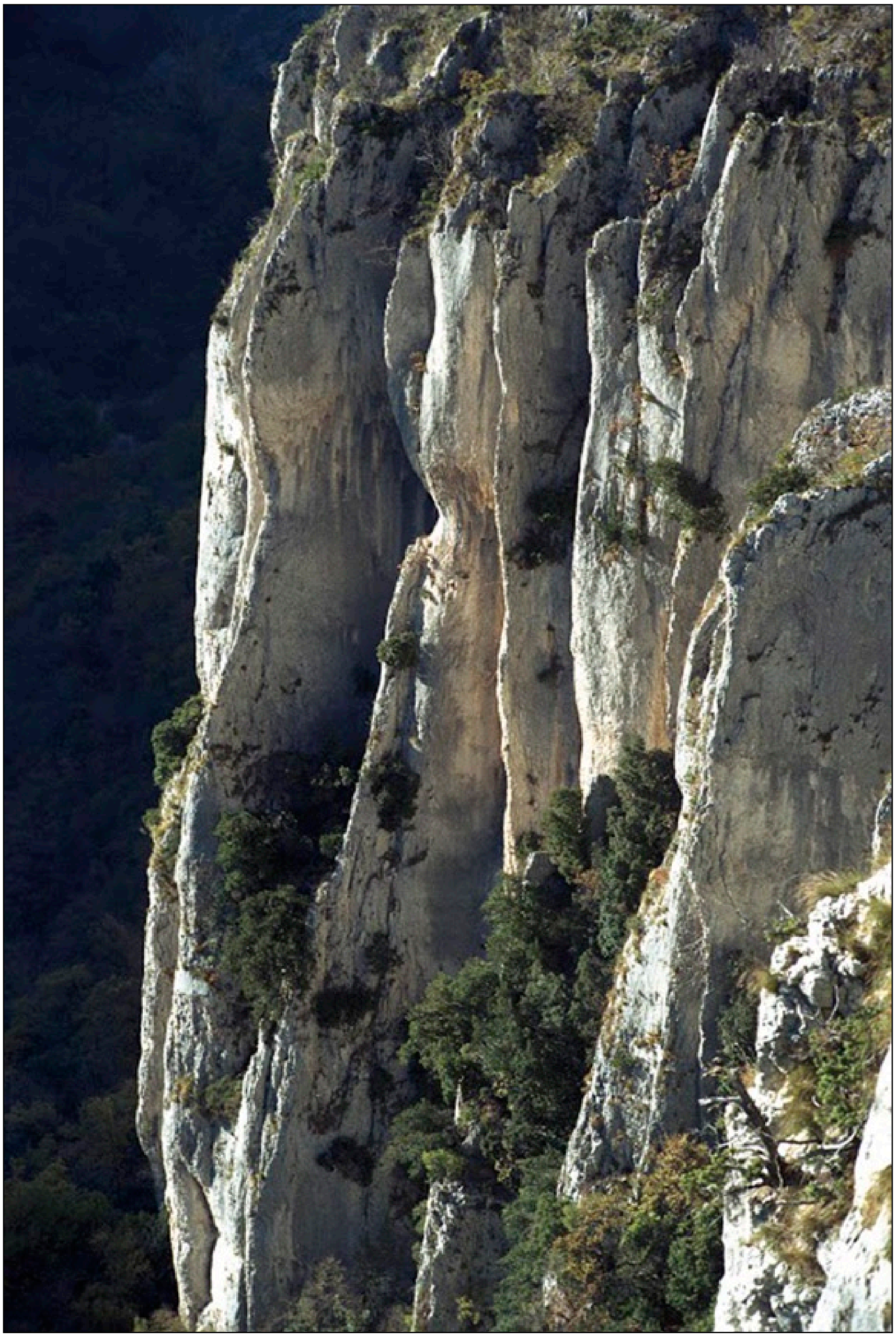
Photo from "Water - Life!" in Istria competition; author: Josip Madračević



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OVERVIEW OF THE HYDROGEOLOGY

Ranko Biondić, Metka Petrič, Josip Rubinić

Introduction

The northern part of Istria in the border region between Croatia and Slovenia is a typically karst area. Water flow is for the most part underground and feeds karst springs, which are an important source of drinking water for Istria County in Croatia and Slovenia's Primorska region. The main water supply systems include the Sv. Ivan and Bulaž springs on the Croatian side and the Rižana spring on the Slovenian side. A common characteristic of these springs is that they have catchment areas that extend across the national borders.

The karst aquifer in their catchment areas is recharged by a complex system that includes both direct infiltration of precipitation on the karst surface and sinking streams that flow from the surface into ponors. Underground flow is rapid and covers considerable distances, following routes which are for the most part unknown. Pollution also spreads rapidly with the water, which represents a threat to water sources. As a result of the characteristics described above, karst aquifers are extremely vulnerable to the consequences of various sources of pollution. Successful protection is possible if we are familiar with the characteristics of their functioning. For this reason, hydrogeological research is the foundation of planning of the protection of karst water sources and optimisation of their use.

Overview of hydrogeological research carried out to date

Before the Second World War hydrogeological research was carried out in Northern Istria by Austrian and Italian researchers (Waagen 1910, Timeus 1910, 1928; Sacco 1924; Bertarelli & Boegan 1926, D'Ambrosi 1931; Veronese 1939). A large number of drinking water reservoirs were constructed in this period and two regionally important water sources – the Rižana and Sv. Ivan springs – were captured.

After the Second World War the first complex regional hydrogeological research was carried out by experts from various institutions in Croatia and Slovenia (Magdalenić & Fritz 1959; Čadež 1963; Bojanić et al. 1966, Cukor & Fritz 1967; Božičević 1967, 1968, 1969, 1980; Raljevič et al. 1968, 1971; Raljević & Čakarun 1969a, b). This was the period in which a basic picture of the hydrogeology of the Istrian peninsula was created. Numerous tracer tests were carried out, and their results are still used today in hydrogeological interpretations of the area. The process of creating a hydrogeological map of Istria included descriptions of numerous water-related and morphological phenomena and specific directions of movement of subsurface waters that are important in the planning of environmental interventions and the protection of waters. The results of speleological research were also interpreted from the hydrogeological point of view (Gams 1966; Habič et al. 1983; Božićević 1985).

In the years that followed, increasing environmental burdens caused the problem of deterioration of surface water and groundwater quality. The considerable expansion of existing settlements in Istria, the growth of tourism, and the development of industry and agriculture without adequate infrastructure also affected groundwater. Studies regarding the protection of karst aquifers therefore came to the fore (Magdalenić et al. 1987, 1992; Krivic et al. 1987, 1989; Magdalenić 1988, 1990; Bonacci & Magdalenić 1993; Urumović et al. 1989, 1995, 1996; Biondić 1996; Vlahović 2000; Bačani et al. 2003). In this period, too, the tracing of underground water flows was an important research method.

At the turn of the century an extensive hydrogeological database was compiled and processed with the help of GIS tools. This enabled even better understanding of the functioning of aquifer systems and represented a basis for their more effective protection (Biondić et al. 1999; Janža & Prestor 2002; Janža 2003, 2010).

In recent years numerous projects involving cross-border cooperation between Slovenia and Croatia have been taking place in the area of study (Biondić et al. 2002a, b, 2004; Kogovšek et al. 2003; Rubinić et al. 2006; Prelovšek & Zupan Hajna 2011). Their aim is to integrate hydrogeological databases and deal holistically with transboundary aquifers as water bodies in which water flows independently of political borders and for which integrated management is necessary at the bilateral level. This category of projects includes the ŽIVO! project that is presented in this book.

Hydrogeological and hydrological characteristics

From the hydrogeological point of view, the selected area is characterised by an alternation of highly permeable Cretaceous and Palaeocene carbonate rocks and highly impermeable Eocene flysch (Fig. 7.1). Karst aquifers with underground water flow developed in carbonate rocks, while flysch areas feature a network of surface streams along which alluvial sediments are deposited. Surface streams from flysch percolate into the karst underground at points of contact with carbonate rocks, while on the other side of the karst aquifer groundwater comes to the surface through karst springs at points of contact of this kind.

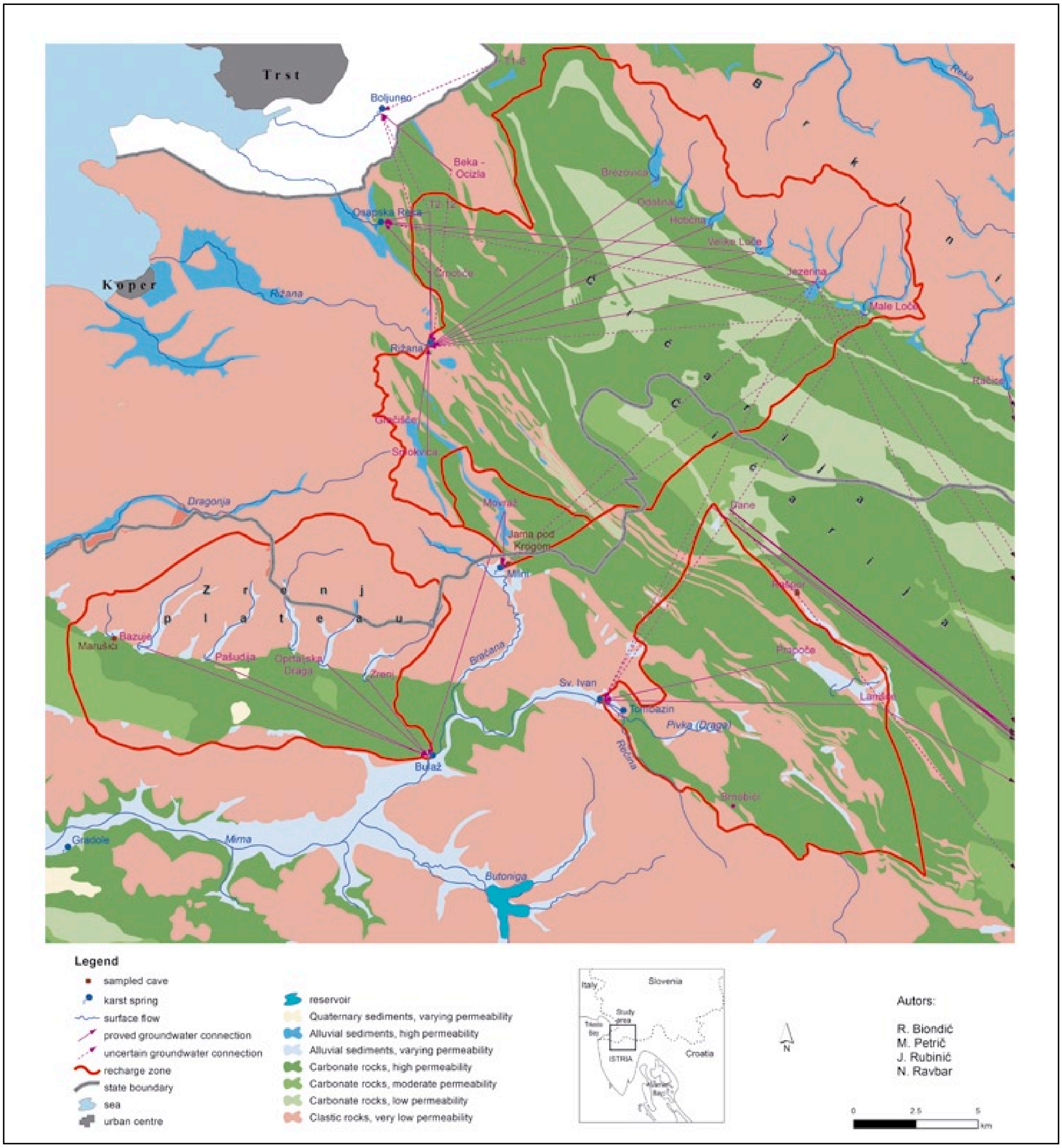

Figure 7.1: Hydrogeological map of the area of study.

The central part of the karst area flows through numerous karst springs into the rivers Rižana and Mirna. The most important permanent springs are the Rižana on the Slovenian side and the Sv. Ivan, Bulaž and Mlini springs on the Croatian side. In an extensive karst aquifer with a ramified network of underground streams with changeable directions of flow and varying hydrological conditions, it is extremely difficult to identify watersheds between the individual springs. Tracer tests in various parts of the aquifer have shown that the imbricate flysch structure does not represent an impermeable barrier to the flow of groundwater towards the springs mentioned, and the possibility of drainage towards coastal springs near Opatija in the Kvarner Gulf has also been confirmed.

The above springs are fed from catchment areas with similar climatic and hydrogeological characteristics and therefore their hydrological regime is also similar. There is a typical correspondence in the occurrence of wet and dry years. This can be seen from Fig. 7.2, which shows mean annual flow rates (for hydrological years and not calendar years because of the better distribution of seasonal wet and dry periods) for the period from 1961/62 to 2012/13. We can see the extremely drought-like character of 2011/12, a year in which owing to the absence of any kind of perceptible inflows, all three of the springs mentioned had very similar mean annual flow rates, when usually these differ considerably. The mean annual flow rates over the 51-year period were, for the Rižana spring (without the quantity of offtake for the water supply system) 3.9 m^3/s (0.75 m^3/s in 2011/12), for the Bulaž spring 1.54 m^3/s (0.29 m^3/s in 2011/12) and for the Sv. Ivan spring 0.87 m^3/s (0.49 m^3/s in 2011/12). A downwards trend in average annual flow rates may be observed in all three springs (Fig. 7.2).

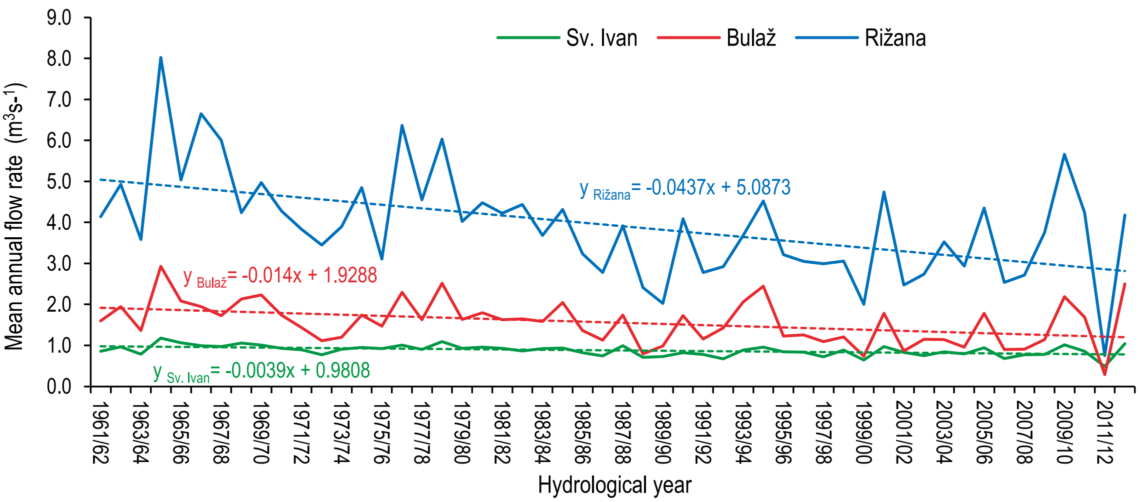

Figure 6.2: Mean annual flow rates of the Rižana, Bulaž and Sv. Ivan springs with associated trends (1961/62–2012/2013).

Rižana and Osapska reka karst springs

The Rižana spring, which lies at 70 m above sea level, is connected to the contact of the carbonate aquifer with the impermeable flysch rocks along which the river Rižana then drains into the Adriatic Sea. Flow rates of the Rižana at the Kubed hydrological station (after offtake for the water supply) ranged from 30 l/s to 63 m^3/s in the period 1981–2010. The mean flow rate was 3.44 m^3/s (ARSO 2015). On the basis of basic geological research and numerous tracer tests (Krivic et al. 1987, 1989) the catchment area of the spring has been estimated to measure 247 km^2. For the most part it lies within Slovenia, with only a small part extending to the Croatian side of the border. Although it is predominantly karstic, the supply of water from sinking streams from flysch at the southern foot of the Brkini hills is also significant.

Figure 7.3: The Rižana spring has been captured to supply Slovenian Istria with drinking water (Photo: Metka Petrič).

The Rižana spring was already in use in the early 19th century, while in 1935 a regional water supply system was instructed to supply Slovenian Istria with drinking water (Fig. 7.3). Today the great majority of the inhabitants of this area (86,000 permanent inhabitants, with the number of users rising to 120,000 during the tourist season) are connected to the public water supply network (Rižanski Vodovod Koper 2015). To prepare the water for consumption, an ultrafiltration process is used which removes suspended substances and particles bigger than 0.01 microns from the water. The Rižana water source is protected by the Decree on a water protection area for the water body of the Rižana aquifers (UL RS 49/2008), in which three distinct protection zones are defined.

Besides the Rižana the only large karst spring in the Slovenian part of the area of study is the intermittent Osapska reka spring, which is only active following heavy rain. When the water level is high, when flow rates can be as much as several m^3/s, water flows out from the cave Osapska jama (Fig. 7.4). The entrance to the cave, which is 1,200 m long and 49 m deep, is at 105 m above sea level. Even before water starts flowing from the cave several springs activate below the cave entrance. This is probably a high-water overflow of waters from the catchment area of the Rižana (Krivic et al. 1989), connected to the contact between the limestone and the very low permeable flysch.

Figure 7.4: Osapska reka spring at high water level (Photo: Metka Petrič).

Karst springs in the basin of the Mirna

The catchment area of the river Mirna is the largest drainage system of the Istrian peninsula and covers an area of around 718 km^2 on the Croatian side of the border (Biondić et al. 2004). It is located in the central and western part of the peninsula and its reserves supply the greater part of Istria with water. The most important water sources are the Sv. Ivan (minimum yield 140 l/s), Bulaž (200 l/s) and Gradole (350 l/s) springs and the surface reservoir at Butoniga (19.5 million m^3). In the ŽIVO! project the area of study includes the headwaters and central part of the Mirna with the catchment of the Sv. Ivan, Bulaž and Mlini springs.

In the imbricate structure of alternating highly permeable carbonate rocks and highly impermeable clastic rocks, the latter do not everywhere have the function of a hydrogeological barrier, and the main quantities of ground water drain towards lower-lying carbonate aquifers. The flysch belts are, however, the reason for the appearance of a large number of small springs in the higher part of the Čičarija/Ćićarija region, which are captured for local water supply.

The imbricate structure of Čičarija/Ćićarija continues as far as the town of Buzet and the Sv. Ivan spring rises in the marginal section of the last of these scales of highly permeable carbonate rocks. After flowing from the limestone formation through impermeable flysch and Quaternary clay, the water flows out onto the surface at 47 m above sea level (Fig. 7.5). The total yield of this spring ranges from 0.13 m^3/s to 2.15 m^3/s and the mean flow rate is 0.818 m^3/s (Rubinić et al. 2006). Because of the limited discharge capacity at the main Sv. Ivan spring, waters also discharge, when the water level is high, from the Tombazin spring, located approximately 1 km towards the south-east. When water levels are highest, the periodic Pivka spring, at a higher altitude, is also active.

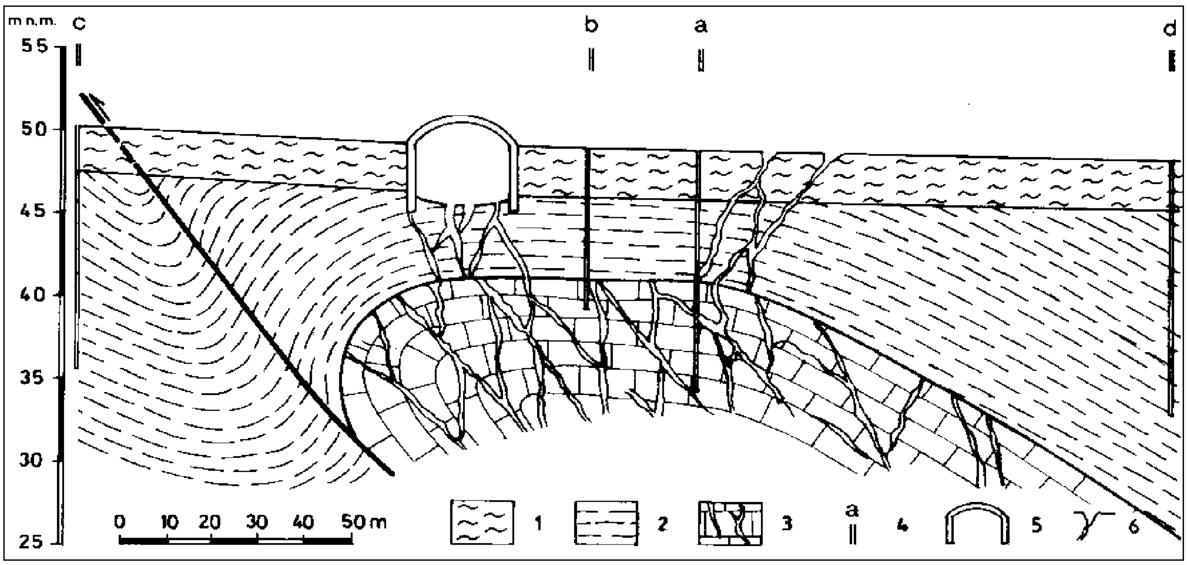

Figure 7.5: Hydrogeological profile of the Sv. Ivan spring (1 - Quaternary clays, 2 - flysch beds, 3 - karstified limestones, 4 - research borehole, 5 - collection reservoir, 6 - periodic spring) (Hidroprojekt-ing 2000).

Using hydrological methods, the size of the potential (apparent) catchment of the spring was estimated to be 60 km^2 (Bonacci & Magdalenić 1993). Owing to the complex system of feeding and emptying of the Sv. Ivan spring and the need to protect the entire area, it was decided, during the process of defining drinking water source protection zones in Istria County, to limit the area of protection to 103 km^2. To this area it is also necessary to add a small section of the 146 km^2 common catchment area with springs near Opatija, which in part extends into Slovenia and is therefore of a transboundary nature.

The Sv. Ivan spring was the first large karst spring to be captured in order to provide drinking water to the Istrian regional water supply system – in as long ago as 1933 (Fig. 7.6). The quantity of water pumped is up to 300 l/s, while in longer summer drought periods it falls to between 110 and 200 l/s.

Figure 7.6: Spring water capture at the Sv. Ivan spring near Buzet (Photo: Josip Rubinić).

The biggest problem is represented by frequent occurrences of extremely high water turbidity, which can reach as much as 2,000 NTU. Such high turbidity is the consequence of the high proportion of surface inflows from predominantly flysch terrain following intense precipitation, and the rapid water flow and transport of sediments through the karst aquifer. The suspended particles also transport other components of pollution, both physico-chemical and bacteriological (Mihalić et al. 2006).

The Mlini spring area on the border between Slovenia and Croatia is located in the central section of the Bračana, a right tributary of the Mirna downstream of Buzet. The springs are at the contact of highly permeable carbonate rocks and very low permeable flysch. The spring zone consists of three springs. The largest of them is the Ara spring in a hamlet at 90 m above sea level (Fig. 7.7), while two smaller springs are located downstream in the field below the hamlet and are only active periodically. When the water level is high, water also discharges from higher-lying intermittent springs. One of these is Jama pod Krogom, a cave whose entrance lies at 144 m above sea level (Habič et al. 1983). This cave, which is 570 m long, extends below the Slovenia-Croatia border.

Figure 7.7: The Ara spring in Mlini (Photo: Ranko Biondić).

Practically the whole of the catchment area of the spring is within Slovenia. There is a collection reservoir at the spring, but this is not connected to the public water supply system and is only used, for local needs, by the inhabitants of the hamlet of Mlini. The discharge capacity at the spring is relatively small (approximately 15 l/s), but exact figures are not available, since the spring is not included in the observation system and data on the quantity of long-term discharge are not available. Measurements have only been made occasionally at the road bridge over the stream that collects all the spring water, in the following hydrological years: 1971/72 (Q_{min}=32 l/s; Q_{max}=2.2 m^3/s), 1986/87 (Q_{min}=19 l/s; Q_{max}=3.3 m^3/s) and 1994/95 (Q_{min}=13.5 l/s; Q_{max}=3.2 m^3/s) (Kogovšek et al. 2003).

Downstream along the river Mirna is the Bulaž karst spring at Istarske Toplice (Fig. 7.8). The spring has the form of a pool with a diameter of 50 m. The height above sea level of the discharge is 15 m, while the maximum depth is 25 m, which is 10 m below sea level. Inflows towards the spring are linked to the permeable carbonate area of the Buje anticline. The total size of the catchment area is around 105 km^2, of which around 60% is developed on very low permeable flysch beds (Magdalenić et al. 1987). Part of this non-karst catchment area also extends into Slovenia.

Figure 7.8: The captured Bulaž spring near Istarske Toplice (Photo: Ranko Biondić).

The Bulaž spring has been captured to supply Istria with drinking water, at a rate of 200 l/s. Its natural maximum yield is around 38 m^3/s, while the minimum discharge is just 42 l/s (Urumović & Vlahović 1999). Since 1988 it has served as a reserve water source that is mainly used in dry summer periods. In 2012 water pumped at this spring played a decisive role in mitigating the unfavourable conditions for drinking water supply. Short-term seasonal pumping of the spring with average monthly quantities of up to 170 l/s compensated at least in part for the shortfall in the usual capacity of other springs in the drinking water supply system (Gradole and Sv. Ivan) in the summer season.

Surface flow on flysch in the catchment area of karst springs

At the southern margin of the Brkini hills, surface waters disappear underground into the karst aquifer at a contact approximately 20 km long, where the limestones dip steeply under the flysch. Blind valleys with solution-widened floors are a typical karst landform. Numerous small surface watercourses drain an area of approximately 30 km^2. The sizes of the catchment areas of individual sinking streams range from 0.5 to 13.2 km^2. The ponors are at a height above sea level of between 490 and 510 m. Some of them continue into karst caves that end with siphons of trapped water at heights of between 370 and 430 m above sea level. The deepest cave has a depth of 150 m and the longest a length of 6 km (Mihevc 1994).

The alternation of Eocene flysch and Palaeocene limestone is also typical of the Gračišče, Smokvica and Movraž area at the watershed between the Rižana and the Mlini. At this contact, elongated shallow karst depressions called vale (singular: vala) have developed at heights of between 168 and 300 m above sea level. In terms of their hydrological characteristics, these are a kind of periodically flooded boundary karst poljes. The floods are caused by the insufficient absorption capacity of ponors when the water level is high. They occur two to three times a year and last from a few hours to a few days (Habič et al. 1983).

On the north-western edge of the catchment area of the Rižana there is a small flysch area south-east of Kozina where waters from an area of approximately 3.5 km² flow into the ponors of the Beka-Ocizla cave system at a height of around 350 m above sea level.

The greater part of the catchment area of the Bulaž spring consists of a series of parallel torrential watercourses in the area of the Zrenj Plateau. Running from west to east, these are: the Sorbar (2.48 km^2), the Bazuje (11.67 km^2), the Gomila (2.01 km^2), the Butori (5.92 km^2), the Šterna (2.32 km^2), the Malinska Vala (11.47 km^2), the Mikilinica (11.0 km^2) and the Tomjak/Katalena (11.97 km^2). The figures in brackets represent the size of their catchment area. All these watercourses create valleys in their lower course and end in ponor zones at heights of between 230 and 340 m above sea level. Highly characteristic speleological features have developed in places – the ponors of Butori, Bazuje 1 and 2 and Vinicio Potleca at Marušići (Hlaj & Poropat 2008).

The Sv. Ivan spring collects water from the area of the thrust structure of Čičarija/Ćićarija, within which there are several closed karst poljes with their own hydrographic network, which ends in ponor zones. The largest of them is the polje near Podgače. It should be mentioned that the catchment area of the Sv. Ivan spring area also includes the surface tributaries the Draga (in its entirety) and the Rečina (in part), since ponor zones connected to the spring appear in individual sections of the beds of these watercourses. Most of the water from these watercourses nevertheless drains into the river Mirna.

Owing to the limited capacities of the ponor zones of the surface watercourses in the catchment area of the described spring areas, when high water levels occur, and for a few days afterwards (or even for several tens of days at individual points), the lowest parts of these depressions can be flooded.

Underground water connections proved by tracer tests

The first tracer tests in the area of study were carried out in the early 20th century when Timeus injected uranine into a stream in the Odolina blind valley on the southern margin of the Brkini hills and proved the existence of a connection with the Rižana spring (Timeus 1910). Later on, following several unsuccessful tests (Čadež 1963), doubts were raised about these results, but subsequent tracings have confirmed them.

The first tracings in the presumed catchment area of the Sv. Ivan spring were carried out in the 1930s (Veronese 1939), when in 1930 researchers injected uranine into a ponor near Brnobići, followed by 25 kg of brewer's yeast. No appearance of the tracers was recorded at the springs, but Kuhta (2000) nevertheless considers a connection to exist. Tracing continued the same year near Rašpor but once again failed to demonstrate a connection with the Sv. Ivan spring. The reason for this was probably the insufficient quantity of tracer used (10 kg of lithium chloride), while 16 days is not a sufficiently long sampling period. In this first group of tracings in the 1930s, only tracing of the ponor zone of the Rečina, which is just 1.5 km away from the Sv. Ivan spring, proved an underground water connection with this spring. On that occasion 10 kg of brewer's yeast was used.

In 1957 uranine was injected into the Oprtaljska Draga ponor in the area of the Buje anticline. Tracer was only detected at the Bulaž spring, although the Sv. Ivan spring was also observed. When tracing was carried out with radioactive tritium from Pašudija in 1979, the Gabrijeli and Bužin springs by the river Dragonja, the Gradole spring by the river Mirna and the Kristal spring in Opatija were observed in addition to the two springs already mentioned, but once again tracer only appeared in the Bulaž spring. Tracing with radioactive tritium from the Zrenj area in January 1983 only resulted in tracer appearing in the Bulaž spring.

In 1979 tritium was injected into a ponor near Prapoče (Haček & Hanich 1980) but the results indicate irregularities in the tracing, since tracer was detected at practically all the observed springs within the catchment area and even outside it. Tracing was carried out again in this location in 1984 (IRB 1992) using the same tracer and the same quantity. An underground water connection with the Sv. Ivan spring was proved, while tracer was not detected at the other springs.

Three combined tracer tests have been carried in the area of the Brkini sinking streams. In April 1985 uranine was injected into a sinking stream near Brezovica, potassium chloride (KCl) in Male Loče, rhodamine in Gračišče and bacteriophages near Smokvica (Krivic et al. 1987). Tracing with KCl was unsuccessful, probably because the quantity of salt injected was insufficient, while despite several springs being observed, the other tracers only appeared in the Rižana spring. In May 1986 researchers injected rhodamine in the Jezerina blind valley, uranine in Male Loče and bacteriophages into a stream near Hotična. The rhodamine from Jezerina appeared in the Rižana, while in the Osapska reka spring it only appeared in low concentrations in the water pulse following rainfall. Even so this connection was considered very probable. The uranine from Male Loče appeared in the Rižana and Osapska reka springs in very low concentrations but the connection was assessed as being very probable. The connection of these two injection points with the observed springs in Croatia (Mlini, Sv. Ivan, springs near Opatija) was assessed as possible but could not be reliably confirmed on the basis of the results. The bacteriophages injected into the stream near Hotična proved a connection with the Rižana.

Two tracings were carried out from the ponor zone near Dane. In 1987 rhodamine proved an underground connection with the Admiral and Kristal springs in Opatija (Krivic et al. 1989). Tracer did not appear in the Sv. Ivan, Rižana and Osapska reka springs. In mid-1989 tracing was repeated with tritium when the water level was slightly higher (IRB 1992). Tracer appeared once again in the Admiral and Kristal springs in Opatija and, in considerably lower concentrations, in the Sv. Ivan spring. In May 1987 bacteriophages were injected in Movraž and, simultaneously, uranine was injected in Račice. The bacteriophages appeared in the Mlini and Bulaž springs and the uranine in the Opatija springs (Krivic et al. 1989).

In May 1988 radioactive tritium was used to prove a connection of the Bazuje ponor with the Bulaž spring.

In 1989 tritium was used for tracing of the ponor zone of the Rečina and the already demonstrated connection with the Sv. Ivan spring was confirmed. The high velocity established by the tracing indicates a direct connection and significant karstification of the subsurface.

In the catchment area of the Sv. Ivan spring tritium was used for the last time in a ponor near Lanišće in 1992. An underground water connection was proved with the Kristal spring in Opatija and the Sv. Ivan spring, which defines this area as the watershed zone of the catchment areas of the Sv. Ivan spring and the Opatija springs.

In March 2001 uranine was injected into a sinking stream in the Beka-Ocizla cave system (Kogovšek & Petrič 2004). A principal underground connection was established with the Bagnoli della Rosandra/Boljunec spring in Italy, while a smaller percentage of tracer was recorded in the spring of the Rižana. In 2009 and 2010, two further tracings were carried out in the catchment area of the Rižana. In the first test, uranine was injected into the karst surface near Črnotiče, while in the second uranine was injected into the research borehole T2-12 and amidorhodamine G into the T1-8 borehole along the planned route of the second line of the Koper–Divača railway (Gabrovšek et al. 2015). In both cases the uranine confirmed a principal underground water connection with the Rižana and Osapska reka springs and a secondary connection with the Bagnoli della Rosandra/Boljunec spring in Italy. The amidorhodamine G confirmed the connection of the T1-8 borehole with the Bagnoli della Rosandra/Boljunec spring.

Table 7.1: Results of tracer tests (? – no data on velocity, / – connection not established).

Point and date of injection	**Tracer**	**Sampling points**	**Apparent flow velocity (m/h)**
Odolina Beginning of 20th century	Uranine	Rižana	104
Brnobići 1930	Uranine, Brewer's yeast	Sv. Ivan	/ /
Rašpor 1930	LiCl	Sv. Ivan	/

Point and date of injection	**Tracer**	**Sampling points**	**Apparent flow velocity (m/h)**
Rečina 1930?	Brewer's yeast	Sv. Ivan	?
Oprtaljska Draga 1957	Uranine	Bulaž Sv. Ivan	36 /
Pašudija 1977	Tritium	Bulaž Sv. Ivan Gabrijeli Bužin Gradole Kristal	29 / / / / /
Zrenj 21/1/1983	Tritium	Bulaž	72
Prapoče 30/5/1984	Tritium	Sv. Ivan Bulaž Gradole	86 / /
Brezovica 10/4/1985	Tritium	Rižana Osapska Reka Mlini Sv. Ivan Springs near Opatija	101 / / / /
Gračišče 10/4/1985	Rhodamine	Rižana Osapska Reka Mlini Sv. Ivan Springs near Opatija	18 / / / /
Smokvica 10/4/1985	Bacteriophages	Rižana Osapska Reka Mlini Sv. Ivan Springs near Opatija	11 / / / /
Jezerina 13/5/1986	Rhodamine	Rižana Osapska Reka Sv. Ivan Mlini Springs near Opatija	30 30 ? ? ?
Male Loče 13/5/1986	Uranine	Rižana Osapska Reka Sv. Ivan Mlini Springs near Opatija	30 30 ? ? ?
Hotična 13/5/1986	Bacteriophages	Rižana Osapska Reka Sv. Ivan Mlini Springs near Opatija	26 / / / /

Point and date of injection	Tracer	Sampling points	Apparent flow velocity (m/h)
Dane 6/5/1987	Rhodamine	Rižana Osapska Reka Sv. Ivan Bulaž Mlini Admiral Kristal	/ / / / / 86 86
Račice 6/5/1987	Uranine	Rižana Osapska Reka Sv. Ivan Bulaž Mlini Kristal Admiral	/ / / / / 40 40
Movraž 6/5/1987	Bacteriophages	Rižana Osapska Reka Sv. Ivan Bulaž Mlini Springs near Opatija	/ / / 50 43 /
Bazuje 19/5/1988	Tritium	Bulaž	47
Kanjon Rećine 14/6/1989	Tritium	Sv. Ivan	396
Dane 27/6/1989	Tritium	Sv. Ivan Admiral Kristal	11 61 61
Lanišće 12/6/1992	Tritium	Sv. Ivan Kristal	40 47
Beka-Ocizla 29/3/2001	Uranine	Boljunec Rižana	33 29
Črnotiče 1/12/2009	Uranine	Rižana Osapska Reka Boljunec	22 33 10
Borehole T2-12 18/11/2010	Uranine	Rižana Osapska Reka Boljunec	62 23 48
Borehole T1-8 18/11/2010	Amidorhodamine G	Boljunec	61

The identified underground water connections are collected in Table 7.1 and shown in Fig. 7.1. The majority of tracings were carried out between 1983 and 1992, when the tracing method was still being developed. For this reason, some of the identified connections are not entirely reliable and would need to be verified by new tracer tests. A quantitative assessment of the quantities of tracers discharged is also necessary, since this would provide, in addition to information about the connections between the studied locations, data on the strength of these connections under different hydrological conditions. In some areas tracings have not yet been carried out at all, and information on the routes of underground water flow is even more incomplete. It is therefore necessary to continue with hydrogeological research, since a good knowledge of the functioning of karst aquifers is the basis for their adequate management.

The transboundary nature of the karst aquifer

All three major water sources in the area under consideration are characterised by the transboundary nature of their catchment areas. The Rižana is mainly fed from areas within Slovenia, while the Sv. Ivan and Bulaž springs are mainly fed from areas within Croatia, but a smaller proportion of the water in these springs comes from the neighbouring country. Underground water flow does not, of course, respect political borders and only obeys hydrogeological laws. For this reason, it is also necessary to plan the protection of water sources with a transboundary recharge area.

In the first phase, a common database needs to be designed, and the transboundary karst aquifer needs to be treated as a single system in hydrogeological research. Following coordination of size and classification of protection zones, it will also be necessary to define a uniform regime of measures for the protection of water sources within the entire recharge area on both sides of the border.

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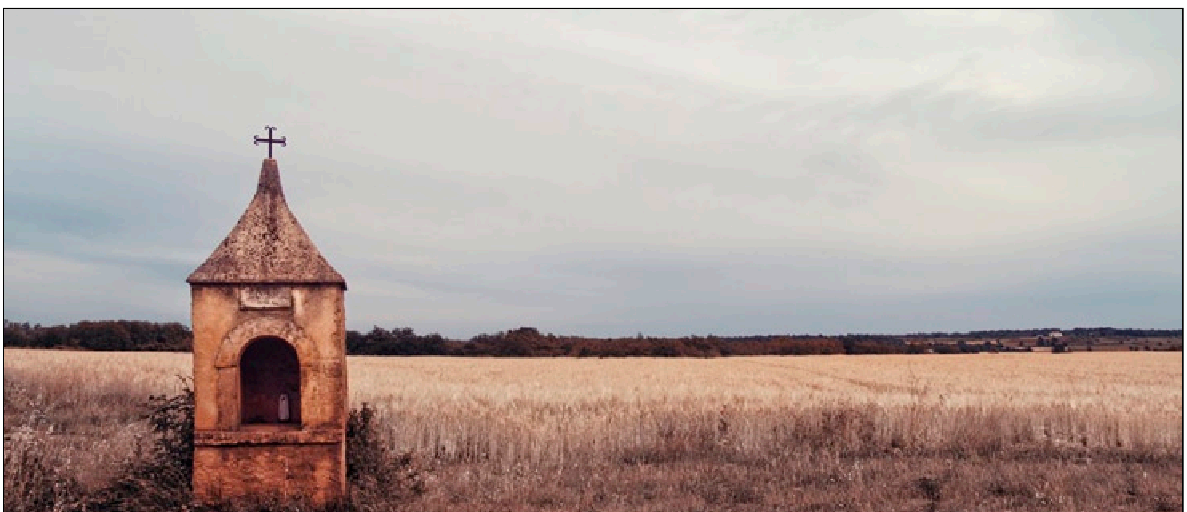
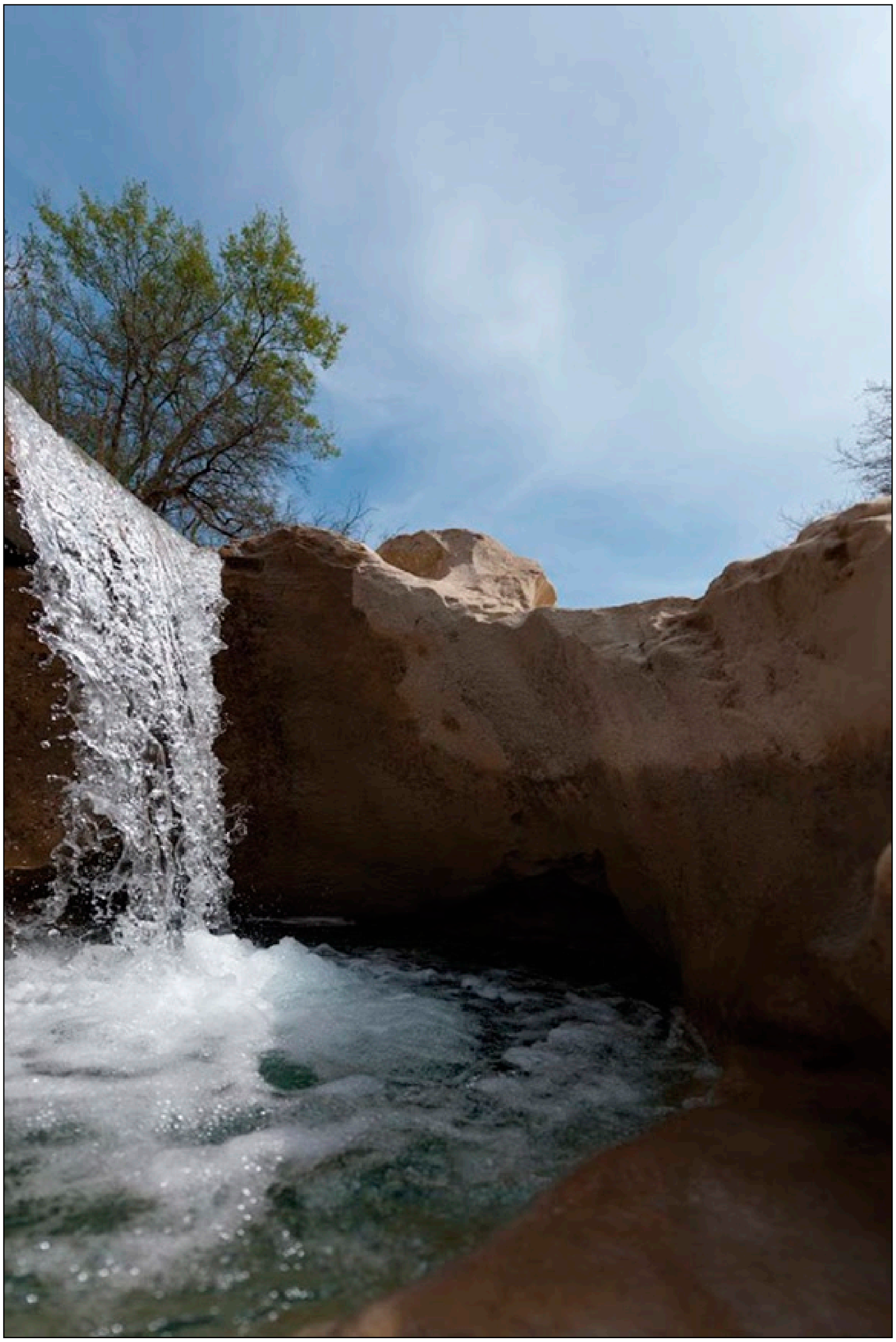


Photo from "Water - Life!" in Istria competition; author: Kristian Macinić



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THE ROLE OF EPIKARST FAUNA AS INDICATORS OF SUBTERRANEAN AQUATIC ECOSYSTEM HEALTH

Tanja Pipan

Introduction

Monitoring of obligate cave-dwelling invertebrates (aquatic stygobionts and terrestrial troglobionts) has been challenged (Culver & Sket 2002). Many of the species of concern are rare and the effective censusing of any rare animal is difficult (Thompson 2004). An additional problem for many rare cave-dwelling invertebrates is that their primary habitat is the epikarst – the small voids and fissures in the uppermost layer of limestone. Often, animals seen in caves, especially cave pools, are animals that have literally fallen out of the epikarst via ceiling drips (Pipan 2005). Epikarst is hydrologically important because it stores significant amounts of water and it is of considerable environmental concern because it is the site of many spills and because contaminants do not clear rapidly (Jones et al. 2004).

Figure 8.1: Precopulatory mating pair of copepods with an ovigerous female (Photo: Tanja Pipan).

Three sites (two ponors at Marušići and the Rašpor cave, and the cave Jama pod Krogom) were sampled in the investigated area (see Fig. 7.1) to detect epikarst subterranean fauna. Biological samples were collected once in the cave Jama pod Krogom and twice at the Marušići and Rašpor sites. The purpose was to identify epikarst fauna washed through the drips for ecological assessment. These data could be used to determine which epikarst habitats are associated with various drip-water sources, to link these habitats with specific geological, hydrological and seasonal conditions, and to determine when and how related epikarst reservoirs and habitats are drained or flushed.

Epikarst fauna

Considerable numbers of both terrestrial and aquatic organisms are washed out of the epikarst into pools and streams (Pipan 2005). Numerous specimens of Copepoda and their nauplii, Turbellaria, Nematoda, Archiannelida (i.e. *Troglochaetus*), Rotatoria, Gastropoda, Oligochaeta, Araneae, Acarina, Ostracoda, Bathynellacea, Isopoda, Amphipoda, Collembola, and Diptera larvae can be collected from percolating water (Pipan 2005; Pipan & Culver 2005). The most common and most abundant metazoans in the epikarst are copepod crustaceans (Fig. 8.1).

Copepods are the most common epikarst fauna that are flushed though drips and may represent the majority of biomass entering shallow caves through drips (Pipan & Culver 2005). They enter caves in relatively large numbers – one copepod per drip per day (Pipan et al. 2006a). It was shown that not only a tremendous number, but a great diversity of copepods are found in epikarst drip waters (Pipan 2005). These copepods include stygobionts, facultative subterranean dwellers (stygophiles), and widespread surface dwelling species (Pipan 2005). Most epikarst stygobiotic copepod species are found in a limited area in a cave, usually less than 100m in linear extent, and are often found in a single drip (Pipan & Culver 2007b). Some stygobiotic copepods can be epikarst specialists (Culver & Pipan 2011) but some can also be found in different shallow subterranean habitats such as the hyporheic zone at groundwater-surface water interfaces (Culver & Pipan 2014). The rate at which animals are flushed though drips, and their diversity, appear to be related to flow rates as well as geochemical parameters (Pipan et al. 2006).

Methods for fauna sampling in percolation water

Epikarst is a perched aquifer, and a major ecotone between surface water and groundwater. In the hydrological classification of the karst underground, epikarst represents the stratum that is closest to the surface and which remains inaccessible using standard research methods. Direct sampling of epikarst habitats is not possible due to the small size of the cavities and their inaccessibility. Because epikarst is almost impossible to sample directly, epikarst fauna must be explored indirectly by taking samples of percolation water (Pipan 2005; Pipan et al. 2006a). But unlike most subterranean habitats, continuous, long-term sampling of epikarst communities is possible. Epikarst communities are best sampled by collection and filtration of drip water over extended periods of time (Pipan 2005).

One way to collect epikarst fauna is by taking samples of percolation water that drips directly from the ceiling. The water from trickles is directed into a funnel and then into a collecting container with plankton netting (Fig. 8.2). On two sides, the plastic container has holes covered with a net of mesh size 60 µm. Collected animals and a small amount of water remain in the filtering bottle (Fig. 8.3), while most of the water exits into a container. This water can be used for measurements of physical and chemical parameters.

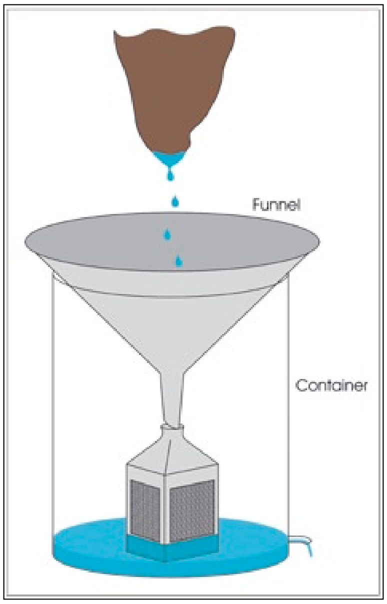

Figure 8.2: Sampling container (from Pipan 2005).

The easiest way to collect epikarst fauna is from pools filled with water which seeps down the walls or drips directly from the cave ceiling. It is also used when long-term monitoring is not provided and only sporadic samples are taken. Pools are sampled by aspiration of the water (Fig. 8.4) filtered through the collecting container (Fig. 8.3) described above. In both cases samples are preserved in a 70% solution of ethanol.

Once in the laboratory the organisms are separated using a stereomicroscope at 40x magnification and then stored in 70% ethanol. Further processing and identification of the organisms is performed under a compound microscope at 400x to 1000x magnification.

Figure 8.3: Filtering bottle (Photo: Tanja Pipan; see also Fig. 8.2).

Figure 8.4: Apparatus for aspirating water in pools. After aspiration, the water is filtered. through a net or filtering bottle (Fig. 8.3) in order to recover the epikarst fauna (Photo: Daniel W. Fong).

Results and discussion

Due to sporadic sampling at each site, the biodiversity in the investigated area was not remarkable but we were focused on epikarst Copepoda. Altogether 45 specimens of Copepoda and one of Amphipoda (Fig. 8.5) were collected from 1300 ml of filtered water. The Copepoda belonged to two groups of Cyclopoida and Harpacticoida. In addition, at the Rašpor site there were ovigerous females (Fig. 8.6) and nauplii in the samples represented 34% of the population at that site. One ovigerous female and nauplii were found also in the samples from Marušići site. Immature individuals and females with eggs suggest that there is a vital population in the epikarst. In contrast to these two sites, Jama pod Krogom is biologically much more investigated. In this cave five stygobiotic and two troglobiotic species were recorded in previous inventories (Polak et al. 2012). Brancelj (1992) carried out the first sampling of copepods from pools filled by dripping water in Jama pod Krogom and identified 16 copepod species, among them 11 stygobiotic species of which five are on the list of threatened species. In our investigation, 100 ml of epikarst water in the cave was filtered and we found specimens of Harpacticoda and Amphipoda, the latter assumed to be a new undescribed species of *Niphargus* (Fig. 8.5). The specimen is about 3.0 mm long and is the smallest *Niphargus*, which suggests that it is an epikarst specialist. Specimens of *Niphargus* were observed also at the Marušići sampling site but were not collected.

Figure 8.5: Niphargus *sp., an Amphipoda (Crustacea) from epikarst water in Jama pod Krogom (Photo: Tanja Pipan).*

This study and other similar studies show that an intact epikarst is important, since many – probably most – stygobionts are not typically found in main cave streams but instead in small first-order streams and pools (Culver & Pipan 2009). Fong and Culver (1994) showed this for the stygobiotic fauna of Organ Cave, West Virginia, where the highest diversity was in first-order streams and the lowest was in third-order streams, the main streams in the cave. Many rare stygobionts found in cave streams are denizens of the epikarst (Pipan 2005). The epikarst is likely to contain the source populations of the stygobionts occupying the cave stream. Any disruption or destruction of the epikarst would isolate the stream population, probably resulting in its eventual extinction due to its limited extent and small population size (Culver & Pipan 2009, 2014).

Epikarst is more than a source population and a connecting corridor to other caves. It is also a major source of carbon and nutrients, especially in caves where there are no sinking streams. Water coming into the entrance may carry carbon and nutrients, but it is unlikely to be either frequent or quantitatively important. Many of the aquatic and terrestrial animals are important food sources for the cave stream invertebrate community. An even more important component of organic carbon is that dissolved in the dripping water (Simon et al. 2007) and it is critical in the formation of a biofilm in caves (Simon et al. 2003). In the context of the flux of organic carbon, any disruption of the epikarst is likely to have major negative consequences.

The epikarst habitat is itself a highly vulnerable and important one. As first described by Mangin (1974) and Williams (1983), epikarst holds a considerable reservoir of subterranean water that is poorly integrated both vertically and horizontally. This makes it very vulnerable to any spills of pollutants either on the surface or from leaking underground storage tanks. Because of the poorly integrated nature of the epikarst, contaminants tend to persist (Aley 2004, White 2004), but still spread from the source in different directions.

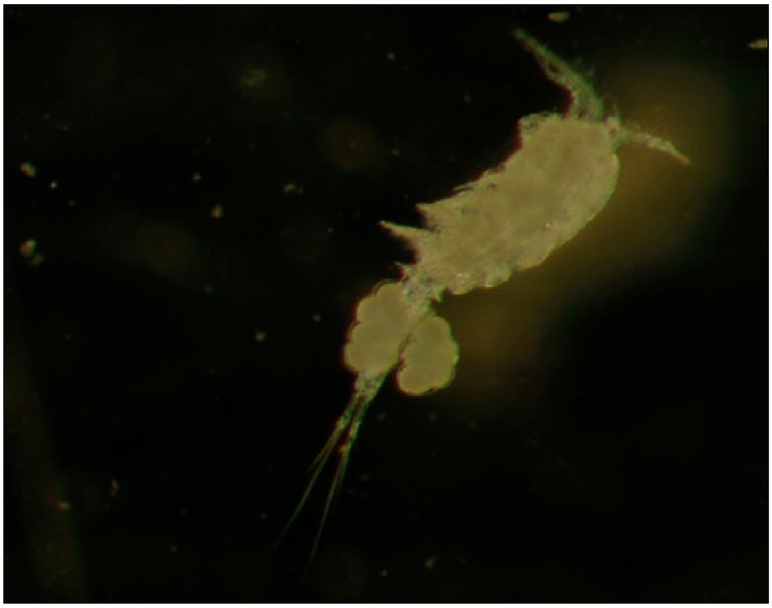

Figure 8.6: Ovigerous copepod female from epikarst water at the Rašpor site (Photo: Tanja Pipan).

Rare cave species are notoriously difficult to monitor, and typically all that can be done is to confirm the continued presence of a species in a cave. Because of the problems of low detectability, repeated visits may be required in order to have some degree of certainty about the presence or absence of a species (Krejca & Weckerly 2007). The relatively simple sampling procedure presented in the text (Figs. 8.2, 8.4) allows long-term sampling, and the accumulation of significant numbers of individuals.

There is no way to determine which drips or habitats will be best, although species richness in other caves is correlated with some aspects of water chemistry as well as ceiling thickness (Pipan et al. 2006b), nor which sampling times are best. Pipan and Culver (2007a) recommend at least four drip samples over a year in order to collect 90% of the rich stygobiotic copepod fauna of Slovenian caves, and this is a good rule of thumb for these studies. Samples should be taken every two to three months to minimise mortality and predation. The presence of surface-dwelling organisms in drips is not necessarily a sign of contamination, but rather a sign of ecosystem health, unless these are not organisms specialised in polluted waters, such as tubificid worms (Pipan 2005, Culver & Pipan 2009).

Conclusions

The presented study and other similar studies show that biology can be used in conjunction with continuous hydrological and geochemical monitoring, which allows epikarst fauna to be used as a proxy for hydrogeochemical conditions in the epikarst. Epikarst is the primary habitat for many of the stygobionts. Water entering the cave from the epikarst is the major source of organic carbon and nutrients, and the major source of stygobiotic migrants into the stream. That is why sampling of an epikarst fauna is a useful way to assess ecosystem health. The health of the epikarst can be assessed by long-term continuous collection of the fauna entering the cave, especially the number of stygobiotic individuals, and the overall number of both copepods and all invertebrates. Although sampling in selected sites in North Istria was not systematic and intensive, we can conclude that stygobiotic epikarst fauna was found, and that epikarst specialists (especially copepods and amphipods) indicate good water quality.

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Photo from "Water - Life!" in Istria competition; author: Josip Madračević

Photo from "Water - Life!" in Istria competition; author: Josip Madračević

RELATIONSHIP BETWEEN MAN AND WATER THROUGHOUT HISTORY

Tamara Crnko, Josip Rubinić, Franci Malečkar

Introduction

This paper presents a brief overview of the historical use of water resources in Northern Istria and its related boundary areas of Brkini, Podgorski kras and Podgrajsko podolje and, within that context, of the relationship between water, the karst landscape and people. The elementary vital preoccupation of the local population with ensuring water supply throughout history, in conditions of water-permeable karst topography, has shaped the spatial and cultural identity of the population. In areas where surface water is rare, the population has long developed an awareness of the need to conserve water and water resources and protect underground karst aquifers. This is an area covered by research aimed at preserving the water resources of the High Istrian karst as part of the ŽIVO! project, which includes the drainage basins of the Rižana spring in the Koper hinterland and the Sv. Ivan and Bulaž springs in the Mirna Valley. It is from these very sources that the system of public water supply and regional water supply systems provide water to a significant part of Istria today. The specific structure of the relief of Northern Istria, dominated on the one hand by mainly dry karst areas, and by its rich underground water on the other hand, has affected and continues to affect the creation of the special physical and cultural identity of Istria. The preoccupation with water, which, due to the soluble rocks of the karst landscape does not stay long on the surface, and the fear of the disappearance of water have shaped the consciousness of the population and have strongly etched themselves into its spatial and cultural identity. Therefore, the strategy for the protection of the water resources of the area, if it aims to be effective, must be built not only on the usual spatial-planning, legislative and technical grounds, but also on cultural ones.

The analysed area is the central part of Northern Istria. The analysed area is located at the interface of the Adriatic and Dinaric tectonic platforms. Due to strong tectonic movements, the area is characterised by a furrowy, scaly relief structure with layers stretching in different directions (Vlahović et al. 2005). This is a very diverse karst relief with soluble limestone rocks that are mostly bare in the mountain areas. Due to the geological substrate and the structure of the relief, the precipitation, although highly significant (with an annual mean value between 1200 and 2500 mm) is rapidly infiltrated or drained into the underground, resulting in the scarcity of surface flows, which, even when they do form, quickly end up in sinkholes to feed underground aquifers. At the edges of these aquifers there are large karst springs that feed into the surface flows of the Mirna and Rižana rivers, while being all but the only respectable portions of their water balance during dry periods.

The karst formation processes give rise to endogenous and exogenous karst land forms, and the analysed area is rich in cave forms. The most prominent underground karst formations in this area also include two pits – sinkholes. These are the Rašpor pit, about 358 m deep and about 5 km wide (Rubinić et al. 2013) and the Dimnice pit, about 180 m deep and 8 km wide (Anon 2010). This type of relief has resulted in a dual structure with regard to water. On the one hand, the surface landscape is characterised by a relative scarcity of water, while there is ample water underground, and the karst aquifer feeds the springs and rivers that are used for water supply.

Water and karst as part of physical and cultural identity

The preoccupation with water and water supply in an area that has few surface flows and water resources has affected the development of consciousness and the cultural and spatial identity of the inhabitants of the area. This is, perhaps, best illustrated by the legend of St. Peter and God, who forgot to give water to the people on Čičarija/Ćićarija (Tončić Štancar 2005). Having realised this, God said that he would occasionally send rain down on their sieve-like soil, but that he knew that these stubborn people would know how to manage despite everything.

Characters from Istrian myths and legends have also been named after the Istrian rivers. The giants that allegedly inhabited Istria were named after the Istrian rivers. The ploughing giant Dragonja bears the name of a river in north-western Istria. This giant was responsible for the formation of the Pazin pit and Pazinčica because he used his strength to plough a furrow in the ground through which water began to flow. The same giant is said to have created the Mirna river by ploughing a furrow from Čičarija/Ćićarija to the sea. As the water flowed quietly, the river was named in accordance with its character (translator's note: "mirna" means "quiet" in Slovenian and Croatian). The wife of the giant Dragonja is also named Mirna. Queen Mirna is linked to the legend of King Albus, who planned to conquer Istria, but who changed under the influence of no other than Queen Mirna (Njegovan 2011). The reflections of the Slavic myths of the gods Perun and Veles are still present in the traditions and place names of the analysed area. Perun is the god of thunder and sky, and Veles (Volos) is the god of earth, water and underground. The eternal struggle between these gods is also reflected in the yearly changes of the water cycle, which is so important for the daily life of the inhabitants of these areas.

There is an interesting legend associated with the emergence of the Istarske toplice spa (near the Bulaž spring). The water with healing properties allegedly sprang from the place where the spa is located today when a young virgin, accused of having lost her chastity, threw herself from the rock of Sv. Stjepan (St. Stephen) to prove her purity (Njegovan 2011). While on the one hand water as the source of life and culture was glorified by having the characteristics of holiness and magnitude added to it, there was also a kind of mystification of water phenomena in the karst. The Tombazin spring, active only after stronger or long-lasting precipitation, provided the backdrop for the legend of mališi, elves playing instruments in the sinkhole and scaring children (Jakovljević 1997) due to the characteristic murmur that can be heard under the ground.

As legends very often have a trace in reality, one such legend is the one about a bond between Brkini and the spring Rižane. According to that legend, the Rižane villagers found a "barilco" (a small barrel of water) in the Rižana River that was used by the mowers on the Brkini Hills, but it floated away through an abyss to the source of the Rižana.

Given the special importance of water in the life of the population, there are several place names in the analysed area that contain references to water. An example of this is Vodice in the municipality of Lanišće, located near sources of drinking water. According to Buršić - Matijašić (2003), the area of Buzeština has fewer place names that refer to water because prehistoric settlers mainly focused on high, strategic positions, which generally did not have access to sources of drinking water in the vicinity. The author mentions Račice and Račja Vas as place names that refer to animals living in water.

The hydronyms of the area indicate the nature of its water. The springs that are permanent and do not dry up were often named after saints such as Sv. Martin (St. Martin) near Buzet and Sv. Ivan (St. John). Their importance is reflected in the character of holiness. The very names of the springs that dry up are indicative of their character, for example, the Sušac spring (translator's note: from "suh" = "dry"). An interesting and very common name for a spring in the Slovenian part of Istria is Studenac, which evokes the cold groundwater and is very often synonymous with the very source of groundwater.

The development of water supply systems from so-called major karst springs and the supply of smaller settlements with water from such public water supply systems did not make the population lose interest in small springs that had once been used for local drinking water supply and other uses by small settlements. These springs became part of their cultural identity, and every major drought points up their economic significance (Ravnik 2005), which is local, but important for this sparsely populated area. The watercourses that begin from abundant karst springs such as the Rižana and Mirna (downstream from the confluence of the overflow waters of the Sv. Ivan spring) had an extremely great significance before the widespread use of electricity, which arrived in most of the smaller settlements of the analysed area only in the early second half of the 20th century. According to the Cadastre maintained for the 1818-1826 period, there were as many as 228 registered mills in the wider Istria area, including its Slovenian part, of which 27 on the Rižana river, and 13 at Buzet on the Mirna alone, while, according to some reports, there were even more of them in the 17th century (Starec 2002). The last professional miller was Anton Fantinić from the village of Mlini on the Croatian-Slovenian border, has at least by its name, preserved a piece of the history and cultural identity of this area formed in its relationship with water. There was a hydropower plant on the Rižana River before World War Two, with its remains still visible today.

As a very specific form of water use one can note the use of ice-storages in Matadorsko podolje where ice for the supply of Trieste was stored.

Population

Northern Istria is an area that has been inhabited since prehistoric times, as evidenced by the continuity of settlement in the Pupičine Peći cave, located on the west side of Učka, near Vranje, from as far back as the time of transition from the Pleistocene to the Holocene, to the Neolithic period to the Bronze Age to the Iron Age (Miracle 2006). Istria had the largest number of inhabitants, as many as 500,000, during the prosperous years of the Roman Empire, only to see this number drop to a mere 130,000 by the 13th century (Darovec 1996). Today, the region of Istria, including its peripheral areas, has about 328,000 inhabitants, with about 210,000 people living in its Croatian part, which belongs to Istria County, 28,000 living in the parts of Istria belonging to Primorje-Gora County, and about 90,000 living in the coastal area of the Slovenian part of Istria and its hinterland. The reason for major changes in population size throughout history should be sought in the consequences of large-scale migrations due to economic circumstances, war, epidemics (especially plague and malaria) and changes brought about by socio-economic conditions in changing political systems. Mention ought to be made of the arrival of Vlach shepherds, Ćići, in the high mountain regions of Northern Istria – named Čičarija/Ćićarija after them – in the 16th century (Darovec 1996).

In contrast to the coastal parts of Croatian and Slovenian Istria, which have in recent past, since the beginning of the 20th century, recorded variations, decreases and even increases in population, the hinterland, including the investigated area of Northern Istria and its peripheral parts, has mostly recorded a very significant decline in population size. This decline is much more pronounced in the Croatian part than in the Slovenian part of the investigated area. Today's low population density of this area is due to the natural characteristics of the karst landscape, but also to a number of political and social factors, such as changes of government, wars and population exoduses, as well as general population trends in society. The emigration trend and negative demographic picture are still present. Those emigrating are mostly younger, working-age people, who are leaving jobs in the primary and secondary sectors of the economy and moving to urban areas. Thus, according to the 2001 census, conducted by the State Statistical Office of the Republic of Croatia, the average age of the population in the entire territory of Istria County was 40.2 years, while in the municipality of Lanišće it was 49.5 years.

Figure 9.1 gives a comparative overview of changes in the number of people in Northern Istria, in two categories, for the Croatian part (the municipalities of Lanišće, Lupoglav, Oprtalj and Grožnjan) and the Slovenian part (Slovenian hinterland). Although data was not available for the Slovenian part before 1961, there are visible similarities and differences in the change of population size – after the large drop in the number of inhabitants in the first fifteen years after World War II, this drop resumed at roughly the same pace on both sides of the border until the beginning of the 1990s. After that, the Slovenian part of Northern Istria recorded a slight increase in population, which reached the number that part of Istria had had forty years earlier. The Croatian part of Istria resumed the previous trend of population decrease due to the war in Croatia in the early 1990s and the socio-economic conditions that resulted in continued emigration.

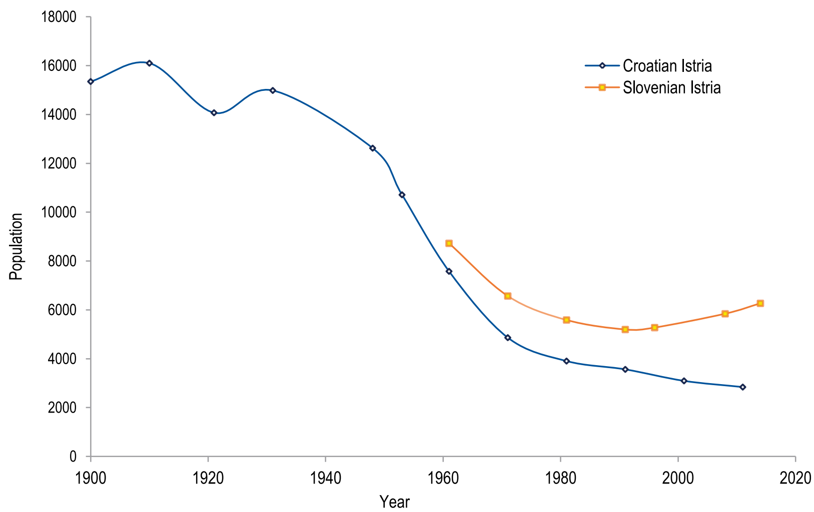

Figure 9.1: Overview of changes in population size in Northern Istria and its peripheral parts (1900-2011).

The result of emigration is also population aging and the consequent disappearance of small settlements on the Istrian peninsula. Smaller settlements are disappearing due to demographic emptying, with empty houses and farms and untended farmland being left behind. Depopulation is also significantly affecting natural and water resources. The reduction in anthropogenic pressures is leading to a decrease in the erosion of the river basins, changes in vegetation, reduced land exploitation and reduced pollution (Prodan 2009). The reduction in the number of inhabitants has had negative consequences due to the dying out of settlements, the disappearance of the working age population and radical changes in the Istria's landscape, where forest vegetation is spreading at the expense of grassland. However, as regards the protection of sensitive karst aquifers and sources of drinking water, an incidental positive impact that emigration has had on the preservation and protection of the quality of drinking water can be observed given that many of the settlements in the analysed area are located in the drainage basin of the Sv. Ivan spring, i.e. in the territory of the distribution of sanitary protection zones of that spring. Nevertheless, the evident reduction in negative anthropogenic pressures that are associated with a higher population density in water protection zones cannot be taken as a model on which we can rely on when making plans for the protection of water, karst aquifers and springs. It is therefore necessary to find a model for the survival of the population in this rural area and for ensuring their economic activities that would not adversely affect water quality.

Traditional forms of water use and local water supply

Before the construction of an organised water supply system that enabled easier access to drinking water in the villages and households of the Istrian Karst, its population was largely dependent on natural and artificial water collection methods. The remains of important ancient buildings have been found near water springs, and in the case of unavailability of springs, the population used alternative forms of water supply. Until the construction of the Istrian aqueduct (1933), which supplies water to the larger part of Istria, and the Rižana aqueduct (1935), which supplies water to part of the Slovenian Karst, the population used water from lakes, ponds, various rainwater collection points or artificial reservoirs such as tanks. Such unregulated water supply resulted in significant losses of energy and an increased risk of disease. An interesting concept is the collection of water from natural depressions and waterbeds as a completely natural and very primitive water supplying method, which was practiced in the Slovenian part of Istria as late as the 1960s (Koštial 2005). However, there are historical records of the existence of local water supply systems in ancient times, even as far back as the Roman times, when spring water was brought to the Funtana locality at Buzet from Sv. Martin about 2 km away.

Water supply was one of the most important tasks of the members of any household. Providing water was mainly the responsibility of women, who fetched water from often distant springs and brought it to the house in pots they usually carried on top of their heads. Large amounts of water were often brought to households by men, either on foot or in horse-drawn carts (Benčić 2013; Godina–Golija 2005). People often had to wait in lines to get water. Water obtained in this way, either from springs or the city and private tanks, was kept in a special place in the household and was used with extreme frugality. Personal hygiene was also maintained frugally. Family members bathed once a week, in a special bath, with an emphasis on saving water. It is not surprising that the importance of water has remained etched on people's minds. Water from natural collection points was mostly used for cooking, laundry washing and watering animals, while water from springs was used as drinking water. Given the scarcity of water in the karst areas and the fact that there is generally more water underground than on the surface in the karst, people had to have a very good knowledge of the environment and terrain in order to use water from natural water reservoirs of different shapes and sizes. Water sources were kept clean and maintained. An awareness of the importance of running water for drinking and health developed very early on.

Rainwater from ponds was mainly used for watering farm animals, while people provided water from small lakes at karst groundwater springs, very often called bulaž on both sides of the Istrian border. Natural water collection points such as ponds often posed a threat of infections disease (Cigui 2013). Malaria epidemics broke out sporadically throughout history, especially in the 17th and 18th centuries. Abandoned farmland, ponds and puddles became malaria zones contributing to the reproduction of malaria vectors. To prevent the breeding of mosquitoes, as malaria vectors, a series of initiatives for combating epidemics were launched in the late 19th century.

Cisterns were one of the most typical traditional forms of water supply in Istria. Cisterns of different depths, made of stone or concrete, with lids made of iron or wood and pulleys with canisters, had long been a status symbol, but today they remain a symbol of the traditional Istrian house. They were mostly public, communal cisterns, and wealthy residents also began to build them in the 18th century. Rainwater passed from the roofs to the cisterns through gutters and sand filters. Cisterns often remained dry, especially during the summer months, and the entire water supply depended on the weather (Benčić 2013).

A good example of such public cisterns is the town of Buzet in which there were two cisterns: Vela Šterna and Mala Šterna. Water could be taken from them in limited quantities, and wealthy residents often charged for water taken from private cisterns (Kraljević 1999). Poorer residents had to fetch water from sources that were away from their place of residence. Cistern areas were often groomed and walled in. Access to such water sources was often guarded by a village guard who had to make sure that water was taken in limited quantities, while at night the gate to the cistern was locked. As the availability of water was limited, even during the times of the Venetian rule there were plans to build a two-kilometre water pipeline connecting the Sv. Martin spring to Vela Šterna. The project fell through as Venice collapsed in the late 18th century, and a similar urban water supply system was built about a hundred years later (Merlić 2008). The town of Buzet thus became the first town in Istria with an urban public water supply system. In fact, until the arrival of Austrian rule in the early 19th century, Istria was mostly organised into independent fiefdoms, municipalities and cities, without adequate conditions for making comprehensive plans to solve the problem of water supply. Local water supply systems were built with intakes from the nearest springs or wells without the possibility of supplying a larger number of people. Despite these activities, most people did not have drinking water near their homes.

The construction of rural water supply systems began to intensify at this time. An example of a public rural water supply system is the Žbevnica – Brest – Rakitovec water supply system, with an intake from the Škobrc spring, whose location at 850 m above sea level put it almost at the top of Žbevnica. The water supply system was built in 1878 and, apart from the village of Brest, it also supplied Rakitovec, where a station for filling steam locomotives with water was also located. Because the railway company was granted the use of water for its own purposes, the Austrian authorities built the Church of the Most Holy Trinity in the village of Brest, without a bell tower, which was not in the contract and was subsequently built by locals as one of the lowest bell towers in Istria.

Such an individual, unregulated regime of water use has led to the need to think about a regulated water supply system that would also bring water to the more remote rural areas of Istria. Due to frequent outbreaks of diseases, while planning a comprehensive water supply system, the authorities in Istria emphasised the importance of extensive amelioration and water-management activities to curb the risks. A dual attitude towards water has been evident throughout history. On the one hand, there has been a great fear of the disappearance and unavailability of water, while there were also risks of unregulated use of water resources on the other. Dependence on geographic characteristics, economic status, the seasons and personal frugality up until the establishment of an organised water supply system shaped the life of the Istrian karst throughout history.

Development of modern water supply

The date of 14 November 1864, when the Istrian Parliament passed the Law on Measures Against the Lack of water in the Province of Istria, after which the Austrian authorities began solving the problem of water supply in Istria in an organised fashion, can be regarded as the beginning of organised development of water supply in Istria. The Law dated 28 August 1870, No. 44 (Gesetz vom 20 August 1870 über Benützung, Leithung und Abwehr Gewässer) can be considered the turning point in this development. The law provided technical guidance related to various water supply structures and orders to provincial and municipal authorities for their construction in public spaces or within public buildings in anticipation of the construction of central water reservoirs. Under this law, even private entrepreneurs were ordered to have rainwater collecting cisterns in their houses. The development of modern water supply was also helped by the activities of the Istrian Agricultural Society, which in 1876 managed to agree with the central government in Vienna on the construction of organised cattle watering facilities; in this way the solution to the problem of providing adequate quantities of water was applied all categories of consumers, including those involved in livestock raising, which was widespread in those days (Milotić & Prodan 2014).

Acting on an invitation from the Imperial-Royal Government and on the basis of a previous field inspection, an engineer called Wolf submitted a report in 1880 entitled "Water supply in the Karst" in which he proposed the construction of a large number of individual local water supply systems with intakes mainly from dug wells and springs located at higher elevations to bring water to the villages. A decade later, the problem of water supply in Istria was addressed Dr B. Schiavuzzi who first presented his report "On Water Supply in Istria and Gorica" at the Congress of the Trieste Hygienic Society in 1890, and subsequently before representatives of the Provincial Parliament of the Margraviate of Istria. He in turn assigned priority to the use of water from groundwater sources (Milotić & Prodan 2014). By the early 20th century, as many as five different conceptual water supply projects were developed, including systems of reservoirs to be located on Istrian foothills, gravity-based systems for supplying water to large urban settlements and regional systems utilising karst springs in the valleys of Istrian rivers. According to Kos (2001), these are the project designed by C. Oberst from 1899; the project by C. Schwartz from 1904 and F. Schiavoni from 1913; the project by G. Posso from 1922, after Istria was placed under Italian rule; and, finally, the project by G. Veronese from 1928, in accordance with which the realisation of the regional water supply system eventually began.

The water supply solution was planned in accordance with Veronese's project through three separate systems: The Mirna system, the Rižana system and the Raša system. Phase 1 works on the Mirna system began in 1930 and were completed as early as 1933 with the inclusion of the Sv. Ivan spring in the water supply system, which made the Istrian Water Supply System a reality. The Sv. Ivan spring was included at a capacity of 208 L/s. This was therefore a very significant source, whose entire drainage basin was in the area of high Istrian Karst, i.e. in its part called Čičarija/Ćićarija.

Although it was initially planned as the third phase, the construction of the Rižana water supply system with an intake from the Rižana spring (Sv. Marije), in 1934, and was completed in 1935 due to the highest population density of the area covered (Krmac 2013). This is a spring that was hydrologically well investigated and planned as a water intake to supply Trieste as early as 1870. Its minimum capacity was estimated at 200 L/s, of which 60 L/s was planned for supplying water to the low coastal zone and 30 L/s for re-pumping water for Dekani and the Pridvor – Korte ridge above Izola in 1987. The aforementioned intakes on the Rižana (Figure 9.2) and Sv. Ivan springs represent not only exceptionally valuable groundwater intakes, which even today are highly important in terms of water supply, but are also extremely valuable architectural achievements that have their value as parts of Istria's cultural and architectural heritage.

Figure 9.2: Water intake at the Rižana spring (Photo: Josip Rubinić).

The so-called "Military Water Supply System" was built simultaneously with the public, civil water supply system. It lifted water from the Sv. Ivan spring by means of two piston pumps by as much as 950 m (which due to exceptionally high pressures is rare even nowadays) to the Žbevnica reservoir, and than utilised gravity to supply the then border area all the way from Hrpelje – Kozina to Klana and Mučići.

Unrelated to this "military water supply system", but very much in relation to the military and the analysed area of the Podgrajsko podolje, mention should also be made of a special military-purpose water supply system built during World War II with a water intake of 100 m below ground level, from the Dimnice pit. This is a pit whose entrance is located at 567 m above sea level, whose investigated length is 8 km, which is 180 m deep (Anon 2010), and along whose lower horizon the underground portion of the Brkini watercourse flows on its way towards the Rižana spring. At the bottom of the pit German troops built an intake whose remains can still be seen (Figure 9.3), but which was soon abandoned after World War II (Malečkar 2004).

By the end of World War II, nearly 80% of the population of Istria had access to potable water since soon after Buzet the towns on the western coast of Istria also started getting water from the Istrian Water Supply System (Doblanović 2013), which also included other springs such as the karst springs of Gradole (1969) and Bulaž (1988), the Butoniga reservoir (2002) in the Croatian part of Istria and the springs/intakes Bužini and Gabrijeli in the Dragonja Valley, and since 1987 also the intake of up to 240 L/s of groundwater near the Rižana spring itself (Ravbar 2005). Work on the development of the water supply system was carried out continuously, with occasional interruptions due to events such as World War II, the separation of the Croatian and Slovenian states in the early 1990s and the war in Croatia soon after that. Today, water from the Istrian and Rižana water supply systems is brought to over 99% of the population of Istria, including the residents of remote, less accessible rural areas. However, such a high supply ratio does not mean that the problems of water supply in Istria have been resolved. Because of wide variations in consumption (during the summer tourist season consumption in coastal areas exceeds the needs during the winter several times over), there are seasonal water shortages and reductions during extremely dry years (recorded in 2012). With the exception of the Rižana, no environmentally acceptable flow or biological minimum has been imposed on the springs that are in use, and no alternative solutions such as runoff-control reservoirs have been implemented so that critical dry periods occur on the Mirna River in periods of drought with parts of the watercourse running dry. It is also necessary to increase the level of security of water supply by better connecting springs due to the risk of occasional pollution accidents, particularly those associated with transport, such as have already occurred in several cases (Kogovšek 1995; Urumović et al. 1999), but also for reasons of optimum use of the available water.

Figure 9.3: Remains of the water intake at the bottom of the Dimnica pit (Photo: Franci Malečkar).

Conclusions

Water in the karst areas has always had a special significance for their people for the very reason that it is less accessible. The issue of water supply has found its place not only in the daily life of the inhabitants of the area of Northern Istria analysed in this paper, but also in legends and myths, and it is also part of their cultural identity. The development of water supply has greatly changed the life of the population, but there is still a special relationship that needs to be nurtured not only for cultural reasons, but also for the sake of caring about the protection of karst aquifers. The waters of the high karst areas are of great importance for the water supply of the Istrian peninsula because several very significant springs – Sv. Ivan and Bulaž on the Croatian side and the Rižana spring on the Slovenian side – are fed from this area. The karst areas in the Northern Istria, the so-called Istrian Karst, are characterised and defined by a relatively meagre network of surface water courses and a predominantly underground runoff component, their being part of the zones of sanitary protection of drinking water sources, and centuries of depopulation, which reduces to an extent the traditional anthropogenic pressures on water quality. On the other hand, however, the development of transport infrastructure, the increasing use of protective equipment in agriculture and the development of the water supply network itself has also increased the risk of groundwater contamination in those areas, which for a long time were not part of regional water supply systems.

The development of regional water supply systems, which began in the 1930s with the springs in the analysed area of Northern Istria, and which has now reached over 99% of the population supplied with water on both sides of the border, has improved living and sanitary conditions in the region of Istria and the Slovenian coast, which, however, has not reduced concerns about ensuring sufficient quantities of water of suitable quality for the current and future water supply of the population. Namely, due to the ongoing global changes/climate variations resulting in negative trends in terms of the availability of water for water supply and other purposes, as well as the implemented technical interventions related to water supply and water course regulation, the significance of available water resources is increasing. Given the sensitivity of the karst groundwater aquifers and the declining water resources, there is a need for implementing adequate protection measures. It is therefore necessary to constantly review and upgrade both the implemented systems and the mechanisms for managing water resources, with special emphasis on ensuring adequate quality. A special role and responsibility in this respect lies with the residents of the karst areas that feed the aquifers of the water springs in the karst.

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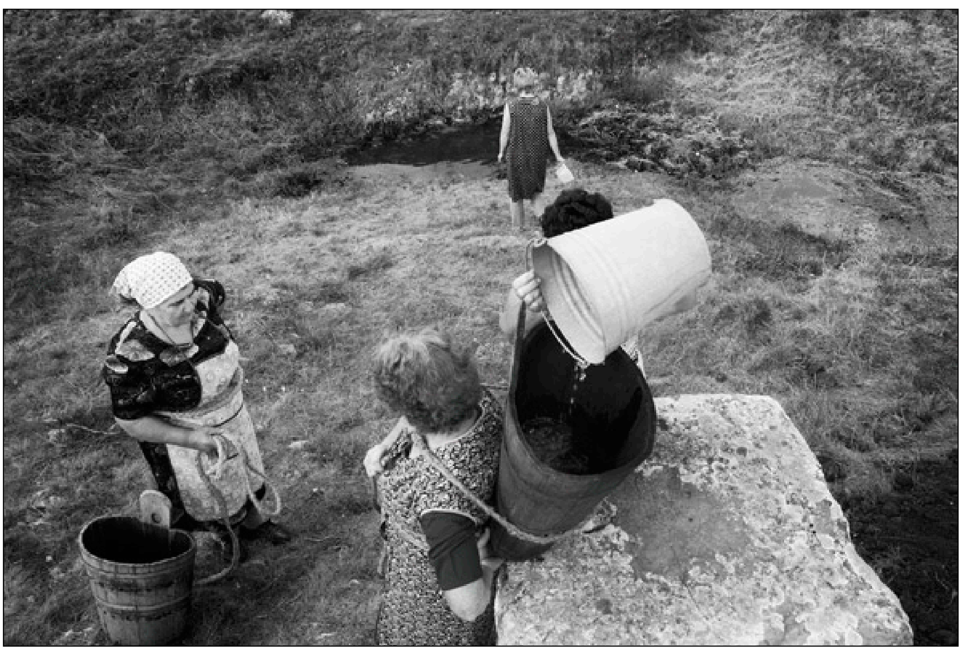

Photo from "Water - Life!" in Istria competition; author: Doriano Orbanić

Photo from "Water - Life!" in Istria competition; author: Kristian Macinić

III. KARST WATER RESOURCES MONITORING

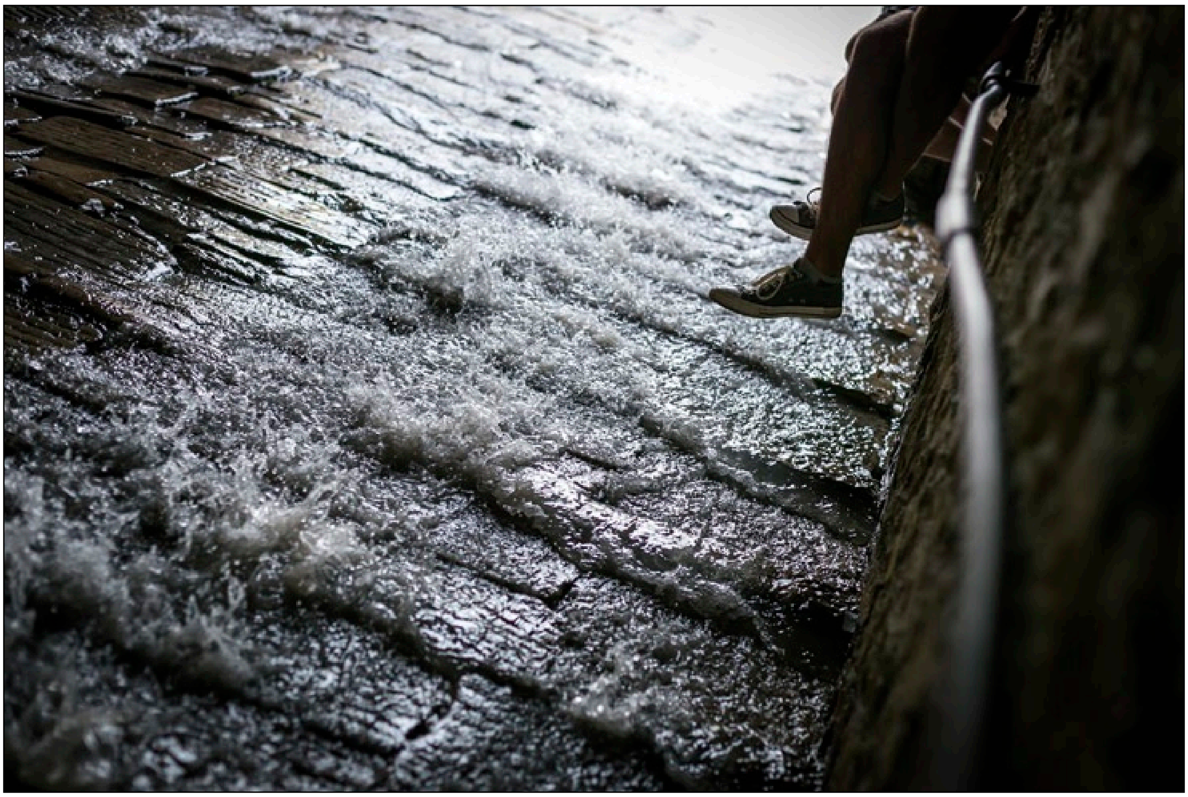

Photo from "Water - Life!" in Istria competition; author: Julien Duval

HYDROLOGICAL CONDITIONS

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Introduction

Hydrological conditions have an important effect on the quality of karst water. This dynamic is reflected in the status and changes to the hydrochemical properties of groundwater in karst (Drever 1997; Appelo & Postma 2005; Ford & Williams 2007; Goldscheider & Drew 2007; Krešić 2009; Krešić & Stevanovič 2010; White 2010; Kogovšek 2012) and in the status of the biological and microbiological composition of the water, subterranean karst spaces and ecosystems (Chapelle 2001; Pronk et al.2006; Romero 2009, Bonacci et al.2009; Culver & Pipan 2009; Culver & Pipan 2014). The system of karst subterranean fissures and speleological structures such as caves, estavelles, ponors and springs are the hydrologically most active parts of karst aquifers. They account for the most dynamic changes involving the disappearance of water from the surface to the subterranean. At the same time they are also a habitat of extraordinary biological value, and it is hydrological conditions that most affect their biological composition.

The issue of water supply is the predominant subject of the research conducted under the ŽIVO! project. So hydrological monitoring in the observed area of the Northern Istria is planned in such a way that we used it to monitor the state of groundwater in locations where it flows out of the system, that is, in the large karst springs that are used for supplying water in Istria. We also monitored the state on other selected surface watercourses in the catchments of these springs, and at certain other permanent and seasonal springs that are hydrologically linked to these main karst springs or their aquifers and catchments. Moreover we monitored the state in two caves representative of the conditions in the subterranean parts of the observed space. In researching and analysing the collected data, alongside the results of our own measurements under the ŽIVO! project we also used data from other institutions, such as the Croatian National Hydrometeorological Institute (DHMZ) in Zagreb, the Slovenian Environment Agency (ARSO) in Ljubljana, Rižanski vodovod of Koper, Istarski vodovod of Buzet, Istramet of Pazin and the Buje Speleological Society, which performed monitoring in the stated caves for the project.

At the main karst springs covered by the research (the Rižana spring, which is used by the Rižana Waterworks in Koper, the Bulaž and Sv. Ivan springs, which are used by the Istrian Waterworks of Buzet), hydrological monitoring has been set up and operating for a number of years, and provides the basis for our knowledge of the basic hydrological properties of the springs.

Based on these data the mean annual flow of the Rižana spring is 3.9 m^3s^{-1}, to which should be added around 0.2 m^3s^{-1} of water used for the drinking water supply. The total flow of the Sv. Ivan spring is around 0.87 m^3s^{-1} and of Bulaž around 1.54 m^3s^{-1}. The Sv. Ivan spring provides an average of around 0.17 m^3s^{-1} of water pumped out for supply purposes. The Bulaž spring is a back up pumping station and is used only in exceptionally dry years, with the mean annual quantity average of pumped water totalling just 0.01 m^3s^{-1}. In favourable hydrological conditions, and even in summer dry periods, the maximum quantity of water pumped from the above-mentioned sources is considerably higher – the maximum quantity of water pumped from the Rižana is 0.24 m^3s^{-1}, from the Sv. Ivan spring up to 0.31 m^3s^{-1} and from Bulaž up to 0.20 m^3s^{-1}.

The idea of the ŽIVO! project was to research the behaviour of water springs and to study the dynamic of change in water quality at those springs and associated watercourses in the wider region on the appearance of greater water quantities following a long dry period. There was a similar background to the previously performed analysis of very condensed monitoring of hydrological conditions and water quality in the autumn of 2001. It was performed on the basis of research and monitoring conducted on the hydrological conditions and water quality in a previous project focused exclusively on the Mlini spring (Kogovšek et al. 2003; Rubinić et al. 2006; Diković 2008). The results of this analysis have shown that regular monitoring of the state of water quality at sources performed periodically with for the most part very long intervals (once a month or even less frequently) does not offer an insight into the actual state of water quality, especially with such sudden changes when the run-off of contaminants is most intense.

For this reason the ŽIVO! project has been conducted in a way where once hydrological monitoring was set up, it was possible to monitor actively the status of hydrological conditions and indications of possible changes owing to intense precipitation after a long dry period. Owing to previous atypical hydrological years in 2012/2013 and 2013/2014, which followed the extreme dry year of 2011/2012, during the period of the ŽIVO! project only one such situation arose. After a distinct hydrological year in 2014, at the end of the observation period, in the second half of June 2015, in which drought conditions predominated, there was intense rainfall.

The peak water pulse resulting from precipitation observed on the night from 23 to 24 June 2015 was noticed very intensely at the Sv. Ivan spring, along with extreme turbidity of the water. At the Rižana spring, too, where a minor peak was recorded a week earlier, the precipitation event also contributed to a change in the state and regime of water outflow from that source. The smallest effect from this precipitation water of 23 June 2015 was observed at the Bulaž and Mlini springs, and also in the monitored surface phenomena of the Butori and Podgaće sinking streams, where there were practically no surface influences relative to the previous lengthy dry period. On the other hand the abundant rainfall changed the level of groundwater in the Rašpor ponor at Čičarija/Ćićarija and to a lesser extent at the Vinicio Potleca ponor by the village of Marušići on the Zrenjska plateau. A major change in the hydrological status during this rainy period could also be observed at the secondary spring of Sv. Ivan – for a short time, just a few hours, the seasonal spring of Tombazin flowed, while the Pivka spring was not at all active. That source was inactive not just at that particular time, the end of June 2015, but throughout the monitoring period. After monitoring water quality during the situation in question, an analysis was made of the basic hydrological properties of the monitored water phenomena during the monitoring period – in the first half of 2015 with special emphasis on the phenomenon of high water levels in the second half of June this year.

Monitoring climatological and hydrological properties

Monitoring of the state of climatological and hydrological conditions in the observed period (first half of 2015) under the ŽIVO! project was tied to the existing network of stations, and also to the newly established monitoring under the project, especially on the Croatian side, where more numerous water phenomena are monitored hydrologically. Fig. 10.1 shows the positions of measuring stations. Climatology stations are managed by the Slovenian Environment Agency ARSO (Dekani, Movraž, Podgrad and Škocjan), and by the Croatian DHMZ (Lanišće, Vela Učka, Filarija and Momjan). In addition to these we used data from the automatic stations operated by the Istramet association (Oprtalj and Lanišće) and the stations at Sv. Jelena and Vodice, which were set up as part of the ŽIVO! project. The hydrological analyses used ARSO hydrology agency data from the Rižana - Dekani and Rižana - Kubed stations, and DHMZ data from the stations at Bulaž, Sv. Ivan and Butori (Fig. 10.2). We also took into account data on the water level at the Rižana spring collected by the Rižana Waterworks in Koper, and data on water turbidity recorded at the Sv. Ivan spring by the Istrian Waterworks of Buzet. The ŽIVO! project also involved setting up a large number of new limnigraphic stations (continuous monitoring of the level, temperature and electrical conductivity of water), where there were no other active hydrological stations: the Mlini spring, Sv. Ivan spring (secondary), Tombazin spring, the Pivka spring, Podgaće – before the ponor – and at locations where DHMZ conducts continuous limnigraphic monitoring of the variation in water levels, temperature and electrical conductivity (Bulaž spring, Sv. Ivan spring, Butori), and at the Rižana spring. As part of the project, in cooperation with the caving society SD Buje we also set up limnigraphic monitoring of the level, temperature and electrical conductivity of water at two speleological facilities – in the cave/ponor of Rašpor and Vinicio Potleca by the village of Marušići. Owing to the short period of time needed for regional checking of precipitation from the DHMZ and ARSO stations, data captured from those stations for 2015 remain verified only on a preliminary basis.

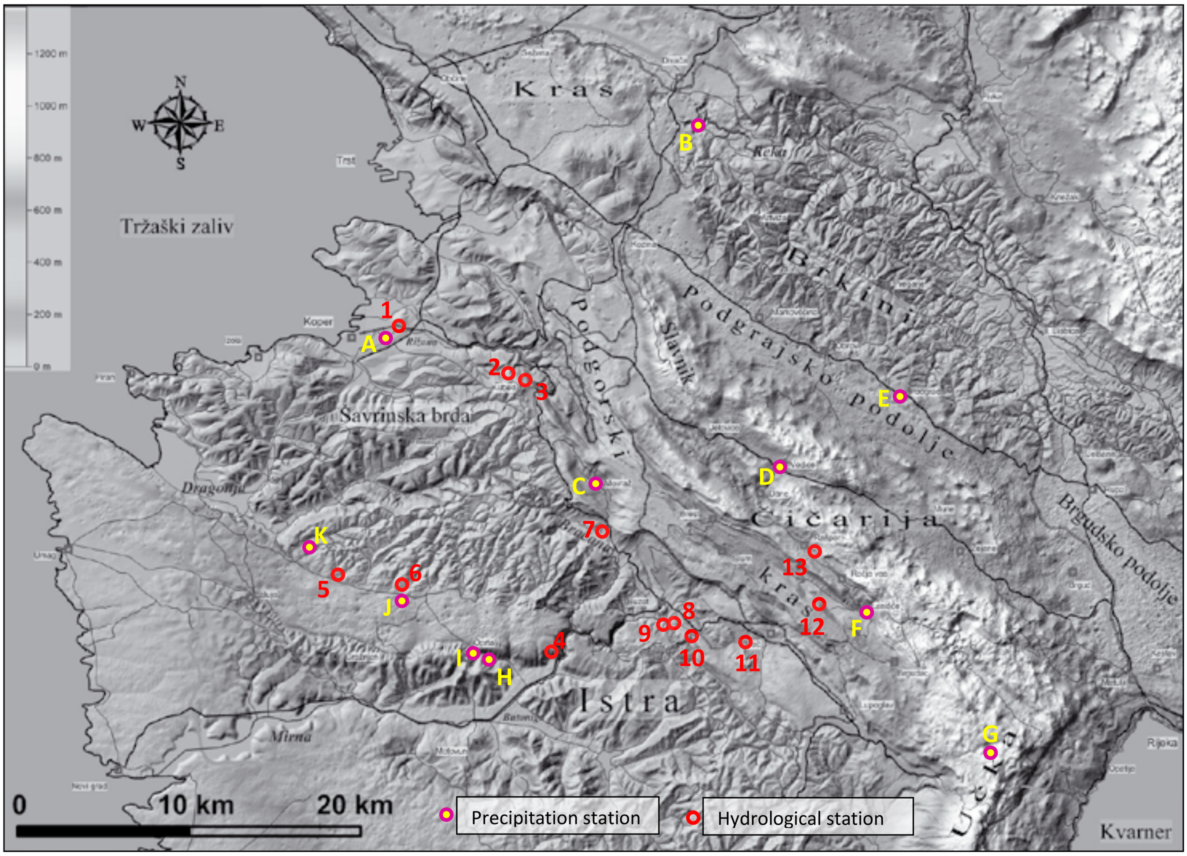

Figure 10.1: Area of research indicating rainfall and hydrological stations: rainfall stations: A – Dekani, B – Škocjan, C – Movraž, D – Vodice, E – Podgrad, F – Lanišće, G – Vela Učka, H – Sv. Jelena, I – Oprtalj, J – Filarija, K – Momjan; hydrological stations: 1 – Rižana - Dekani, 2 – Rižana - Kubed, 3 – Rižana spring, 4 – Bulaž spring, 5 – Vinicio Potleca ponor, 6 – Butori, 7 – Mlini spring, 8 – Sv. Ivan spring, 9 – Sv. Ivan secondary spring, 10 – Tombazin spring, 11 – Pivka spring, 12 – Podgaće, 13 – Rašpor cave.

Figure 10.2: Butori watercourse: a) limnigraphic station with part of the team the Civil Engineering Faculty of Rijeka (Photo: Igor Ružić), b) Butori waterfall in the area of the ponor (Photo: Josip Rubinić).

Results of monitoring in the first half of 2015

Status of water supply sources (1 Jan. - 30 June 2015)

The last few years prior to setting up the system of monitoring in the area of Northern Istria under the ŽIVO! project were marked by unusual hydrological conditions – the exceptionally wet year of 2010 was followed by a dry period in 2011, which continued even more markedly in the first eight months of 2012. After this came two very wet years – 2013 (in which the very wet last four months of 2012 continued) and 2014. The beginning of 2015 saw the onset of a long, exceptionally dry period, which covered the entire 6-month period of analysed monitoring under the ŽIVO! project. In this period the total quantity of registered monthly precipitation at the Lanišće station, which generally shows conditions in the basin of the Sv. Ivan spring, amounted to just 507 mm, representing only 57% of the average quantity for the long period of 1953–2015. At the Momjan station, which generally shows conditions in the basin of the Bulaž spring, this difference is even greater – in the first six months of 2015 there was a total of 168 mm of rainfall, which is around just 36% of average quantities for this period and represents an absolute minimum for the entire observed period of 1961–2015. The Podgrad station in the catchment area of the Rižana recorded 413 mm of precipitation in the first half of 2015, which is 61% of the average for the period of 1970–2015. Of this, 74.5 mm fell in the night from 23 to 24 June 2015, so the quantity of precipitation in the first five months of 2015 represented only around 50% of the long-term average.

The characteristic of the state of drought prior to the water pulse of June 2015 was assessed by means of an estimate of the probability of the phenomenon of total monthly quantities of precipitation for the first five months of 2015. The total quantity of precipitation, i.e. 429 mm at the Lanišće station, was estimated using the Gumbel distribution function with a probability of a 25-year return period. The assessment of the status at the Momjan station, which registered a total of just 114 mm of precipitation in the first five months, was even more critical, for it exceeds a 100-year return period. Assessment of the previous precipitation in the Rižana basin, where the Podgrad station recorded 277.7 mm in the same period, shows the characteristics of a 50-year return period.

A presentation of the daily quantities of precipitation in the observed period of the first half of 2015 is given in Fig. 10.3. Quantities of precipitation are calculated as an average based on available data on the quantity of precipitation in individual areas of the basins of the analysed the Rižana, Sv. Ivan and Bulaž springs. This also shows registered flows at reference hydrological stations in Croatia and Slovenia, where part of the data was not taken from the competent services but rather, given the short time needed for their primary processing, was determined as part of actual project activities based on regression analyses (associations of data from the Dekani and Kubed stations on the Rižana) and analyses of flow curves.

These presentations show that the phenomenon of precipitation in the stated basins matches in terms of dates, but differs in intensity, being most pronounced in the basin of the Sv. Ivan spring, where daily average precipitation in the observed period was 2.8 mm/day. The least precipitation fell in the basin of the Bulaž spring, where the average was 1.5 mm/day, and in the Rižana basin it was 1.9 mm/day. There are even bigger differences in the reactions of individual sources to the effect of precipitation. The Sv. Ivan spring reacts very quickly to any precipitation over 10 mm, while there is no great difference in the amplitude of the recorded highest flows during a period of observed flood pulse. The reason lies in the fact that in the phenomenon of greater quantities of water owing to the aforementioned possibility of overflow at the Sv. Ivan spring at approximately 2 m^3s^{-1}, as a spillover in the entire area, this activates the Tombazin spring and a number of smaller springs in the direct vicinity of the main spring of Sv. Ivan. At the Bulaž spring we observed the least pronounced phenomena of major flood pulses, specifically owing to the characteristics of the system filling and draining, and also owing to the small quantity of precipitation that fell. Fig. 10.3 shows that in 2015 only one distinctly large flood pulse was registered, at the beginning of February, and that daily precipitation in later periods had less and less effect on flow – partly owing to the increasingly long duration of the dry period and owing to increased evapotranspiration in the basin. Equally, it is clear that the effect of precipitation on the Rižana spring is similar to that at the Sv. Ivan and Bulaž springs: in the first half of 2015 we observed three major flood pulses, but with ever dwindling flow – despite the fact that the last recorded quantities of precipitation during a flood pulse at the end of June 2015 were more pronounced than previous precipitation episodes during major flood pulses.

The maximum registered daily precipitation in the observed period differed greatly by individual area – in the Rižana basin we recorded the maximum precipitation quantity of 75.9 mm, registered right at the time of the selected flood pulse, when as part of the ŽIVO! project we performed detailed sampling of water quality, i.e. in the period between 23 June and 8 July 2015, specifically as a consequence of the precipitation in the night from 23 to 24 June 2015. In the basin of the Sv. Ivan spring the maximum daily quantity of precipitation amounted to 53.1 mm, being registered on 22 February, while at the end of June, during the flood pulse, a daily maximum of 28.2 mm was recorded. In the Bulaž spring basin the daily maximum was registered in the period of the analysed complete 6-month period, and amounted to 29.6 mm, with 23.7 mm being registered on 23 June 2015. In the case of precipitation during the phenomenon of the analysed flood pulse in the basins of the Sv. Ivan and Bulaž springs, this involved the normal phenomenon of daily precipitation which can occur several times a year, while the daily maximum recorded on the Rižana is a somewhat rarer phenomenon with a one-year return period.

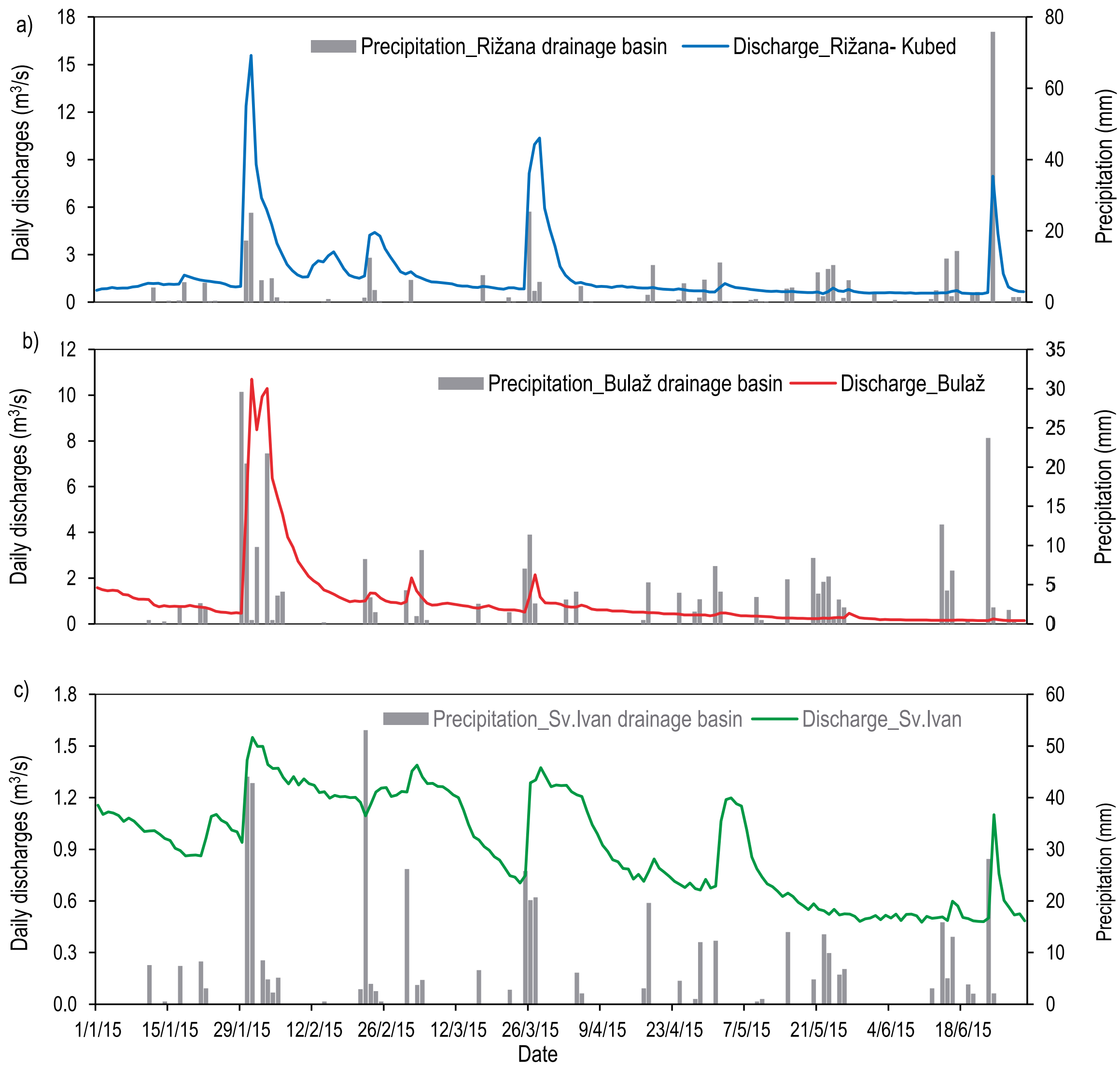

Figure 10.3: Daily quantities of precipitation and mean daily flows in the period 1 Jan. – 30 June 2015 at hydrological stations: a) Rižana - Kubed, b) Bulaž spring and c) Sv. Ivan spring.

The average daily flows during the time of the analysed 6-month period of monitoring are given in Table 10.1. It shows that these are springs that do not differ much in magnitude of average flow in the analysed period, but their amplitude and variation are entirely different. The Sv. Ivan spring showed the least variation in flow, precisely because of the previously mentioned hydraulic limitations regarding the phenomenon of flood pulses at the main source itself, while flow at the Bulaž spring had the highest coefficient of variation precisely because that spring has more frequently the smallest flow. As for registered maximum values of mean daily flows – both in the entire 6-month analysed period and at the time of the major water pulse in June – these involve at all springs the normal phenomena of high water levels, which are common throughout the year.

Table 10.1: Basic typical statistical indicators of recorded mean daily flows in the period 1 Jan. – 30 June 2015 at the analysed springs in Northern Istria.

Spring/Statistical indicators	Rižana	Sv. Ivan	Bulaž
Mean (m^3s^{-1})	1.68	0.918	1.01
St. deviation (m^3s^{-1})	2.12	0.302	1.62
Coeff. of variation	1.26	0.329	1.61
Max (m^3s^{-1})	15.58	1.550	10.70
Min (m^3s^{-1})	0.534	0.476	0.137

State of other hydrologically observed water phenomena (1 Jan. – 30 June 2015)

Hydrological characteristics were also monitored on other watercourses in the observed area. Fig. 10.4 shows the results of monitoring the water level on all such locations with long enough duration of measurement in the 6-month period, while Table 10.2 shows the basic statistical indicators of the recorded fluctuations of water status in that period. It is clear that there is a similarity in the rapidity of response to individual precipitation episodes for almost all the observed watercourses, except for the intermittent spring of the Pivka, which did not respond to precipitation and where according to measurements a dry period prevailed throughout. Very minor changes were also recorded at the Butori watercourse and in the cave or ponor of Vinicio Potleca in the area of the Zrenjska plateau. The reason for this was the marked dry period in this area, and partly also perhaps because a gauge was placed on this measurement profile that was intended for a greater range of variation in groundwater. The dry period and minor fluctuations meant a reduction in its accuracy. On the other hand in the cave or ponor of Rašpor we observed major fluctuations in the water level, which did not result from the inflow of precipitation water directly into the ponor area, but chiefly from their rapid infiltration after the rain.

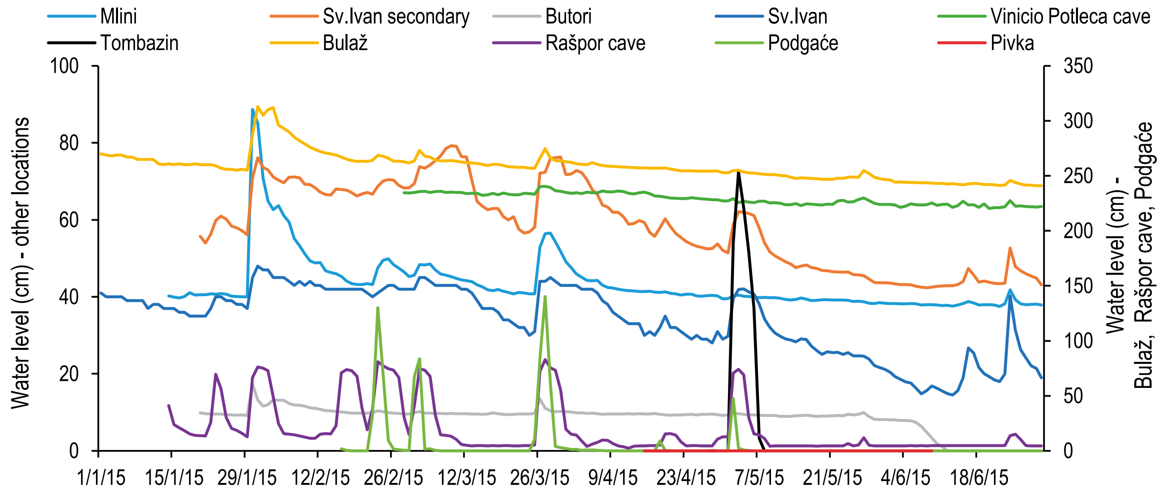

Figure 10.4: Results of monitoring the water level in the period 1 Jan. – 30 June 2015 at selected measuring locations in Northern Istria.

Table 10.2: Basic statistical indicators of fluctuations in the state of water in the first half of 2015 at selected locations in Northern Istria.

Station/ Stat. indicators	Sv. Ivan	Sv. Ivan secondary	Bulaž	Mlini	Butori	Podgaće	Tombazin	Pivka	Vinicio Potleca	Rašpor
Monitoring period (year 2015)	3 Feb - 30 Jun	20 Jan - 30 Jun	12 Feb - 30 Jun	14 Jan - 30 Jun	20 Jan - 30 Jun	16 Feb - 30 Jun	15 Apr - 10 Jun	15 Apr - 10 Jun	28 Feb - 30 Jun	14 Jan - 30 Jun
Mean (cm)	33.0	58.5	245.5	43.4	8.4	5.7	5.1	0	65.4	19.8
St. dev. (cm)	9.3	11.3	8.5	5.4	3.5	24.8	16.9	0	1.6	23.7
C. of var.	0.28	0.19	0.03	0.12	0.42	4.33	3.34	/	0.02	1.19
Max (cm)	47.0	81.6	279	117.3	23.4	184.1	76.4	0	69.8	98.6
Min (cm)	9.6	40.8	239.3	34.8	0	0	0	0	62.4	2.1

Analysis of state during major flood pulse at the end of June 2015

The last item in the hydrological analysis – but extremely important for the ŽIVO! project – is a presentation of the state of hydrological conditions during the flood pulse of June 2015, when several series of water quality sampling were carried out. At the Rižana spring, two such series of sampling were carried out – upon the initial change in the state of the spring with higher water on 16–19 June 2015 and during the flood pulse from 23 June – 8 July 2015. For the other sources and locations, sampling was performed only during the aforementioned major flood pulse at the end of June 2015.

The results – a comparative presentation of hydrological conditions by individual basin of analysed water sources for the period 14 – 30 June 2015 – are presented in Figs. 10.5 – 10.7. Alongside the recorded hourly data on precipitation from the nearest rain gauge station covering the specific basin, the figures also show hourly data on the water level at individual measuring points.

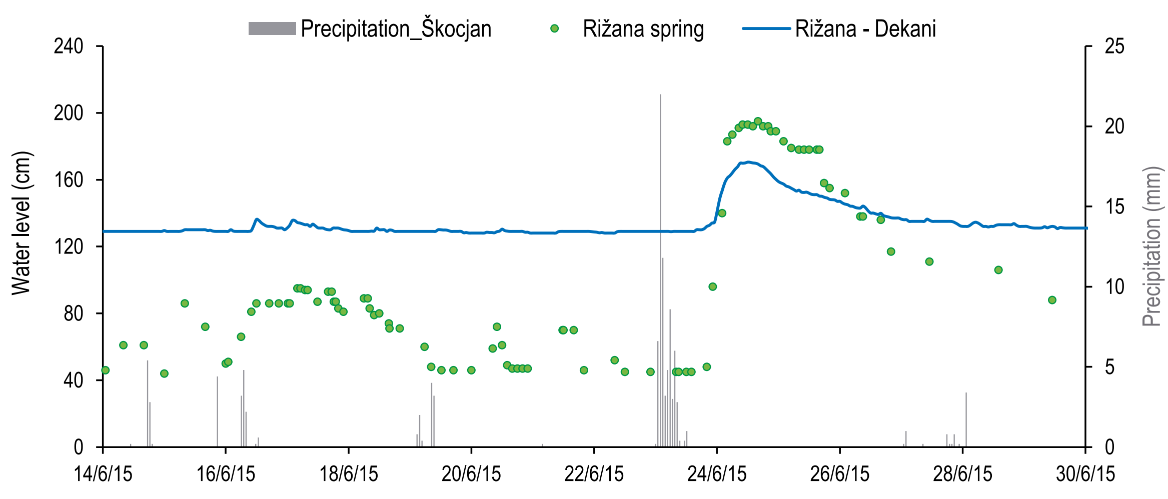

Figure 10.5: Rižana basin – flood pulse in the second half of June 2015 with recorded hourly data on precipitation from the Škocjan station.

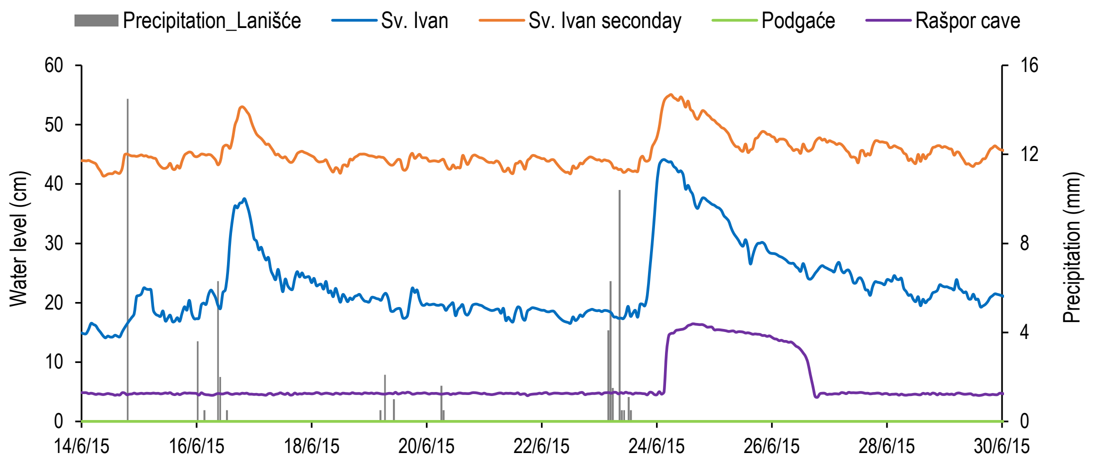

Figure 10.6: Sv. Ivan spring basin – flood pulse in the second half of June 2015 with recorded hourly data on precipitation from the Lanišće station and hourly data on the water level from the stations at the Sv. Ivan spring, the secondary Sv. Ivan spring, the Podgaće ponor and Rašpor cave.

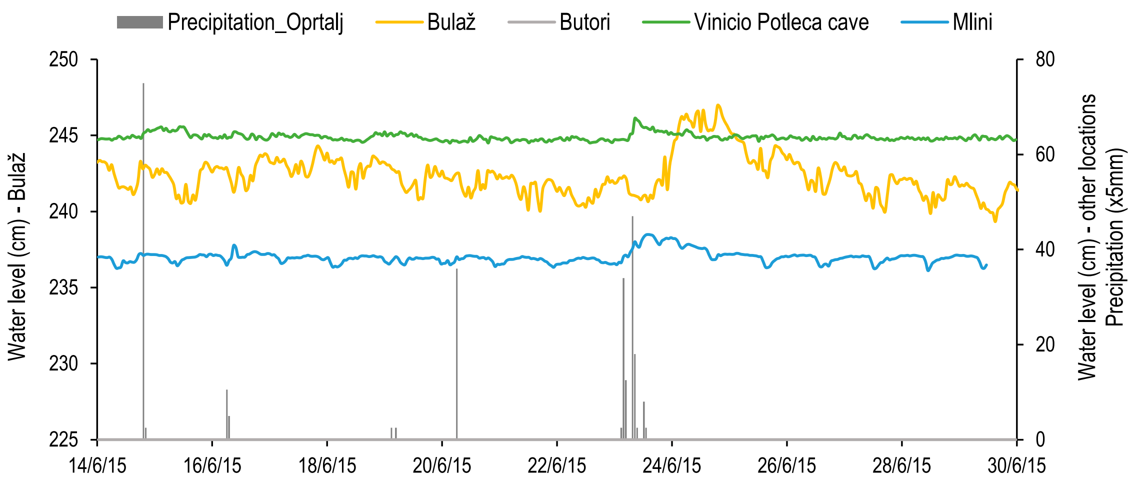

Figure 10.7: Bulaž and Mlini springs basins – flood pulse in the second half of June 2015 with recorded hourly data on precipitation from the Oprtalj station and hourly water level data from the stations at the Bulaž spring, Butori watercourse, ponor/cave of Vinicio Potleca by the village of Marušići and the Mlini spring.

The data presented for the Rižana spring (Fig. 10.5) show that precipitation between 14 and 16 June 2015 caused a brief rise in the water level at the actual catchment of the Rižana spring of 40 cm. Owing to the previously low level, this growth at the spring caused very little change to the level of the watercourse. More intense precipitation was recorded in the night from 23 to 24 June 2015, with a maximum hourly quantity of precipitation of as much as 22 mm. This caused a more pronounced change to the river level – both at the spring itself (the water level rose more than 1.5 m, with the highest flow on the Rižana - Kubed section reaching around 8 m^3s^{-1}) and at the Rižana - Dekani hydrological station, where these changes show a 4-hour time lag relative to the source.

In the Sv. Ivan basin (Fig. 10.6) we can see that the precipitation of 16 June 2015 caused a change in the water level both at the main Sv. Ivan spring and at its secondary source, although there was greater intensity of change following the precipitation of 23 June 2015. This precipitation indeed caused a rise in the water level in the Rašpor ponor, but did not affect the surface flow in the Podgaće ponor. Alongside water sampling at this location, samples were taken right from the Podgaće source, which was active throughout. Its estimated yield is just a few dL/s, and its water flows out and drains towards the area of the ponor at Podgaće. The source of the Pivka was not active, while the Tombazin spring became active for a few hours on 24 June 2015.

The Bulaž spring and its basin (Fig. 10.7) yielded the weakest response to the precipitation event at the end of June 2015 owing to the previous longest dry period and the low intensity of the precipitation recorded at that time in the area of its basin; a similarly low response was recorded at the Mlini spring, for which the data are included in the data collected for the Bulaž spring basin. We can see, therefore, that the change owing to precipitation on 23 June 2015 also affected the groundwater of the Vinicio Potleca ponor, but not the surface water of that basin and the Butori basin, where the limnigraph recorded a state of drying out. The periodic daily fluctuations recorded at the Bulaž spring, and to a lesser extent at certain other measuring points, are the result of two physical phenomena. On the one hand the pressure compensation on the measuring probes for monitoring the water level flowed from common gauges (a baro-diver) which were several kilometres away from the individual measuring points. On the other hand in the case of the Bulaž spring, the daily fluctuation resulted from daily variations in the state of the water owing to wind and a different dynamic of evaporation through the day and at night from the lake, which is at the same time a pumping pool, in which a fluctuation in the state of the water was also observed.

It should be underlined that alongside this separate part of the analysis of recorded data on fluctuations in the state of the water and flow at selected locations in the Northern Istria related to the analysis of the flood pulse at the end of June 2015, data from other hydrological observations (water temperature and electrical conductivity, and at the Sv. Ivan spring also the turbidity of the water) are presented in subsequent chapters of the monograph.

Conclusion

The hydrological monitoring performed as part of the ŽIVO! project in the first half of 2015 and the results obtained, combined with the results of long-term observations from meteorological and hydrological stations, alongside the sampling of water quality during the flood pulse of June 2015, provided relevant assessments of the hydrological state of the analysed watercourses. That flood pulse arose in consequence of the intense precipitation after half a year of marked dry period in the analysed basins of the Rižana, Sv. Ivan and Bulaž springs. The precipitation and consequently the effect on the springs were more intense in the Sv. Ivan and Rižana basins, and to a considerably lesser extent in the Bulaž basin, which owing to a previous dry period had the lowest reserves of water in its karst aquifer. This was the last relatively intense precipitation before the onset of the normal summer dry period, in conditions of increased evapotranspiration, such that there were not major changes to the state of flow in sinking streams. The intensity of the changes in the hydrological state of springs was for this reason also lower than it would have been if there had been a flood pulse in the autumn, coming after a long summer dry period and with the even more marked precipitation usual for that season. However, the results obtained enable an interpretation of the recorded changes in the quality of water and its microbiological system in given conditions, and represent a starting point for weighing up similar analysis in different hydrological conditions.

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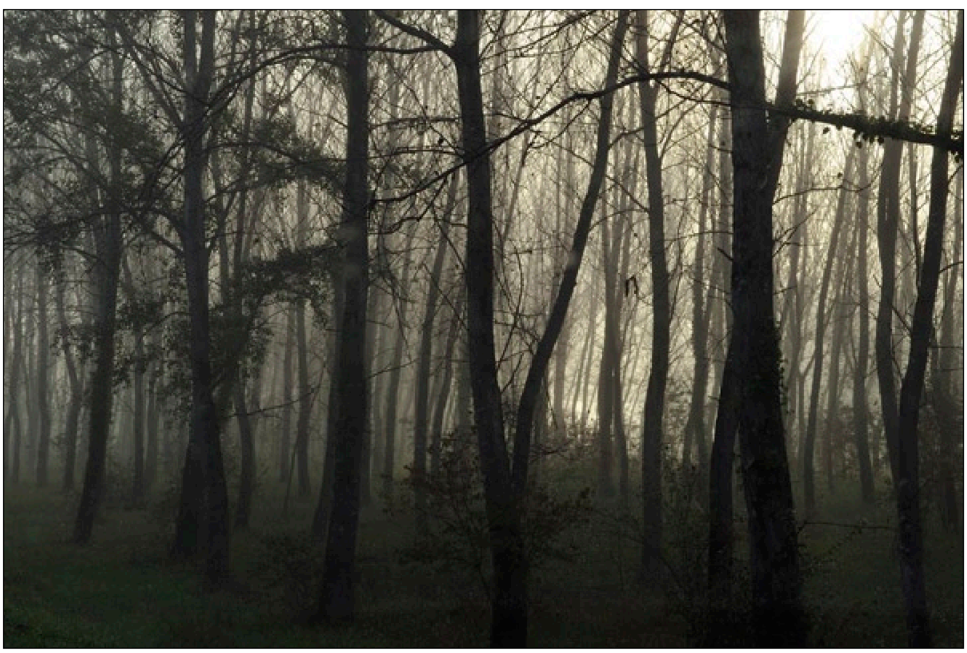

Photo from "Water - Life!" in Istria competition; author: Julien Madračević

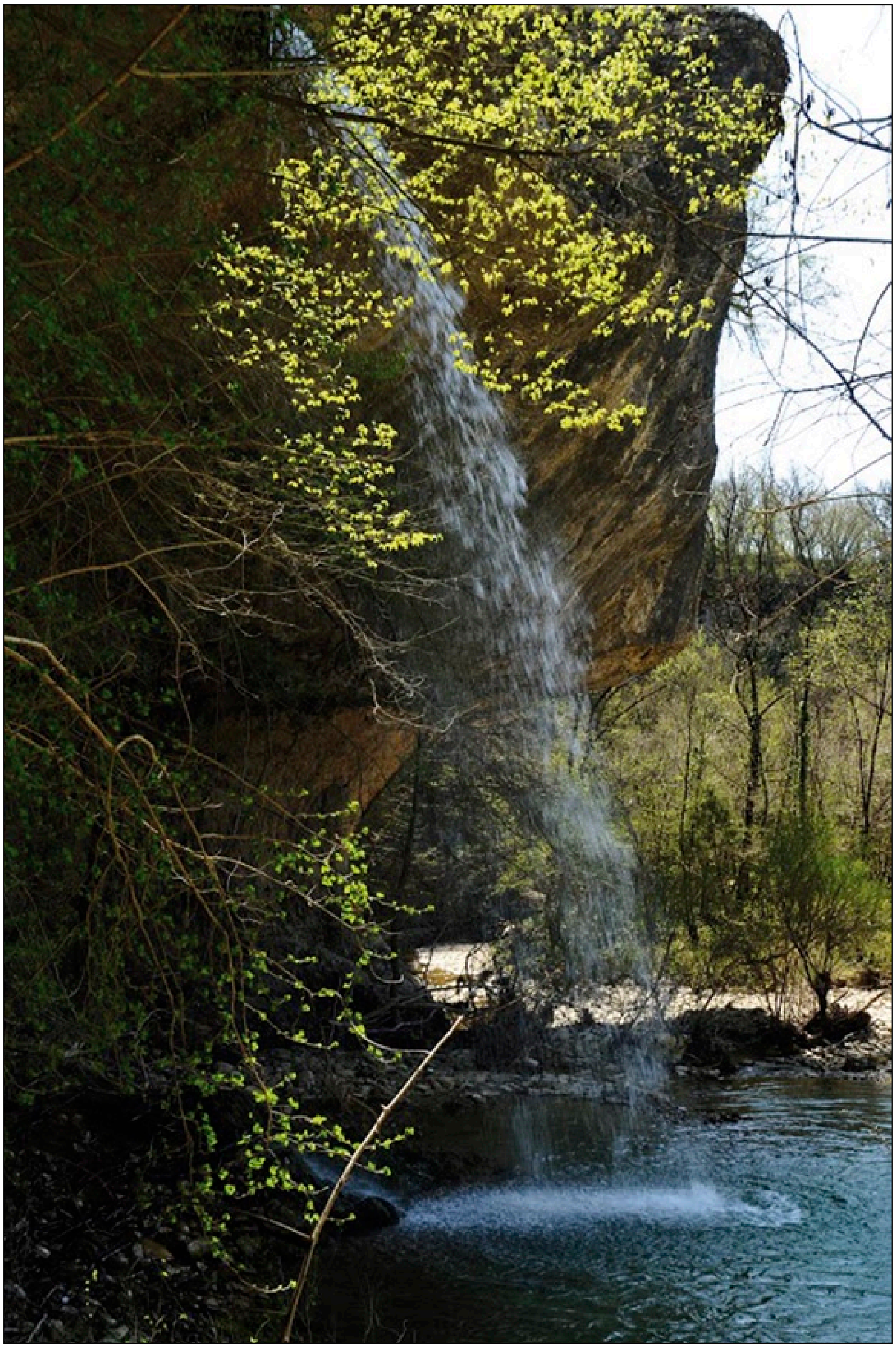

Photo from "Water - Life!" in Istria competition; author: Đani Celija

GROUNDWATER QUALITY IN CHANGING HYDROLOGICAL CONDITIONS AND COMPARISON WITH THE RESULTS OF LONG-TERM MONITORING

Sonja Diković, Alenka Koželj

Introduction

Karst groundwater is tha main natural water resource in the area included in the ŽIVO! project. Although stable water flow and quality is desired for the water supply and other general water use purposes, karst springs often deviate from these requirements. Due to the network of conduits and fissures created through chemical dissolution, which permit fast and occasionally turbulent water flows, all contaminants can enter the karst aquifer through the thin soil layer or via ponors and can spread quickly, particularly upon changes in hydrological conditions. Rapid changes in flows are accompanied by changes in the chemical composition of the water, which is time and space dependent (Mayer 1999; Smith & Wahl 2003; Katz et al. 1998; Toth 1998). During periods of rain the inflow of rainwater and surface water increases dramatically, and therefore the quantity and velocity of the water also increase significantly, which leads to the mixing of water from various sources and shorter retention in the aquifer.

Data on groundwater quality, in addition to data on the natural chemical composition, which depends on the hydrogeochemical composition of the layers through which the water flows, also include data on pollutants and changes due to human influences. The capacity of a system to accumulate or eliminate pollutants is thus dependent on the layers which form the aquifer, the course of the flow and the nature of the pollutants themselves (Vesper & White 2004). The basic groups of pollutants are formed by water soluble compounds, organic or inorganic compounds which move together with the mass of water, organic compounds which are poorly soluble in water and whose density is lower than that of water, and whose motion depends on the velocity of the water layer, organic compounds which are poorly soluble in water and whose density is greater than that of water and which primarily build up in sediment, pathogenic microorganisms, metals and general waste of various size, shape and origin.

Of particular importance in the transport of pollutants is the mobile solid phase (McCarthy & Zachara 1989), where contaminants adsorbed onto particles outflow at springs during heavy precipitation events. The sediment in the karst aquifer – both allochthonous and autochthonous – is also mobile, and is a vector for the transport of nutrients and other pollutants, in particular metals, hydrocarbons, pesticides and bacteria (Vesper & White 2003).

The water quality of karst springs included in the ŽIVO! project is at present monitored using long-term monitoring, which is carried out occasionally with varying frequency (once a month or less) in time periods planned in advance, which are usually aligned with seasonal changes. The goal of the project was therefore to focus on a detailed research of the occurrence of flood pulses after dry periods of several months, and to monitor the water quality at short intervals and compare this with the results of the long-term monitoring.

The monitoring of the measuring sites was set up in different ways, since it was necessary on one hand to closely monitor the chemical changes over time, and to monitor spatial changes on the other. In order to monitor water quality over time, the Rižana spring on the Slovenian side was selected, and altogether 36 samples were taken for chemical analysis. For spatial measurements of changes in water quality, springs on the Croatian side were selected: the Sv. Ivan (8 samples), Bulaž (7 samples) and Mlini springs (5 samples), and the small springs Sv. Ivan – secondary, Tombazin and Podgaće and the Rašpor and Vinicio Potleca ponors near the village of Marušići and the Jama pod Krogom cave near the Mlini spring. At the small springs and ponors, 1-3 samples were taken for chemical analysis, depending on the measuring site and the technical capacities for sampling.

All the sample analyses were performed in compliance with the standard procedures and accreditation document by the project partner National Laboratory of Health, Environment and Food. The ionic composition of the water samples was measured using various laboratory analyses (hydrogen carbonate, total and dissolved calcium, total and dissolved magnesium, chlorides, sulphates), silicates, oxidation capacity, BOD, TOC, nutrient indicators, ammonium, nitrates, phosphates and total phosphor, mineral oils and metals (iron, manganese, aluminium – total and dissolved) and various groups of pesticides (organochlorine and organophosphorus pesticides, triazines, urea-based pesticides). Using CT and CTD Divers, continuous measurement was taken of water temperature and electrical conductivity at the Rižana, Sv. Ivan, Bulaž, Mlini, and Sv. Ivan-secondary springs, the Podgaće spring near the ponor and the Rašpor and Vinicio Potleca ponors. At the Sv. Ivan spring, Istarski vodovod d.o.o. (the Istrian water supply system) in Buzet also used an automatic turbidimeter to make continuous measurements of turbidity.

Rižana spring

The Rižana spring is extremely important for Slovene Istria, as it is the main and only water supply source for the coastal region. The organoleptic properties of the water at the spring are acceptable, but it is unrefined water which requires processing in order to be potable. The water turbidity at the spring is usually between 2 NTU and 6 NTU, and the average turbidity for the period 2010 – May 2015 is 3.9 NTU. During rainy periods the turbidity can increase to 10 NTU or even as high as 70 NTU. The average annual water temperature is between 10 °C and 12 °C. It is classified as moderately hard water (11 °dH–15 °dH or 195 mg $CaCO_3$/L–263 mg $CaCO_3$/L). Under normal hydrological conditions during the year there are no significant changes in the water's chemical composition.

The water's ionic composition has not significantly changed over the years of research, but there are seasonal variations relating to changing hydrological conditions. The average electrical conductivity of the water for the period 2010 – February 2015 is 390 µS/cm, the levels fluctuated within an interval of (390 ± 70) µS/cm.

The purpose of this research is to identify changes in the quantity and quality of water at the source under special hydrological conditions – after a heavy rainfall following a drought of several months. The observed hydrological period includes two flood pulses, the first of which lasted from 16 to 19 June 2015 with the water level increasing from 51 cm to a maximum measured 95 cm, before returning to the initial level. During this period there were no significant appearances of turbidity as a consequence of sediment mobility. In all of the data on turbidity, with small fluctuations of less than 3 NTU there are no visible changes in the appearance of the water, while conductivity increased, by 80 µS/cm or 21.1% with respect to the initial level. This indicates that during this period the water at the spring was more mineralised than during the drought period, when the water level was low and stable.

A second flood pulse occurred from 24 to 29 June 2015, during which the water level increased by a factor of four (maximum 195 cm) with respect to the initial level, with a turbidity of 13.9 NTU. Only minor oscillations in conductivity with levels (380 ± 15) µS/cm were recorded. A more detailed analysis of conductivity and turbidity changes during the flood pulses are presented in Chapter 12.

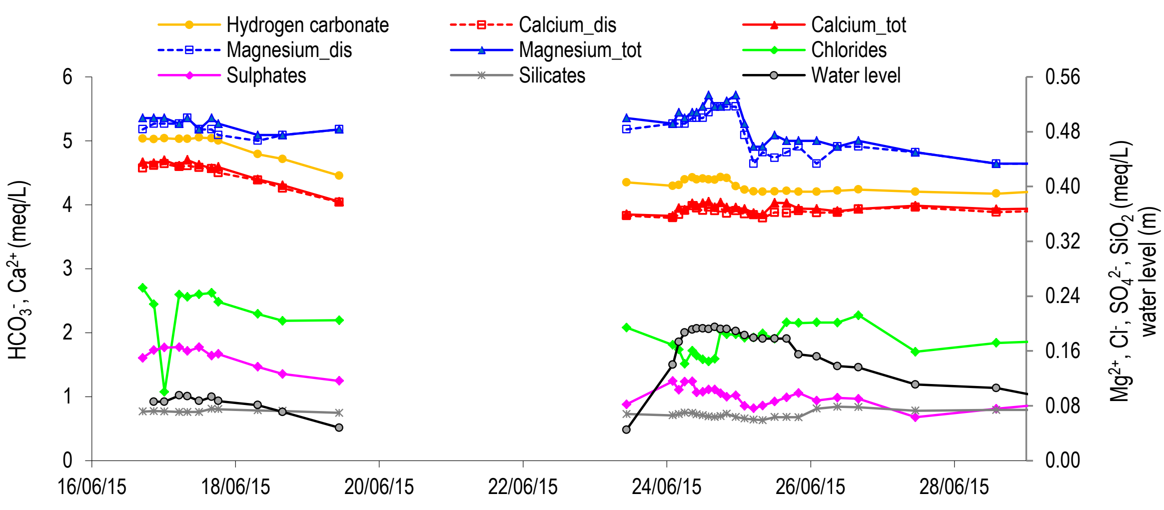

Figure 11.1: Changes in ionic composition during the two flood pulses from 16 to 29 June 2015 at the Rižana spring.

The predominant ions in the water at the Rižana spring are calcium and hydrogen carbonates. The concentration of dissolved calcium in 2014 ranged between 75 mg/L and 85 mg/L. The average concentration of hydrogen carbonate for the period 2010 – February 2015 was 249 mg/L and ranged between 230 mg/L and 280 mg/L. In the same period the average concentration of sulphate was 4.5 mg/L and chloride 3.6 mg/L.

During the first flood pulse, as can be seen on the basis of the increased conductivity levels, there was an increase in the presence of the main ions: hydrogen carbonate from 260 mg/L to 307 mg/L, calcium from 85 mg/L to 93 mg/L, sulphate from 5.5 mg/L to 8.0 mg/L and chloride from 5.5 mg/L to 9.0 mg/L. On Fig. 11.1 concentrations in meq/L are presented.

During the second flood pulse, as can be seen on the basis of the decreased conductivity levels, dilution occurred, leading to a reduction in the total content of the main ions, while their ratio remained the same. Chlorides and sulphates expressed small fluctuations, but without significant changes that would indicate the inflow of another type of water. At the end of the second flood pulse, the levels returned to the initial values recorded before the observed rainy period. The maximum content of dissolved silicates, expressed as SiO_2, increased by 30% in both pulses with respect to the results of the regular monitoring from the period 2014 – March 2015, which could be the result of the influence of sediment or torrential surface water, in which silicon from the soil is always present.

We evaluated the content of organic pollutants at the spring with respect to the total organic carbon (TOC) content and the five-day biochemical oxygen demand (BOD). The average concentration of TOC at the spring during the period 2010 – February 2015 was 0.92 mg C/L and ranged between 0.6 mg C/L and 1.6 mg C/L. We do not have data for BOD for this period.

During the first flood pulse there was a slight increase in TOC level to 1.1 mg C/L and then a drop to the initial level. In the second pulse there was a more pronounced growth in both parameters, which is particularly evident towards the end of the second pulse. This could be the consequence of increased decomposition of transferred biodegradable material (Fig. 11.2).

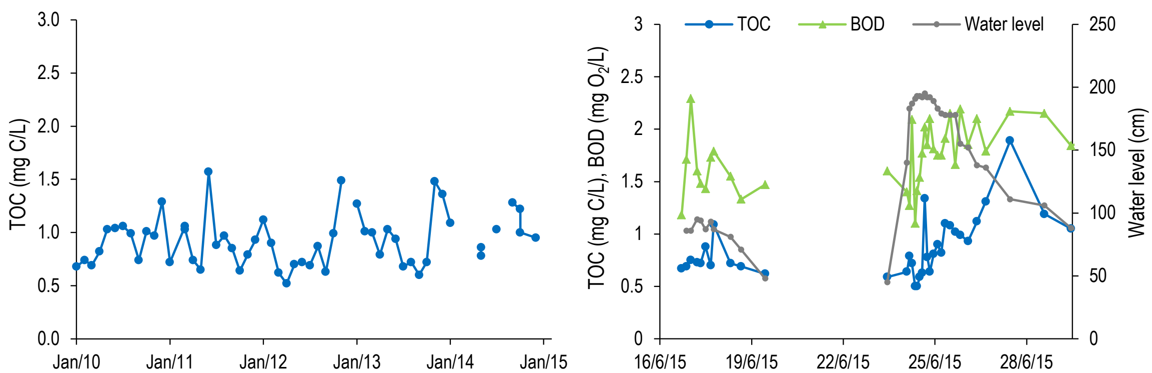

Figure 11.2: Measured TOC in the period from 2010 – February 2015, and measured TOC and BOD in the flood pulses from 16 to 29 June 2015 at the Rižana spring.

The content of nitrates at the Rižana spring in the period from 2010 – February 2015 ranged between 2.8 mg NO_3/L and 7.3 mg NO_3/L with an average level of 4.4 mg NO_3/L. The content of nitrite and ammonium during this period were below the limit of detection for the method used (below 0.010 mg NO_2/L or below 0.026 mg NH_4/L). Therefore nitrate-nitrogen is the most important indicator of nitrate loading in the water.

Nitrates are dissolved compounds which move together with the mass of water. A common occurrence when water is diluted with rainwater is that the concentration of nitrate per unit volume of water decreases (Fig. 11.3). Since there was no rain for four days between the flood pulses, despite a large dilution effect in the second pulse, the nitrate growth trend indicates the oxidation of nitrogen-based organic compounds from the first pulse and the influence of the total nitrogen input.

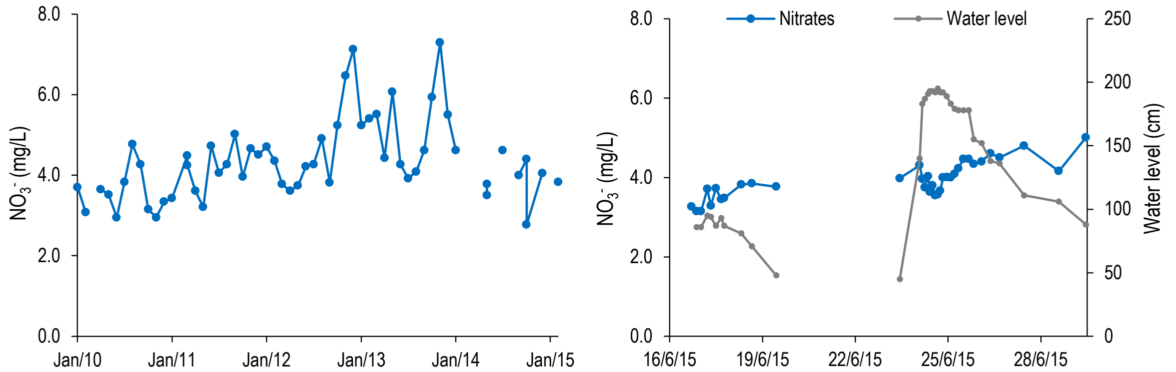

Figure 11.3: Measured nitrate content in the period from 2010 – February 2015 and in the flood pulses from 16 to 29 June 2015 at the Rižana spring.

Phosphor compounds are occasionally identified in regular monitoring, while total phosphor is not included in the monitoring. In the period from 2010 – February 2015, the o-phosphate content ranged from 0.018 mg PO_4/L to 0.044 mg PO_4/L or 0.006 mg PO_4/L and 0.014 mg P/L with an average level of 0.030 mg PO_4/L or 0.010 mg P/L (Fig. 11.4). The phosphate concentrations are low, and in the second pulse appear only in trace amounts and occasionally below the detection limit of the method (less than 0.006 mg P/L). The total phosphor concentrations are also very low, but these measurable concentrations could indicate resuspension from the sediment, which was disturbed by the turbulent water flow, which is also indicated by the increased turbidity.

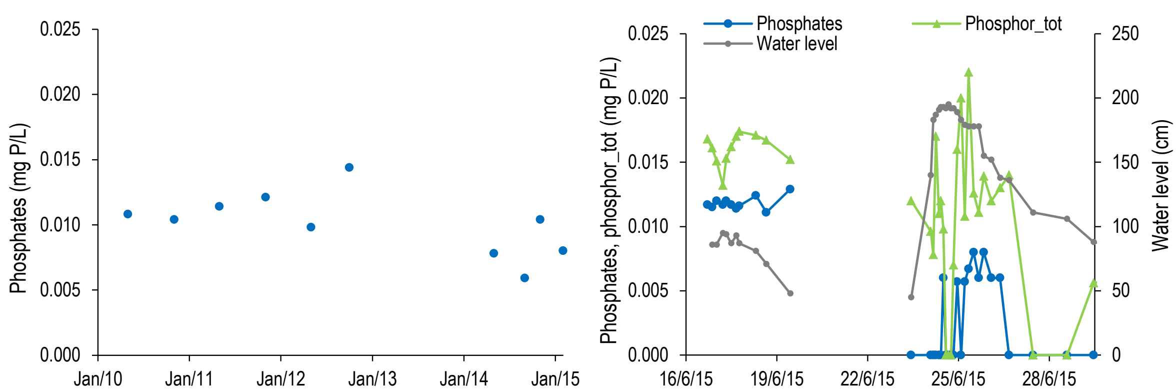

Figure 11.4: Measured o-phosphate content in the period from 2010 – February 2015, including total phosphor, and in the flood pulses from 16 to 29 June 2015 at the Rižana spring.

The raised sediment introduces solid particles into the water column and increases the concentration of compounds (primarily metals) which tend to bond to the particles. Iron, manganese and aluminium are naturally present in sediments in the karst region, so the concentration of these metals is an indicator of how much mass is suspended in the water in a given period. During the flood pulses the highest concentrations were recorded at maximum turbidity (Fig. 11.5), which confirms the transport of these metals by particles suspended in the water. There was an increase in total, but not also dissolved metals, whose concentration was mostly below the detection limit of the method: for iron less than 3 µg/L, for manganese less than 1 µg/L and for aluminium less than 4 µg/L. With respect to the relatively low turbidity of the water in comparison with springs in the Croatian region, the content of dissolved metals is very low and below the detection limit of the method.

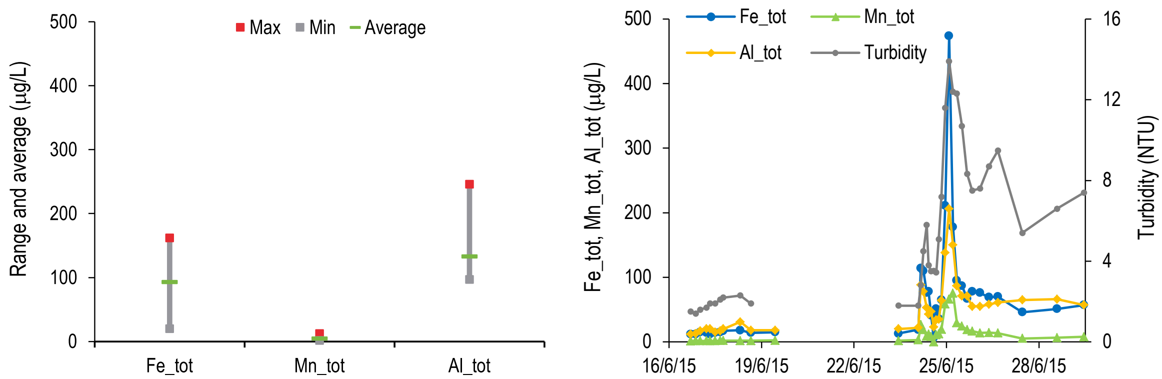

Figure 11.5: Characteristics values of total iron, manganese and aluminium content in the period from 2010 – February 2015, and measured values of these metals and turbidity in the flood pulses from 16 to 29 June 2015 at the Rižana spring.

The organic compounds researched included mineral oils and several pesticide compounds – 107 compounds of various groups of pesticides, insecticides, herbicides and fungicides (by chemical composition organochlorine, organophosphorus, triazine and phenyl urea pesticides). In the first flood pulse, dimethoate was measured in concentrations of up to 0.008 µg/L, and trace amounts of metalaxyl, desethyl terbuthylazine, pyridate and azoxystrobin below the quantification limit, while in the second pulse measurable concentrations of metalaxyl (0.001 µg/L) and diethyl toluamide (0.13 µg/L) were recorded, with dimethoate and dimethomorph in trace amounts below the quantification limit. The remaining compounds were in concentrations below the detection limit. The fungicides and insecticides identified are used primarily to protect fruit trees and grapevines.

Mineral oils are in concentrations below the detection limit (less than 5 µg/L), which is very good, as it indicates that leaching of pollutants from the numerous roads in this part of Istria does not occur during rainy periods.

Sv. Ivan spring

The water from the Sv. Ivan spring has good organoleptic properties with occasional increased turbidity during rainy periods, which varies from low levels all the way to above 1000 NTU. It is classified as moderately hard water (207–263 mg $CaCO_3$/L or 12–15 °dH) and in sampling during regular monitoring in normal hydrological conditions during the year does not show any significant deviations in its chemical composition.

The emphasis in the research conducted was on the occurrence of heavy precipitation after a period of several months of falling water level and the resulting reactions of the springs.

In the period from February to June 2015 there was not a great deal of precipitation, and the occasional precipitation was not heavy (less than 20 mm) and did not affect the water level. Since a falling water level trend has been observed since the beginning of the year (Fig. 11.6), the observed precipitation event has begun in the conditions of the lowest water level. The reaction of the spring was very intensive, with a rapid rise in the water level and high turbidity. Turbidity reached its maximum level a few hours after the heaviest period of rainfall, which followed a series of smaller rain episodes in the preceding week, which did not affect the groundwater level. Turbidity increased by a factor of nearly 2000, and the highest recorded value was 1812 NTU. In the next twelve hours the values fell below 10 NTU.

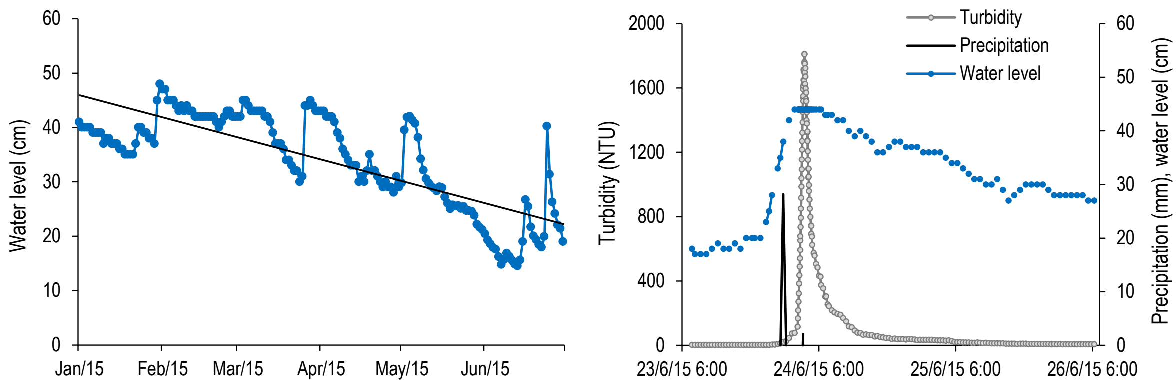

Figure 11.6: Mesured water levels from January to July 2015 (with trend line) and measured values of precipitation, turbidity and water levels during the flood pulse from 23 to 25 June 2015 at the Sv. Ivan spring.

Turbidity occurs as a result of increased content of suspended particles in torrential water, and also due to resuspension from sediments which are located in the karst conduit network due to the increased velocity of groundwater movement.

The ionic composition of the water during the annual observations does not show any major deviations, but there are fluctuations in the content of the main ions due to seasonal, primarily hydrological changes. The level of the electrical conductivity (at 20 °C) during the period of five-year monitoring ranged within an interval of 370 ± 80 µS/cm.

With the occurrence of heavy precipitation in June 2015 and a higher water level (inflow), the conductivity level fell from 398 to 373 µS/cm, and this minimum value was achieved after the stabilisation of the water level and the turbulence of the suspended particles. During a growth period toward the maximum value 451 µS/cm, a slight decrease in conductivity was recorded, which coincided with a small flood pulse and an increase in the water level due to light but all-day precipitation at the catchment area of the springs on 24 June 2015. A more detailed analysis of conductivity and turbidity changes during the flood pulses are presented in Chapter 12.

Water from the Sv. Ivan spring contains mainly calcium and hydrogen carbonate, which are also the primary factors of the water classification type (Fig. 11.7), and around 6% is magnesium and non-carbonates. The largest oscillations were found in the concentrations of calcium and hydrogen carbonates – calcium ranged from 84.9–102.2 mg/L, and hydrogen carbonate from 276–313 mg/L. The remaining ions do not have a significant effect on the water type, but do affect changes in conductivity. The chloride level, along with a rapid rise in the water level, dropped from 7.1 mg/L to 5 mg/L, and upon a later one-day stabilising of the water level and cessation of turbidity returned to its initial level. The magnesium level showed a slight increase during the flood pulse – from 3.8 to 5.2 mg/L, while the sulphate level ranged from 5.1–9.2 mg/L and showed a slight growth trend towards achieving stability. The silicate levels were uniform throughout the duration of the flood pulse.

The flood pulse primarily caused dilution and a change in the total concentration of dissolved ions. The water type did not change. At the time of maximum turbidity the total calcium content increased by 25% in comparison with dissolved calcium. During this time there was also no increase in either dissolved or total magnesium, and also silicates, and the fluctuations were less than 1 mg/L.

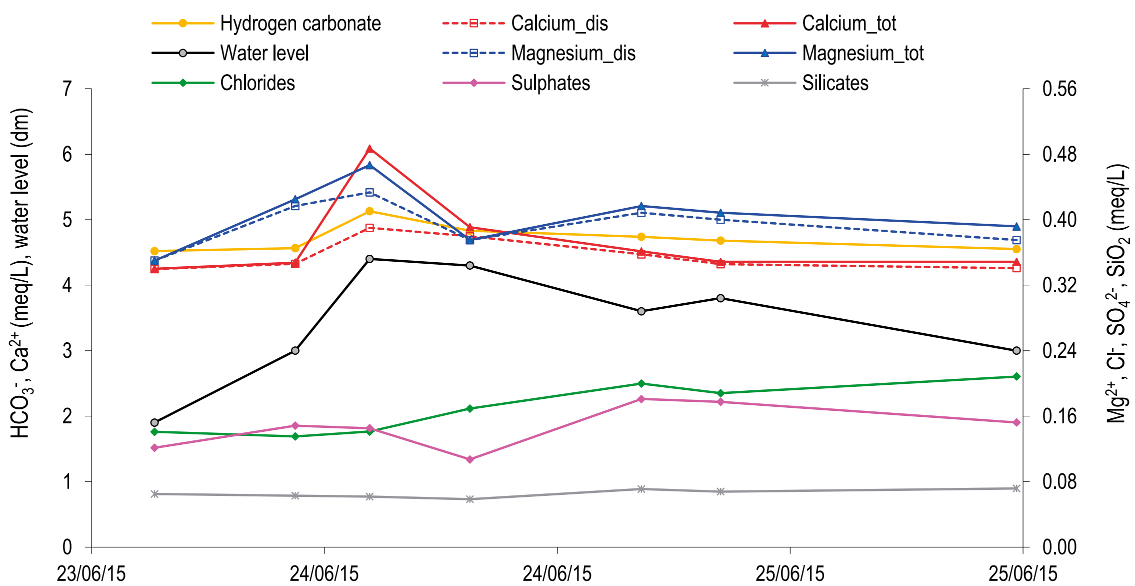

Figure 11.7: Changes in ionic composition during the flood pulse from 23 to 25 June 2015 at the Sv. Ivan spring.

The water from this spring is well-saturated with oxygen, and annual averages are over 90%. Along with the hydrological change in June 2015, total organic carbon (TOC), although in a low level range of 0.78–1.52 mg C/L, showed a slight increase in levels during the time of the stabilising of the water level and decreasing turbidity (Fig. 11.8). BOD as a measure of biodegradable material showed an increase over the same period which was around five times higher than the average levels during annual monitoring. This indicates an increased mass of biodegradable matter transported by torrential water.

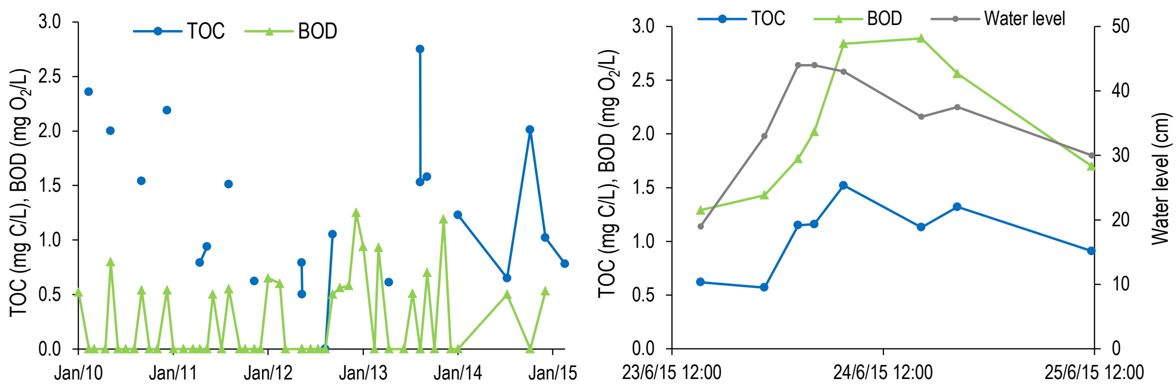

Figure 11.8: Measured TOC and BOD in the period from 2010 – February 2015 and in the flood pulse from 23 to 25 June 2015 at the Sv. Ivan spring.

Nutritional salts, particularly the nitrate form of nitrogen (Fig. 11.9), are the most significant indicator of the total nitrogen loading of the spring. In the period from 2010 to 2015 its level ranged from 1.6–7.0 mg/L, with an average level of 3.2 mg/L (expressed as NO_3). Nitrate is the main component of both inorganic and total nitrogen. Ammonium is rare among the remaining inorganic components of nitrogen compounds in the water from this spring, and in very low concentrations, while nitrite is not identified. The samples taken during the period of the flood pulse indicated that at the time the water level was at its maximum level, nitrate showed lower concentrations, while ammonium was identified in trace amounts at the time of maximum turbidity.

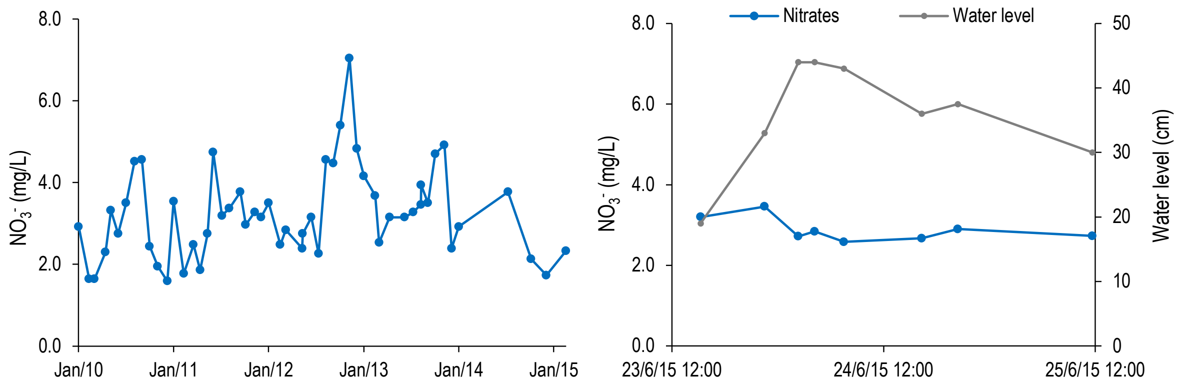

Figure 11.9: Measured nitrate content in the period from 2010 – February 2015 and in the flood pulse from 23 to 25 June 2015 at the Sv. Ivan spring.

In the majority of data, phosphate content was at lower than measurable concentrations – 0.02 mg P/L, with an average level of 0.03 mg P/L (Fig. 11.10), while total phosphorus was up to 0.1 mg P/L, with a median level of 0.04 mg P/L. Phosphorus compounds do not exhibit a marked trend of changes.

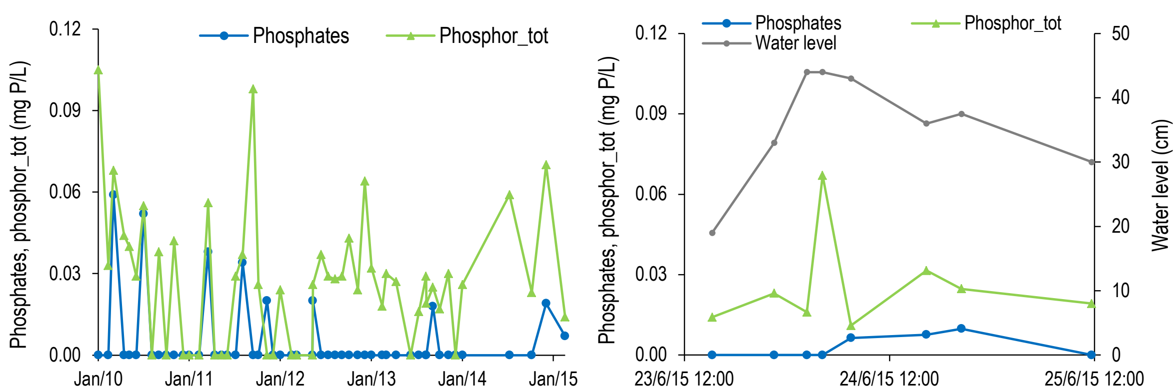

Figure 11.10: Measured phosphates and total phosphorus contents in the period from 2010 – February 2015 and during the flood pulse from 23 to 25 June 2015 at the Sv. Ivan spring.

Episodes of precipitation in June 2015 in comparison with the normal range of annual levels did not exhibit changes in nutrient content. Phosphates were measured in concentrations lower than 0.010 mg P/L, with an increase upon the stabilising of the water level. Total phosphorus reached its maximum level of 0.07 mg P/L at the highest water level.

In modern planned programmes for monitoring water quality it is becoming increasingly frequent that only dissolved metals are identified, particularly in groundwater used for drinking water. Table 11.1 shows the concentrations of the most common metals at the Sv. Ivan spring. The other metals, zinc, nickel, chromium, lead, cadmium and mercury, were not identified in the water at the spring.

Table 11.1: Iron, manganese and copper at the Sv. Ivan spring in the period from 2010 to 2015.

Year	Iron, dissolved (µg Fe/L)	Manganese, dissolved (µg Mn/L)	Copper, dissolved (µg Cu/L)
2010	4.3 – 63.4	<2.0 – 4.0	<2.0
2011	<2.0 – 5.9	<2.0	<2.0
2012	<2.0	<2.0 – 12.4	<2.0 – 5.4
2013	3.3 – 58.9	<2.0 – 4.5	<2.0 – 6.6
2014	7.3 – 21.7	<2.0 – 3.9	<2.0 – 4.5

The hydrological change in June 2015 indicated a large input of iron, manganese and aluminium, in both total and dissolved concentrations. The maximum levels of iron, manganese and aluminium coincide with the maximum levels of turbidity (Fig. 11.11) and indicate a tendency of the metals to bond with suspended particles in the water column, and the concentrations of total metals are significantly higher in comparison with dissolved metals. The high concentration of dissolved iron and manganese indicates the presence of silt from the ground – soil in the torrential water, and at the same time of a risk in the use of the water. At high turbidity, metal particles dissolve in the water at concentrations above the permitted limit values for use. Although the phenomenon is of short duration, it is an instance of excess, which remains undesirable within the framework of regular monitoring. The other metals (copper, lead, nickel, chromium, cadmium and mercury) – for both total levels and in dissolved form – were not measured in concentrations above the quantification limit.

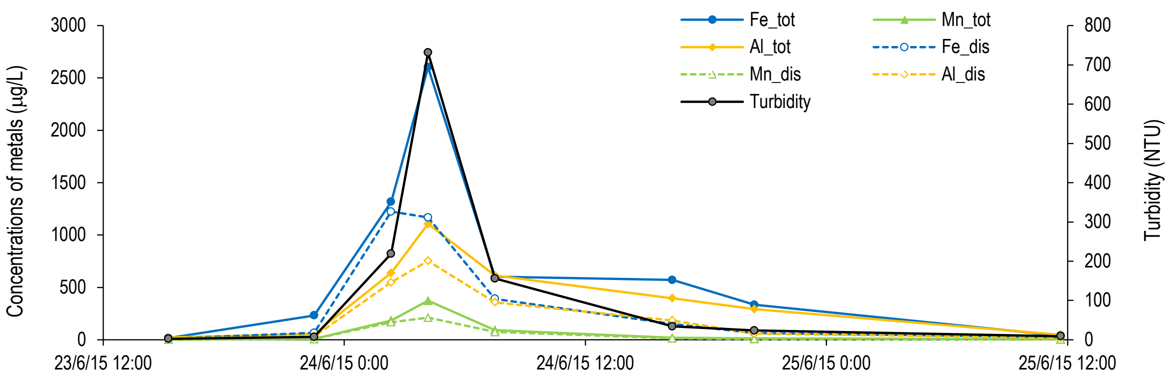

Figure 11.11: Measured values of iron, manganese and aluminium (total and dissolved) during the flood pulse from 23 to 25 June 2015 at the Sv. Ivan spring.

During the flood pulse the samples were tested for 107 compounds of various groups of pesticides (insecticides, herbicides and fungicides, by chemical composition organochlorine, organophosphorus, triazine and urea-based pesticides). The concentrations of all of the compounds are below the quantification limit. Trace amounts of metalaxyl, dimethoate, desethyl terbuthylazine, imidacloprid and dimethomorph were found, compounds from fungicides and insecticides which are primarily used to protect fruit trees and grapevines.

Mineral oils were not detected.

Bulaž spring

As with the other karst springs, the water has good organoleptic properties until rainy periods, which cause increased turbidity and content of suspended silt in the water. The water is classified as moderately hard. Its levels range from 253–296 mg $CaCO_3$/L or 14–16.5 °dH, and with respect to this indicator the water is hard in comparison with the Sv. Ivan spring.

The median annual temperature of the water from this spring is 13.4 °C and exhibits a slight growth trend due to the extreme annual temperatures, and also due to the fact that the sampling is conducted in the lake at the spring and subject to the influence of the air temperature.

During the time of the flood pulse there were minor changes to the water level, but due to typical day-night temperature oscillations, surface effects and the total volume of the lake, a slight trend of decreasing water temperature was recorded.

In this spring the turbidity was not marked, even during the flood pulse the turbidity levels were low and uniform, at around 2 NTU. Electrical conductivity did not show significant changes, but despite minor changes in the water level the decrease in conductivity for 5–10 µS/cm was detected during the time of the maximum water level.

The flood pulse at the Bulaž spring did not cause significant changes in the water's chemical composition, the osciallations are within a very narrow range, which is also expected due to the very slight changes in water level and the low and uniform turbidity levels (Fig. 11.12), so that the differences between the total and dissolved levels of calcium and magnesium are negligible.

Chlorides and sulphates exhibit slightly lower levels during the time of the highest water level level, although these oscillations are very small for the momentary samples, while no changes in the concentration of silicates were recorded.

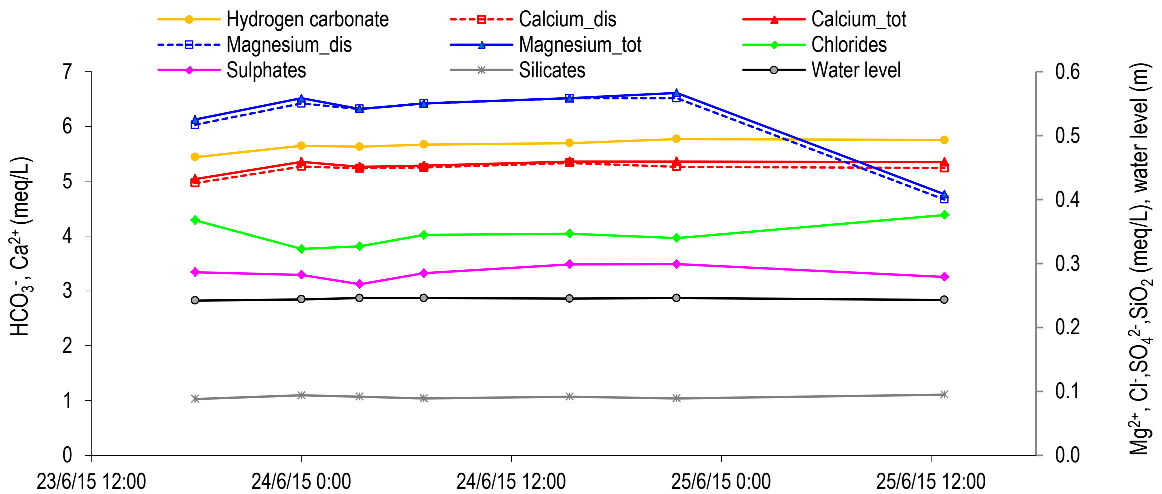

Figure 11.12: Changes in ionic composition in the flood pulse from 23 to 25 June 2015 at the Bulaž spring.

The input of contaminants during the flood pulse was very low. Total organic carbon (TOC), as a measure of the presence of organic contaminants in water, shows very low levels in a range of 0.83–0.89 mg C/L, which are lower than the annual averages. With regard to the ratio between BOD and TOC, TOC is at a higher level during the long-term monitoring than BOD, while during the flood pulse BOD was higher, which indicates the input of microbiological biodegradable organic matter (Fig. 11.13).

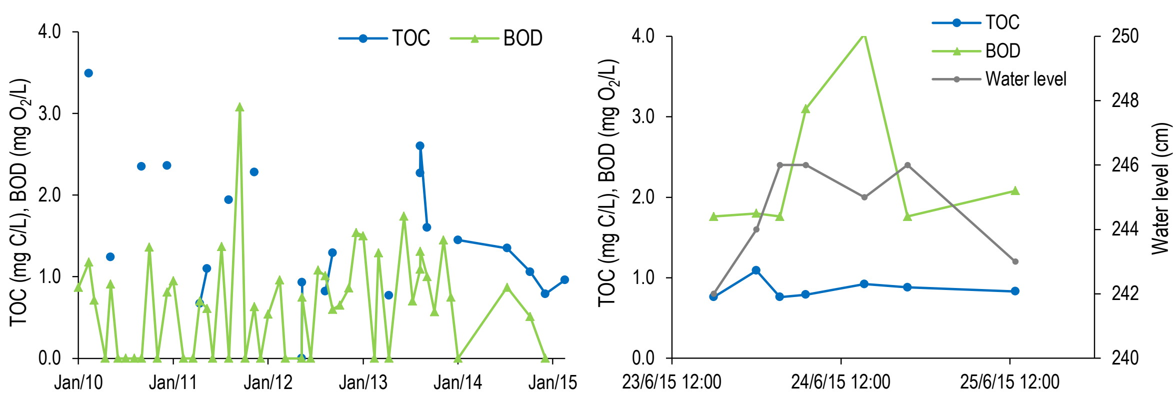

Figure 11.13: Measured TOC and BOD in the period from 2010 – February 2015 in the flood pulse from 23 to 25 June 2015 at Bulaž spring.

Nutrients are present in low concentrations as at the other springs. Nitrate is the main component of both inorganic and total nitrogen. Nitrate levels range up to 7 mg NO_3/L with occasional higher readings up to 8.8 mg NO_3/L. During the flood pulse the levels were very low, at around 3 mg/L (Fig. 11.14).

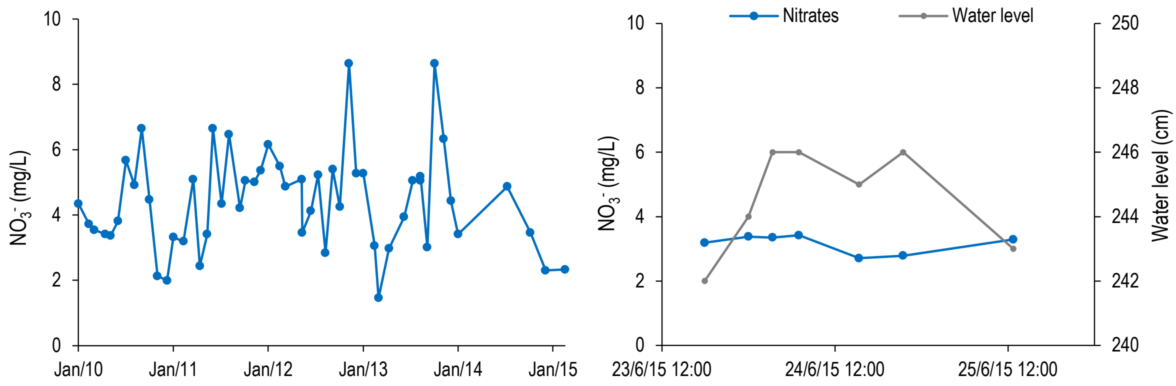

Figure 11.14: Measured nitrate content in the period from 2010 – February 2015 and in the flood pulse from 23 to 25 June 2015 at the Bulaž spring.

The levels of phosphates and total phosphorus during the more weakly expressed flood pulse were lower than the annual levels, phosphate was not detected, while the concentration of total phosphorus was 0.02 mg P/L (Fig. 11.15).

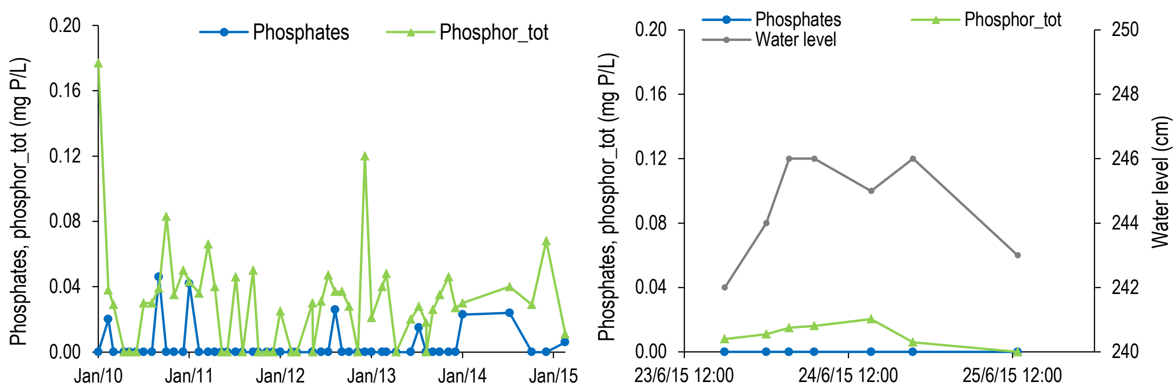

Figure 11.15: Measured phosphates and total phosphorus contents in the period from 2010 – February 2015 and during the flood pulse from 23 to 25 June 2015 at the Bulaž spring.

Table 11.2 shows the concentrations of the most common metals at the Bulaž spring. The other metals, nickel, chromium, lead, cadmium and mercury, were not detected in the water from this spring, but zinc occurs occasionally – as total (average level 33 μg/L) and dissolved (average level 10.5 μg/L).

Table 11.2: Iron, manganese and copper at the Bulaž spring in the period from 2010 to 2015.

Year	Iron, dissolved (μg Fe/L)	Manganese, dissolved (μg Mn/L)	Copper, dissolved (μg Cu/L)
2010	<2.0 – 4.6	<2.0 – 2.9	<2.0 – 2.9
2011	<2.0 – 4.6	<2 – 14.9	<2.0 – 2.9
2012	<2.0 – 6.8	<2 – 24.7	<2.0 – 2.9
2013	<2.0 – 56.7	<2.0 – 16.6	<2.0 – 5.1
2014	5.1 – 42.6	4.3 – 6.7	<2.0 – 6.3

During the flood pulse there was no increase in metal content or turbidity (Fig. 11.16). Iron as the most common metal exhibited two slight increases, which coincide with slight increases in the water level, while manganese and aluminium have uniform levels, characteristic of the stable conditions at the spring.

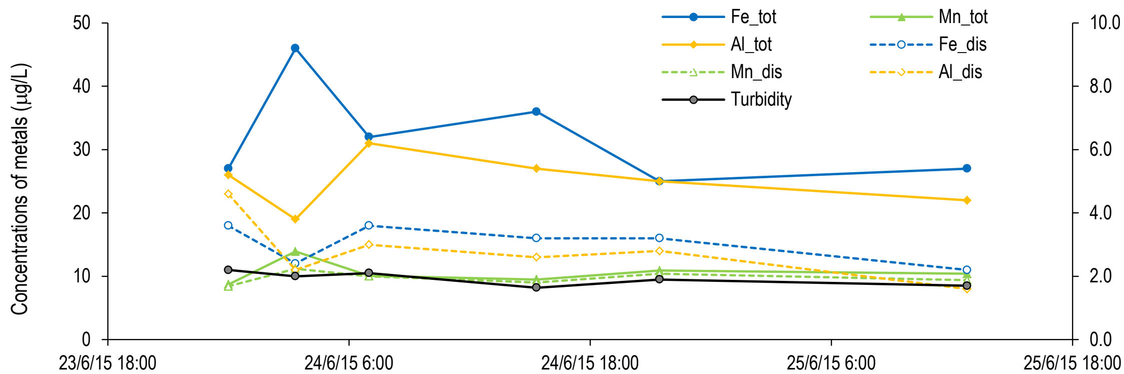

Figure 11.16: Measured values of iron, manganese and aluminium (total and dissolved) during the flood pulse from 23 to 25 June 2015 at the Bulaž spring.

During the flood pulse a series of compounds of various groups of pesticides (insecticides, herbicides and fungicides, by chemical composition organochlorine, organophosphorus, triazine and urea-based pesticides) were observed in the water samples. Dimethoate and dimethomorph were detected in trace amounts, as well as insecticides and fungicides used to protect grapevines and fruit trees. The concentrations of both compounds are below the quantification limit.

Mineral oils were not detected.

Mlini spring

The water from the Mlini spring has good organoleptic properties, with very low turbidity throughout the year; the water is practically clear under varying hydrological conditions. The average water temperature is 12.7 ºC. Water hardness ranges from 234–288 mg $CaCO_3$/L or 13–16 °dH.

The water temperature at the spring varies annually from 12–14 °C. During the flood pulse in June 2015 it was 12.7 °C, while after the stabilising of the water level it increased by 0.1 °C.

Despite changes in the water level, there were no changes in turbidity. Electrical conductivity decreased along with the rise in the water level – to 21 µS/cm, which is around 5% with respect to the level before the beginning of the flood pulse. There were no changes in the relations of ions in the ionic composition of the water, only a dilution effect.

The chemical composition of the water did not significantly change with the changes in the hydrological conditions (Fig. 11.17). The main ions are calcium and hydrogen carbonates, while the other ions are detected in very low concentrations, among which there was a slight decrease in chlorides during the flood pulse. In research conducted at the Mlini spring in 2001 (Kogovšek et al. 2003; Diković 2008), three successive flood pulses were monitored, which caused a change in the flow by a factor of around 100 in comparison with the preceding dry period. The measured change is the combined result of the dilution of the water with a decrease in the levels of all indicators which are dependent on the concentration of dissolved ions: electrical conductivity (as a measure of the total ion content), total mineralisation or total and carbonate hardness, and the content of both dominant (calcium, hydrogen carbonate) and less common ions (magnesium, sodium, potassium). The change in the chemical composition of the water is most marked during the first flood pulse after the long-lasting dry period. The succeeding flood pulses, which caused identical increases in flow, did not significantly decrease the levels of the indicators in question. The flood pulse in June 2015 was moderate, and therefore there were no marked changes in the chemical composition of the water with respect to the average annual levels.

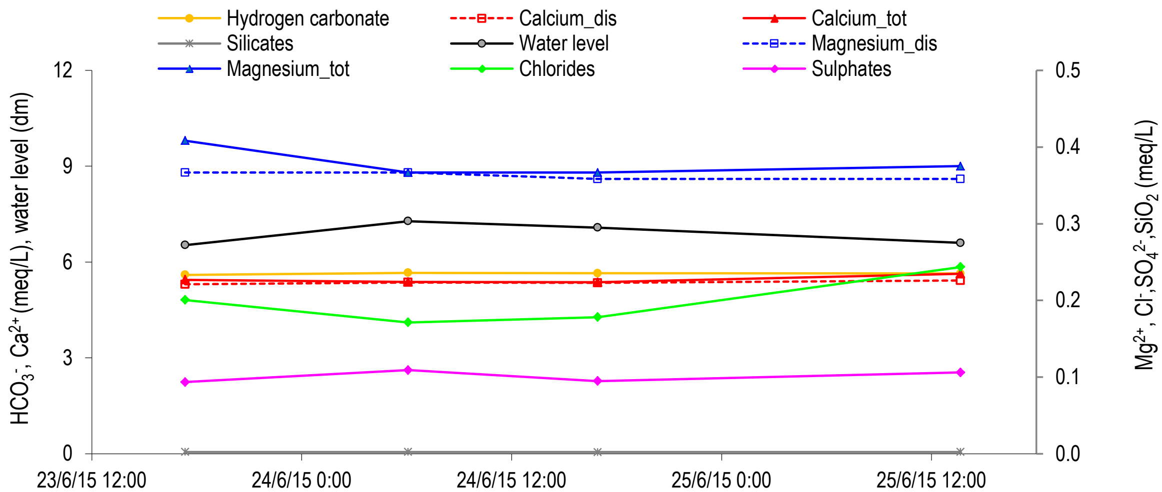

Figure 11.17: Changes in ionic composition during the flood pulse from 23 to 25 June 2015 at the Mlini spring.

Organic loading of the spring is very low under normal conditions in the long-term monitoring. The organic matrix is comprised of natural organic compounds (primarily humic substances – fulvic and humic acids) without anthropogenic pollutants. The increase in BOD during the flood pulse indicates a short-duration input of allochthonous biodegradable material from torrential water, in which the quantity of oxygen used by microorganisms in the natural aerobic self-cleaning of the water increases, which influences the subsequent increase in TOC due to the degradation of these organic residues (Fig. 11.18); increases in TOC occur upon the stabilisation of hydrological conditions. This phenomenon was observed at all of the monitored springs.

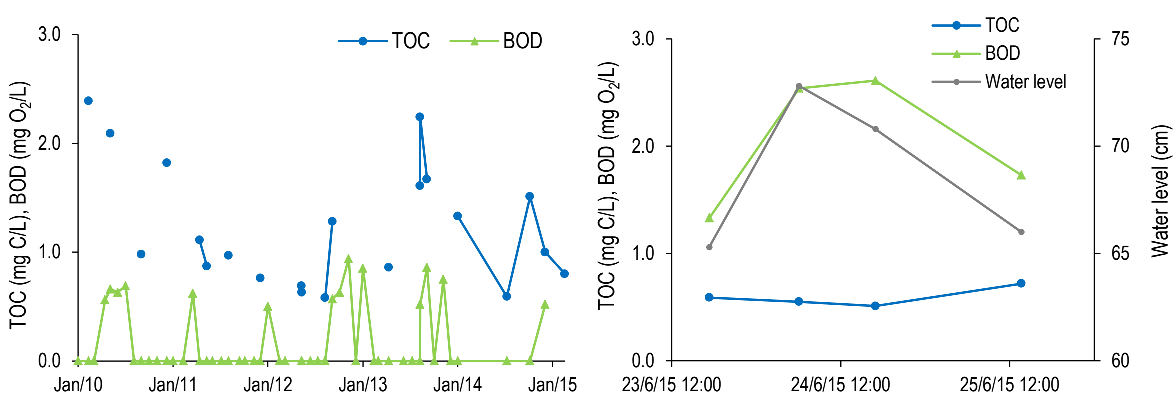

Figure 11.18: Measured TOC and BOD in the period from 2010 – February 2015 and in the flood pulse from 23 to 25 June 2015 at the Mlini spring.

Nitrates, as at the other observed springs, are the main carriers of nitrogen, but the growth trend is more marked than at the Sv. Ivan and Bulaž springs. Nitrates decreased during the flood pulse (Fig. 11.19), and showed an increase after the stabilising of the hydrological conditions. The latter is dependent on the input of low-valence nitrogen compounds in view of the fact that nitrates represent the final degree of oxidation in the nitrogen cycle and the final inorganic product in the process of the mineralisation of organic matter. Due to the low input of ammonium and nitrites, as well as TOC as a measure of total organic pollution, the growth trend is very slight, without a significant impact on the average annual levels.

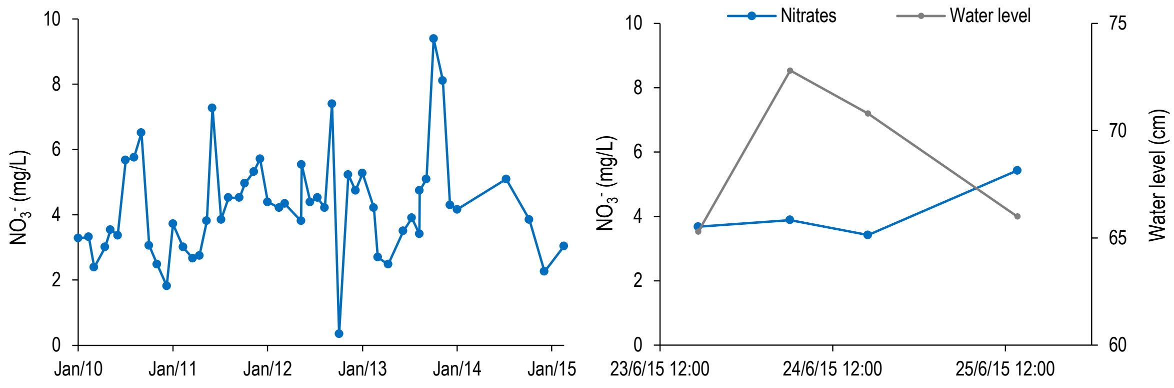

Figure 11.19: Measured nitrate content in the period from 2010 – February 2015 and in the flood pulse from 23 to 25 June 2015 at the Mlini spring.

The content of phosphorus compounds is characterised by oscillations of up to 0.06 mg P/L measured as total phosphorus, while phosphates range up to 0.025 mg P/L. The flood pulse caused an increase in these compounds from trace concentrations before the flood pulse, which indicates input due to torrential water, and also due to movement of sediment, in which organic phosphorus is usually stored after plant and animal decomposition or is returned to the water column via microbiological decomposition. Since inorganic phosphorus can be dissolved, as well as bonded to suspended particles, the result of the increased turbidity usually indicates an increase in the concentration of phosphates and total phosphorus. Oscillations of phosphorus compounds were within the limits of the average annual levels (Fig. 11.20).

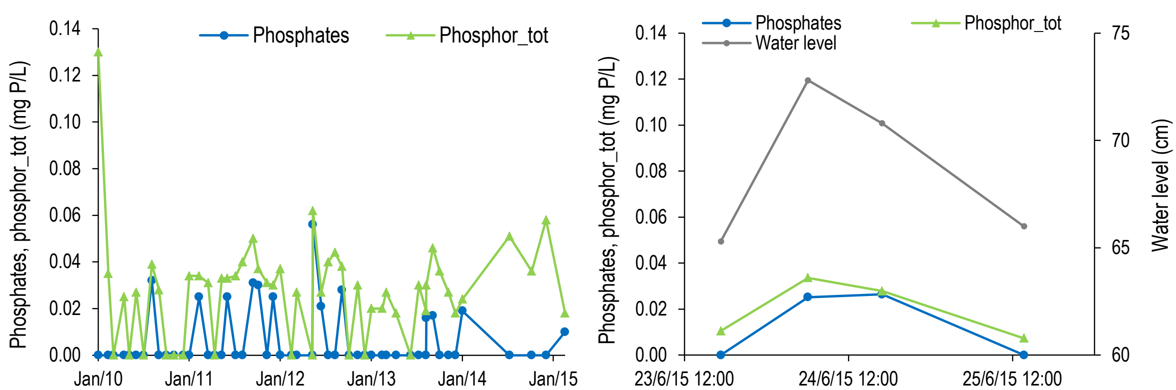

Figure 11.20: Measured phosphates and total phosphorus contents in the period from 2010 – February 2015 and during the flood pulse from 23 to 25 June 2015 at the Mlini spring.

Table 11.3 and Fig. 11.21 show the concentrations of the most common metals at the Mlini spring. The other metals, nickel, chromium, lead, cadmium and mercury, were not detected in the water from this spring, but zinc occurs occasionally – as total (average level 33.5 µg/L) and dissolved lead (average level < 2 µg/L – 9.5 µg/L) – probably due to the influence of rainwater which flows from the road above the spring.

Table 11.3: Iron, manganese and copper at the Mlini spring in the period from 2010 to 2015.

Year	Iron, dissolved (µg Fe/L)	Manganese, dissolved (µg Mn/L)	Copper, dissolved (µg Cu/L)
2010	17.7 – 69.4	2.3 – 4.0	<2.0
2011	<2.0 – 12.7	<2.0	<2.0
2012	<2.0 – 7.8	<2.0	<2.0 – 3.4
2013	3.9 – 26.6	<2.0 – 2.2	<2.0
2014	<2.0 – 12	<2.0 – 7.4	<2.0 – 7.7

The flood pulse did not cause significant turbidity, and the metals content is also low in comparison with the levels detected in the regular monitoring, although all samples taken during the flood pulse showed measurable concentrations of metals which had been transported into the aquifer.

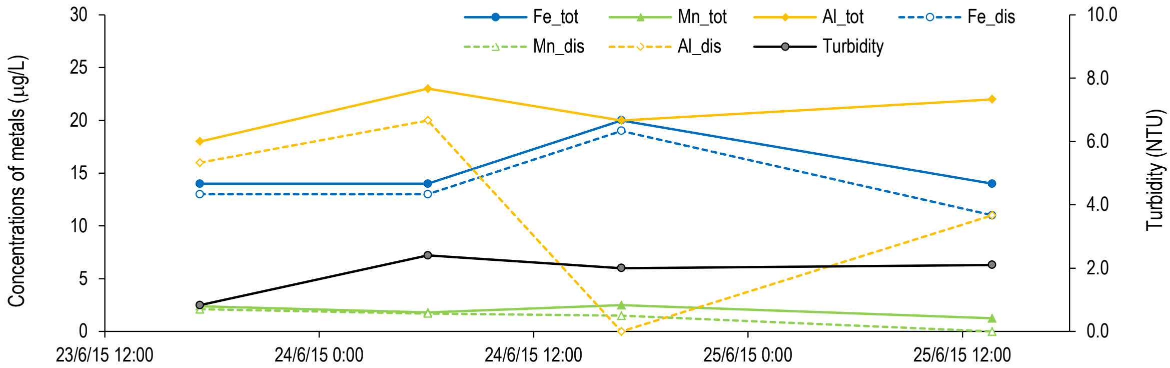

Figure 11.21: Measured values of iron, manganese and aluminium (total and dissolved) during the flood pulse from 23 to 25 June 2015 at the Mlini spring.

None of the various types of pesticides researched in the spring water was detected during the flood pulse, nor were mineral oils.

Small springs and sinking ponors

There is almost no data on water quality from small springs and ponors in the area of observations. Observation of some ponors and small springs was initiated within the framework of the ŽIVO! project.

Sites were included where there are no active hydrological stations with limnigraphic data on water level – the Sv. Ivan secondary spring, the Tombazin intermittent spring, the Podgaće spring near the ponor and the Rašpor and Vinicio Potleca ponors near the village of Marušići and the Jama pod Krogom cave, where chemical analyses (1–3 samples) were conducted.

Sv. Ivan secondary spring

The Sv. Ivan secondary spring is a small spring located in the district of the Istrian Water Supply System in Buzet. The chemical analyses of 3 water samples were conducted during the flood pulse from 23 to 25 June 2015. The water temperature ranged between 13.7 °C and 14.2 °C, which is one degree higher than during the same period at the Sv. Ivan spring. The ionic composition is also different, with a higher content of non-carbonates (chlorides and sulphates) and total sodium and potassium. While high turbidity of up to nearly 2000 NTU occurred at the Sv. Ivan spring, the levels at this spring ranged between 2.2 NTU and 7.12 NTU. The water had a higher concentration of phosphorus compounds (phosphates up to 0.026 mg P/L, total phosphorus 0.064 mg P/L). Iron, manganese and aluminium were found in measurable concentrations in all samples, in which the total metals content was twice as high on average (order of magnitude less than 60 µg/L).

Podgaće spring near the ponor

The water temperature from the beginning of continuous measurements in February all the way to July 2015 ranged from 1.9 °C to 19.0 °C and corresponded to the rise in the air temperature. The water was harder than the water from the large springs at Sv. Ivan and Bulaž, with a slightly higher concentration of magnesium. Increased turbidity was not recorded during the flood pulse (0.24–0.54 NTU). Even the presence of phosphorus compounds was not detected. The iron and aluminium content was very low (1–10 µg/L), while the presence of manganese was not detected.

Tombazin spring

The Tombazin spring is not a permanent spring. It is located to the south-east of the Sv. Ivan spring. Two analyses were conducted – one during a period without precipitation, and the other during a flood pulse. The water temperature is similar to that of the Sv. Ivan spring, 11.4–12.6 °C, and here, as at Sv. Ivan, high turbidity occurred due to a rapid rise in the water level; turbidity of 321 NTU was recorded. High concentrations of iron (1761 µg/L), manganese (161 µg/L) and aluminium (666 µg/L) are associated with turbidity, whereby the content of dissolved metals is very high, two times higher on average than the total concentration. The presence of phosphorus compounds was measured in trace amounts, and nitrates between 2.11–2.79 mg NO_3/L, which is within the limits of the average levels at the Sv. Ivan spring.

Vinicio Potleca ponor near the village of Marušići

The water temperature from the beginning of continuous measurements in February all the way to July 2015 ranged from 9.5 C to 11.7 °C and corresponded to the rise in the air temperature. Electrical conductivity varied over a range of 370–458 µS/cm. The water is more mineralised than the water from the Podgaće spring and the Sv. Ivan secondary spring. Low turbidity was measured during the flood pulse – 6.3 NTU, while iron, manganese and aluminium were at measurable concentrations. This is also the sole sample in which pollution was measured which indicated a human influence (phosphates 0.286 mg P/L, and trace amounts of nitrite and anionic detergents).

Rašpor ponor

Continuous measurements of water temperature were taken at the Rašpor ponor from the middle of January to July 2015, which varied over a very narrow range – 8.4–9.1 °C. A one-time analysis indicated the following: low turbidity – 2.7 NTU, a nitrate level of 7.61 mg NO_3/L, trace amounts of phosphorus compounds, low iron, manganese and aluminium content (max. 20 µg/L).

Jama pod Krogom cave

A chemical analysis was conducted on a one-time sample in the second half of July 2015. The water sample was not turbid (0.34 NTU), nitrate content was low – up to 1.3 mg NO_3/L, and the sample contained trace amounts of phosphorus compounds and iron, manganese and aluminium (less than 10 µg/L). The water was slightly harder in comparison with the Mlini spring (16.6 °dH), due to the increased content of calcium and hydrogen carbonate.

Comparison of ionic composition of the water from the small springs and ponors

Although there is very little data for the small springs and ponors, a comparison was made of the ionic composition in order to determine the differences during the flood pulse – in view of the fact that the samples were taken during that time period (Fig. 11.32).

There were no significant differences in ionic composition at the large springs at Sv. Ivan and Bulaž, the small Mlini spring and the ponor at the Mlini spring, and at the Tombazin intermittent spring. The water from the Rižana spring is softer, with a higher proportion of magnesium. The other small springs, the Sv. Ivan secondary spring, Podgaće near the ponor and the Marušići ponor show a higher non-carbonate content, while the Rašpor ponor has the softest water, which is of the calcium-hydrogen carbonate type.

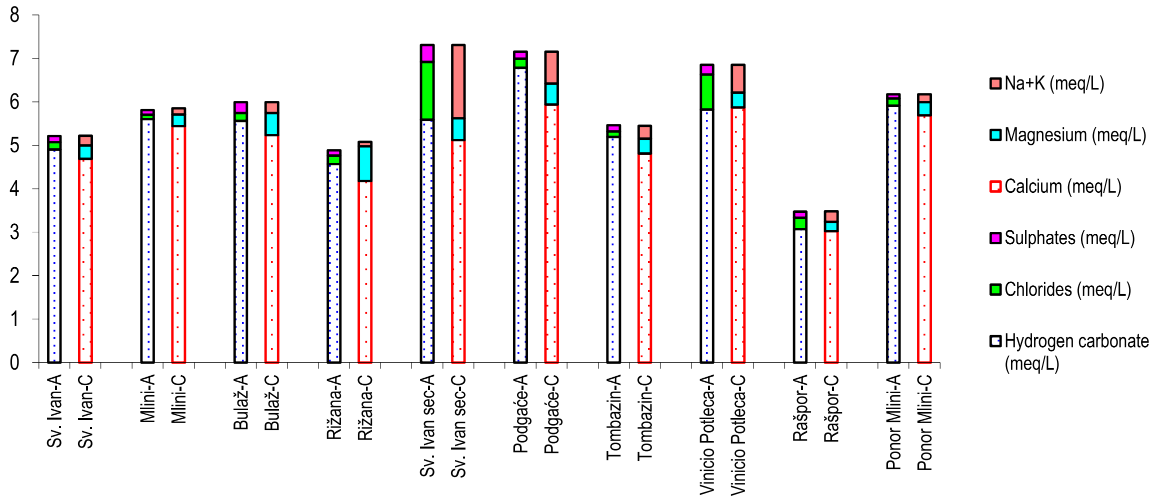

Figure 11.22: Comparison of ionic composition of the water from the observed springs and ponors.

Conclusions

During the conducting of regular annual monitoring of groundwater quality, hydrological changes of a rapid increase in water level are usually not recorded. The research conducted at short time intervals during the flood pulses clearly showed that this is the period in which the largest changes occur in the water's chemical composition, as well as the input of various substances – both natural, which are deposited in the sediment or are transported by torrential water, and contaminants, which are the result of human influence.

At the springs observed in this project, the hydrological conditions were varied: at the Sv. Ivan spring, measurements were conducted on a very short, one-day, but very intensive flood pulse, at the Rižana spring over a longer, two-weeks period with two marked flood pulses, while the flood pulses at the other springs were of lower intensity. The large amount of precipitation in the recharge areas caused changes to the chemical composition of the water due to mixing of water from different sources – the baseflow and in particular rainwater. During the first stage of the flood pulse, electrical conductivity increased as a result of the pressurising of older water with higher mineralisation. Thus the largest change was recorded at the Rižana spring, and to a lesser extent at the Mlini spring, while it was not observed at the other springs. Changes were expressed in the dilution of the total concentration of dissolved ions, primarily the predominant calcium and hydrogen carbonates, and smaller oscillations of ions which make up less than 10% of the total ionic composition, which led to a rapid decrease in electrical conductivity. The change in the ion ratio at low and high water levels was very small, which means that the water type did not change. Only the total concentration of dissolved ions changed.

The input of pollutants was very low at all springs. Thus all of the characteristic parameters used as measures of organic pollution, such as total organic carbon and nutrients, were as a rule found at lower concentrations in comparison with the results of the long-term monitoring, since during the flood pulses there is a decrease in dissolved substances. Increased concentrations of nutrients and other organic matter can occur in later periods of stabilisation of the water level, after the establishing of equilibrium with respect to the processes of decomposition, self-cleaning of the water and a steady water level. Increases in turbidity or suspended material are accompanied by increased concentrations of substances which are adsorbed on the surfaces of particles in suspension – primarily heavy metals. The high content of suspended substances binds the high proportion of iron, manganese and aluminium, i.e. metals which are commonly found in sedimentary rocks, as well as in sediments which are transported by torrential water.

Since there were no significant increases in pollutants during the period of observation, except for the ubiquitous metals during times of extreme turbidity, we can conclude that the ecological status of the catchment area and the area of the springs is good. However, with rapid increases in water level there are changes in the chemical composition of the water and input of pollutants which for a brief time period exceed the limit values for use in the water supply, and can later have a negative impact at low water levels. The standard periodic sampling (quarterly or monthly, and even daily) is often not sufficient to describe the influx of turbidity and the input of pollutants. The occurrence of rapid increases in the water level, accompanied by intensive movement of sediments and a high concentration of pollutants and microorganisms, is often not recorded, which indicates a need for careful planning of the monitoring of the water quality of karst springs in order to recognise their responses to various hydrological conditions.

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Photo from "Water - Life!" in Istria competition; author: Aleksandar Tumulić

ASSESSMENT OF FLOW DYNAMICS AND SOLUTE TRANSPORT BASED ON THE MONITORING OF A FLOOD PULSE

Metka Petrič, Nataša Ravbar, Clarissa Brun, Ranko Biondić, Janja Kogovšek

The physical, chemical and microbiological properties of karst springs change very rapidly in different hydrological conditions. Detailed monitoring of these changes and their comparison with precipitation and hydrological data enables analysis of flow dynamics and solute transport processes in the karst aquifers that feed these springs. Research to date (e.g. Kogovšek 2001; Vesper et al. 2001; Williams et al. 2006; Hunkeler & Mudry 2007; Ravbar et al. 2012) has shown that changes in the quality of karst water are most pronounced in the case of flood pulses caused by intense precipitation events following a long dry period. A special feature of karst is allogenic recharge with sinking streams from non-karst zones, which represents a concentrated input of frequently polluted water into the highly permeable conduits of a karst aquifer and onwards towards karst springs (e.g. Kogovšek 2002; Bailly-Comte et al. 2007; Pronk et al. 2007). The selected area of study in the transboundary area of the Northern Istria represents such a complex system, where diffuse infiltration in the highly permeable karst surface combines with concentrated recharge from sinking streams, and the diverse nature of recharge is also reflected in flow dynamics and solute transport. In order to better understand these processes, in June 2015 we carried out detailed monitoring of the quality of major karst water sources during two consecutive flood pulses following a dry period that had lasted since the end of March 2015, while at the same time monitoring precipitation and hydrological conditions.

The Rižana spring

The most exhaustive monitoring of changes in physical, chemical and microbiological parameters was in the Rižana spring. We obtained data on precipitation at the Škocjan station and the flow rates of the Rižana at the Dekani station from the website of the Slovenian Environmental Agency (ARSO). In the previous period in 2015, the last marked increase in the flow rate of the Rižana occurred at the end of March 2015, when it reached 12.6 m^3/s at the Dekani station. This was followed by a lengthy period of low water levels, with flows not exceeding 1.5 m^3/s. Individual more intense precipitation events were not reflected in increased flows owing to the small proportion of effective rainfall and the retention of precipitation in the vadose zone. In June 2015, a total of 25 mm of rain fell in the three-day period from 14 to 16 June at the Škocjan station and flow increased from 0.5 to 1.2 m^3/s (Fig. 12.1). We decided to observe this small flood pulse and therefore took 11 samples for chemical and microbiological analysis between 16 and 19 June. The measured parameters are presented in the previous chapter on groundwater quality. A few days later there was a brief but more intense precipitation event, when 71 mm of rain fell at the Škocjan station, beginning on the afternoon of 23 June and continuing overnight into 24 June, and the flow of the Rižana at the Dekani station increased from 0.5 to 10.6 m^3/s. We monitored this pulse even more closely, taking samples every two hours while the precipitation event was at its most intense. In this second flood pulse we just took 24 samples between 23 and 29 June, and one further sample after stabilisation of conditions on 8 July 2015. During both flood pulses we obtained data on water levels at the spring during the sampling period from the water company Rižanski vodovod d.o.o. and used an Onset HOBO Conductivity Data Logger to measure electrical conductivity (EC) and temperature at 30-minute intervals. These data are missing for the time when the Data Logger was above the surface of the water.

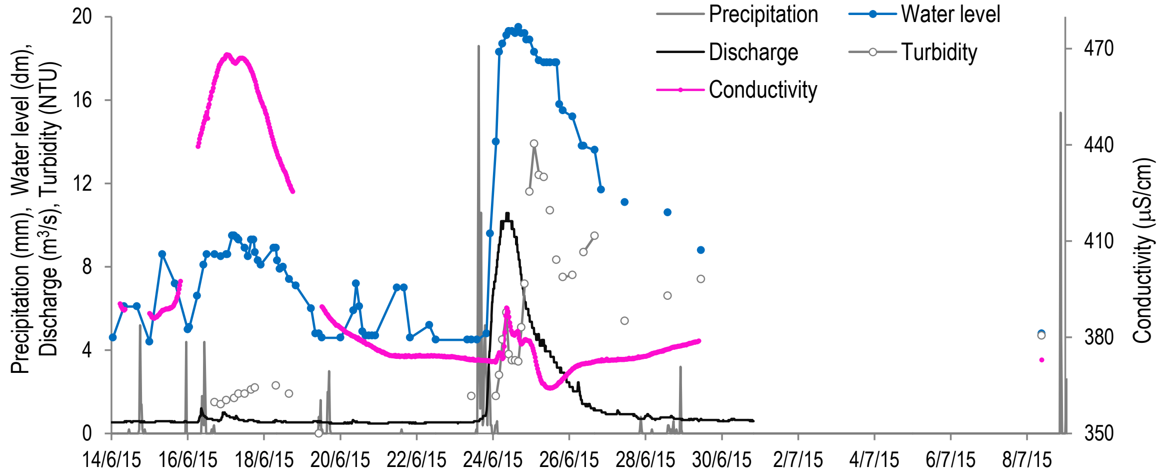

Figure 12.1: Precipitation at the Škocjan station, flow rate of the Rižana at the Dekani station, conductivity of the Rižana spring at 30-minute intervals and water levels at the Rižana spring in the sampling period during the first and second observed flood pulses.

During the first pulse we slightly delayed the start of sampling because the weather forecast did not indicate sufficiently heavy rain. We did not take the first sample until 5.00 p.m. on 16 June 2015, when EC had already increased from 386 µS/cm to 460 µS/cm and was approaching its maximum value of 468 µS/cm (17 June 2015, 1.00 a.m.). Although the water level at the spring rose by approximately 40 cm in this period, the increase in flow at the Dekani station was nevertheless minimal. Thus only the first three samples were taken during the period of increasing EC. Subsequent samples were taken during the decrease period (Fig. 12.1). As can be seen in Figs. 12.3, 12.4, 12.8 and 12.9, these first three samples differ significantly from the others in the first flood pulse. Since the observed flood pulse was the first following a lengthy dry period, we may conclude that the discharge consisted entirely of older water that had already been in the system for some time.

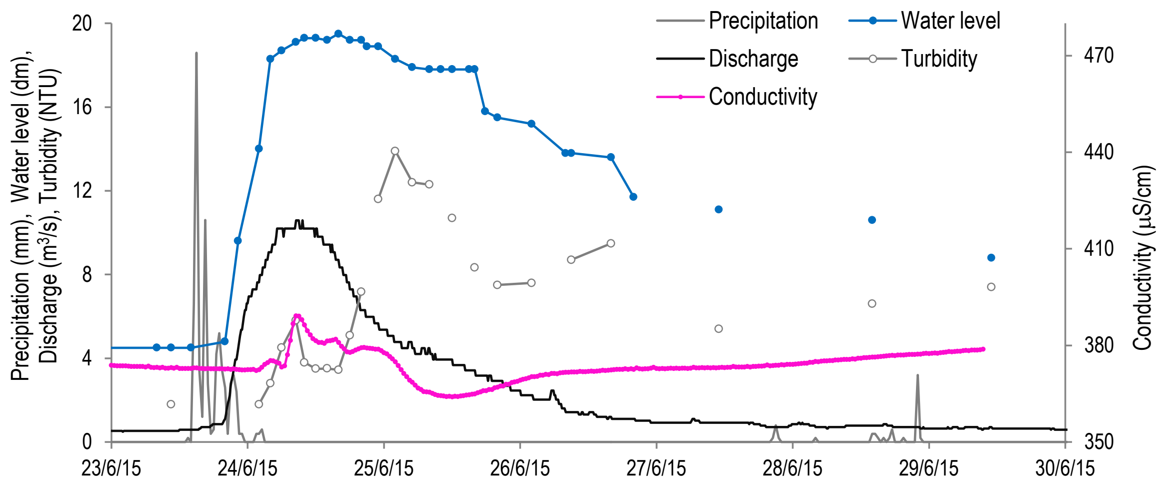

Figure 12.2: Data as in Fig. 12.1 but showing only the second flood pulse.

The next flood pulse, in which the increase in flow was more marked, was monitored more closely (Fig. 12.2). Approximately five hours after the heavy rainfall, when 60 mm of rain fell at the Škocjan station, the water level at the spring began to grow. The unchanged EC and turbidity values indicate the further discharge of water previously stored in karst conduits and fissures.

The increase in EC by up to 17 µS/cm in the next phase is the consequence of the forcing out of water from less permeable areas of the vadose zone. This water has a higher mineral content as a result of being stored in the system for longer. The increase in flow dynamics also moves the sediments deposited in conduits and fissures, which is reflected by a small increase in turbidity. The beginning of a decrease in EC and turbidity values indicates an influx of newly infiltrated rainwater from the karst surface. The sharp fall in conductivity to values that are lower than before the flood pulse (~ 364 µS/cm) and the typical subsequent increase in turbidity reflect the fact that the Rižana spring is fed by sinking streams from the flysch margin. Towards the end of the flood pulse, declining flow is accompanied by a gradual increase in EC and lower values of turbidity. This pattern of changes in the observed parameters during a flood pulse has been monitored at numerous karst springs (e.g. Mahler et al. 2000; Pronk et al. 2006).

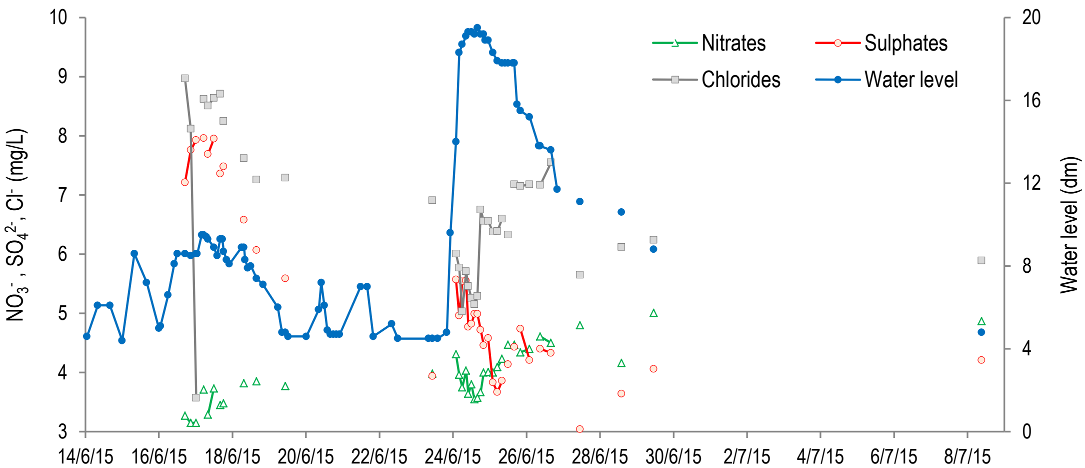

Figure 12.3: Water levels and concentrations of nitrates, sulphates and chlorides in the Rižana spring during the first and second observed flood pulses.

The characteristics of groundwater discharge dynamics at the Rižana spring are also reflected in the analysed chemical parameters. Changes in concentrations of nitrates, sulphates and chlorides are relatively small, but should be considered thoroughly in the cases of drinking water sources. These differences result from the discharge of water from different parts of the karst aquifer in the catchment of the spring (Fig. 12.3).

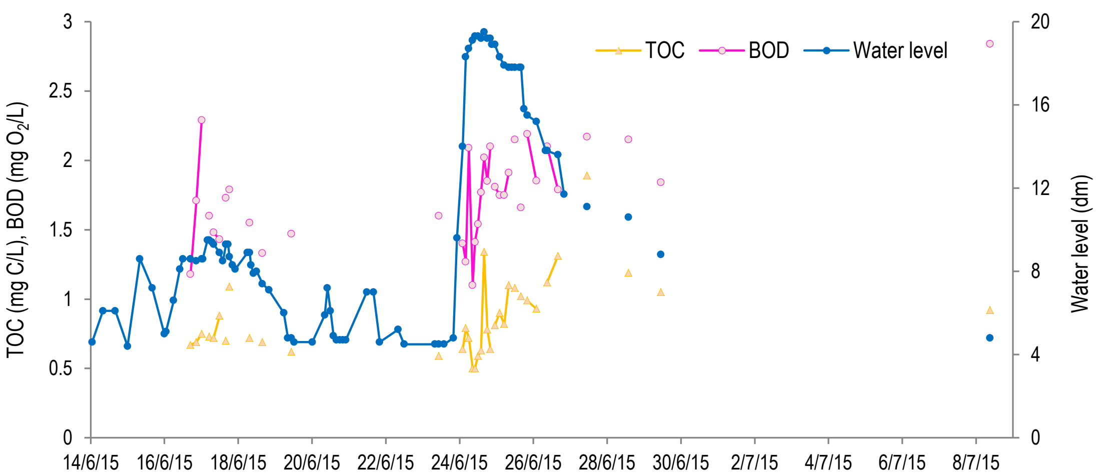

Figure 12.4: Water levels, TOC and BOD of the Rižana spring in the first and second observed flood pulses.

BOD and TOC parameters (measured in unfiltered samples), which we use to assess contamination with organic matter, have relatively low values but an upwards trend is noted during the influx of new water in the second flood pulse (Fig. 12.4). This corresponds to findings from the literature (Batiot et al. 2003).

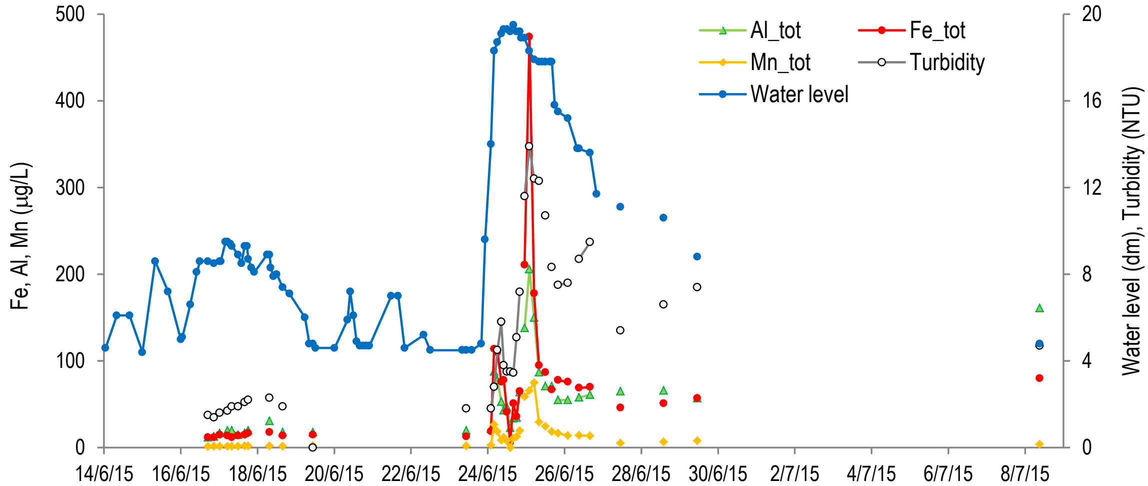

Figure 12.5: Water levels and total concentrations of aluminium, iron and manganese in the Rižana spring during the first and second observed flood pulses.

The high concentrations of the total iron, aluminium and manganese content in samples in which increased turbidity was also identified (Fig. 12.5) confirmed the transport of these metals through particles suspended in the water. The main source is allogenic recharge. The concentrations of metals dissolved in the water are typically lower (Fig. 12.6).

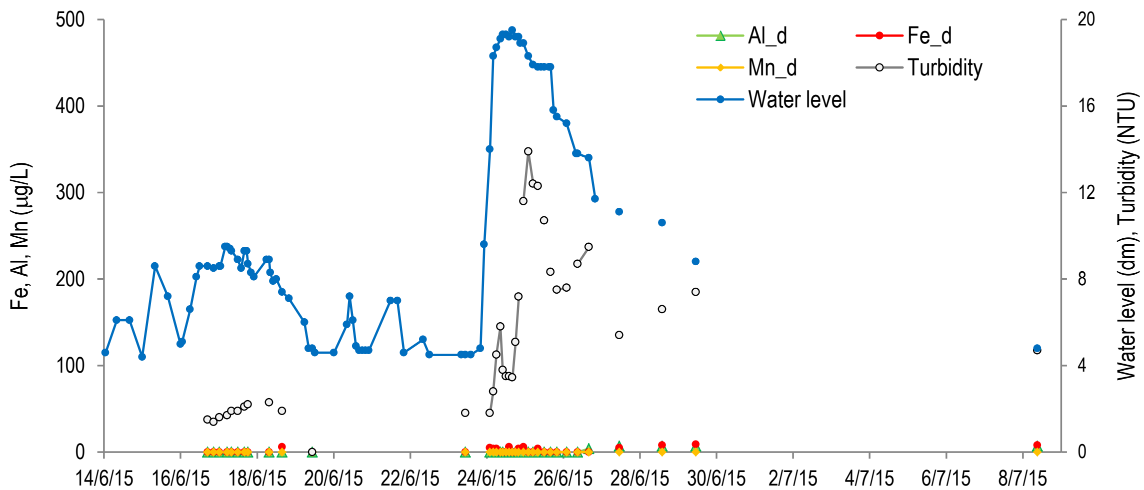

Figure 12.6: Water levels and concentrations of dissolved aluminium, iron and manganese in the Rižana spring during the first and second observed flood pulses.

Total hardness and EC were compared for the entire period of observation of the Rižana spring (Fig. 12.7). The linear dependence with a correlation coefficient of R^2=0.98 indicates that EC reflects the dissolution of carbonate rock and that pollution does not have a significant influence on this parameter.

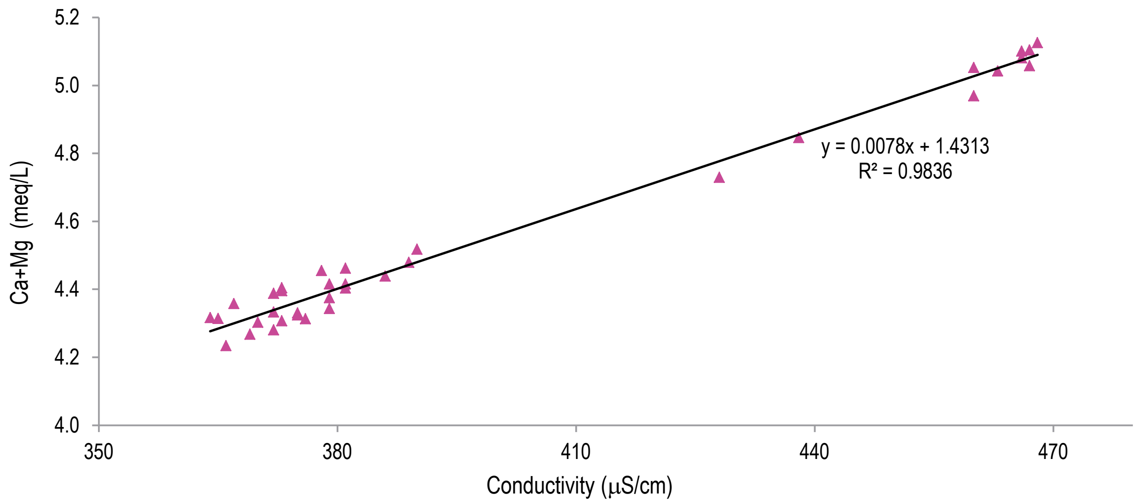

Figure 12.7: Comparison of EC and total hardness (Ca+Mg) in all analysed samples from the Rižana.

Similar conclusions on water flow dynamics in the catchment area of the Rižana spring were reached on the basis of isotopic analyses of water. Unfortunately we have no data on the isotopic composition of precipitation at the time of the observed precipitation events, but changes in the isotopic composition confirm findings on the mixing of different types of water in the Rižana spring. In the first pulse, more negative values indicate the outflow of older water that had already been in the system since winter months (last more intensive precipitation event in March 2015). In the second pulse, with a growth in the water level and the start of the decrease in EC, reflecting the start of discharge of newly infiltrated water, δO^{18} and δ D reached values of -6.5‰ and -46.8‰ (Fig. 12.8). These less negative isotopic values are typical for precipitation water in summer months. Later decrease in isotopic values and flow rate indicates outflow of water previously stored in less permeable areas of the vadose zone.

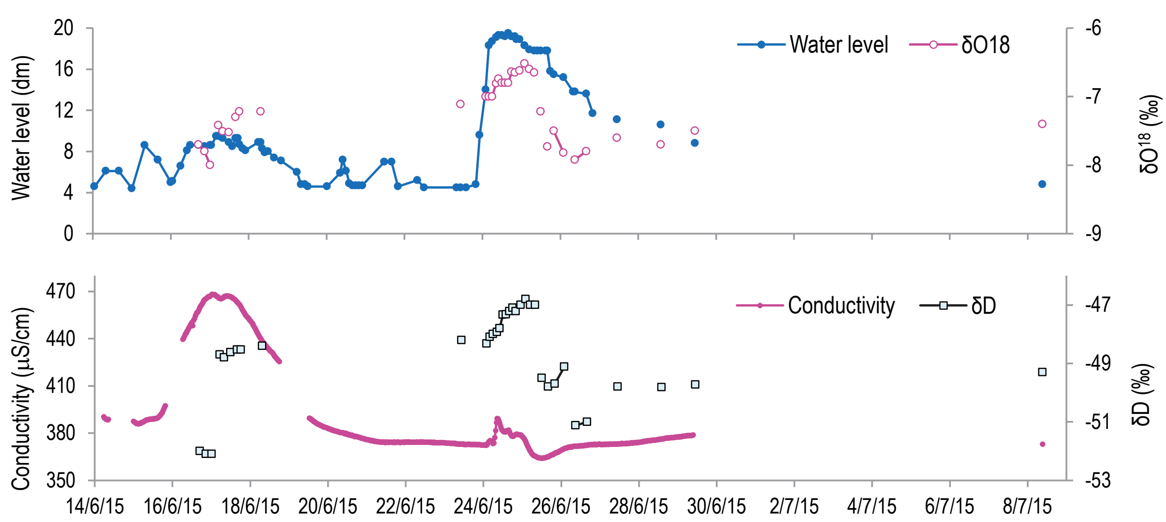

Figure 12.8: Water levels, EC, δO^{18} and δD in the Rižana spring in the first and second observed flood pulses.

Monitoring of the two flood pulses also indicates the very great variability in the microbiological quality of the Rižana spring (Fig. 12.9). The high values for coliform bacteria and *E. coli* in the first, less intense water pulse with less dilution are interesting, in that this points to increased values in discharging water that has been stored in the karst aquifer for a longer period.

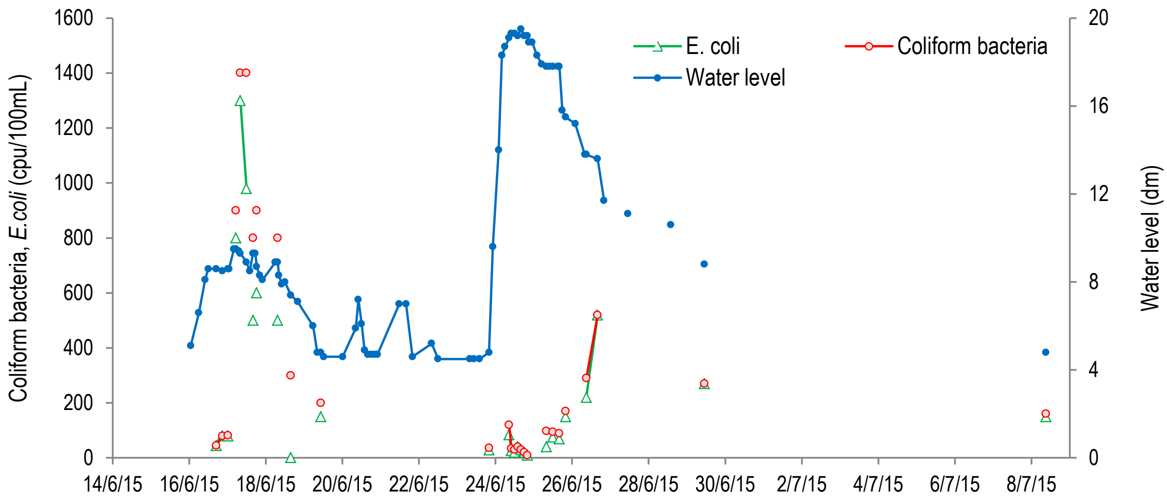

Figure 12.9: Water levels and the number of coliform bacteria and E. coli in the Rižana spring during the first and second observed flood pulses.

Springs on the Croatian side of the study area

On the Croatian side of the study area, we carried out parallel monitoring of several springs, ponors and karst caves, which meant that the sampling frequency for chemical and microbiological analyses was lower, while the duration was limited to the central part of the second flood pulse. In our detailed analysis of the flood pulse, we thus only obtained the results of analyses in the Sv. Ivan, Bulaž and Mlini springs, where, respectively, 8, 7 and 5 samples were taken between 23 and 25 June 2015.

We obtained precipitation figures for the Lanišće station from the automatic station operated by IstraMet and flow data for the Sv. Ivan and Bulaž springs from the National Hydrometeorological Institute (DHMZ). At the Mlini spring we established our own measurements of water level, electrical conductivity (EC) and temperature. Istarski vodovod d.o.o. of Buzet regularly measures turbidity in the Sv. Ivan spring.

There was considerably less rainfall in the Croatian part of Istria than on the Slovenian side, with a total of just 25 mm of rain falling at the Lanišće station between 5.00 p.m. on 23 June 2015 and 3.10 a.m. on 24 June 2015 (Fig. 12.10). The reaction of the springs was correspondingly smaller. Compared to the Rižana, which at its peak reached 2.5 times its mean flow rate, the Sv. Ivan spring only slightly exceeded its mean flow, while the Bulaž and Mlini springs only reacted minimally. Changes in quality in the springs were also correspondingly smaller, so in our analysis of the results of flood pulse monitoring we decided to compare flow dynamics and solute transport in the Rižana and Sv. Ivan springs, which are also the two most important sources of drinking water supply in the area in question.

Although rainfall appeared in the catchment area of the Rižana approximately 3 hours earlier than in the Croatian part of Istria, the Sv. Ivan spring reached its peak flow approximately 6 hours before the Rižana did, which reflects the larger and more complex catchment area of the Rižana.

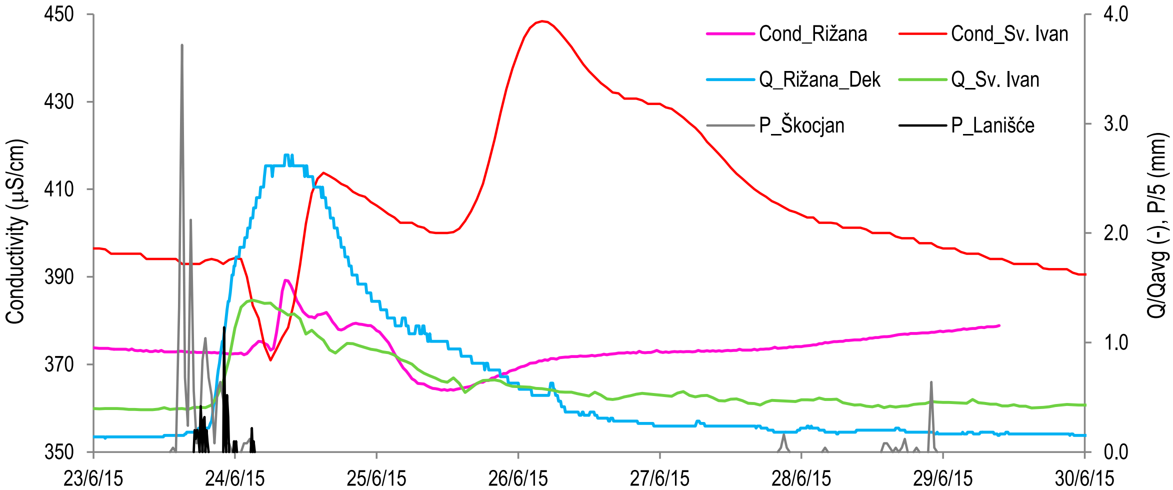

Figure 12.10: Precipitation P (divided by 5) in the catchments of springs on the Slovenian and Croatian sides, measured flows normalised to mean flow (Q/Q_{avg}) of the Sv. Ivan spring and the Rižana at the Dekani hydrological station, and conductivities of the Sv. Ivan and Rižana springs during the second flood pulse.

Differences between the two springs are also apparent from a comparison of EC changes during the flood pulse (Fig. 12.10). The increase in EC in the Rižana as the flow increases is explained by the forcing out of more highly mineralised water from less permeable areas of the vadose zone, and the beginning of the decrease in EC by the influx of newly infiltrated precipitation water from the karst surface. Little initial increase is observed in the Sv. Ivan spring, but the spring immediately reacts to an increase in flow with a reduction in EC, which indicates the rapid influx of newly infiltrated water to the spring. At the same time, turbidity also increases very quickly (Fig. 12.11). This is followed by a slowing of the flow rate with the discharge of more highly mineralised water from the wider catchment area. Fluctuations in EC values are the consequence of the complex catchment area feeding the spring.

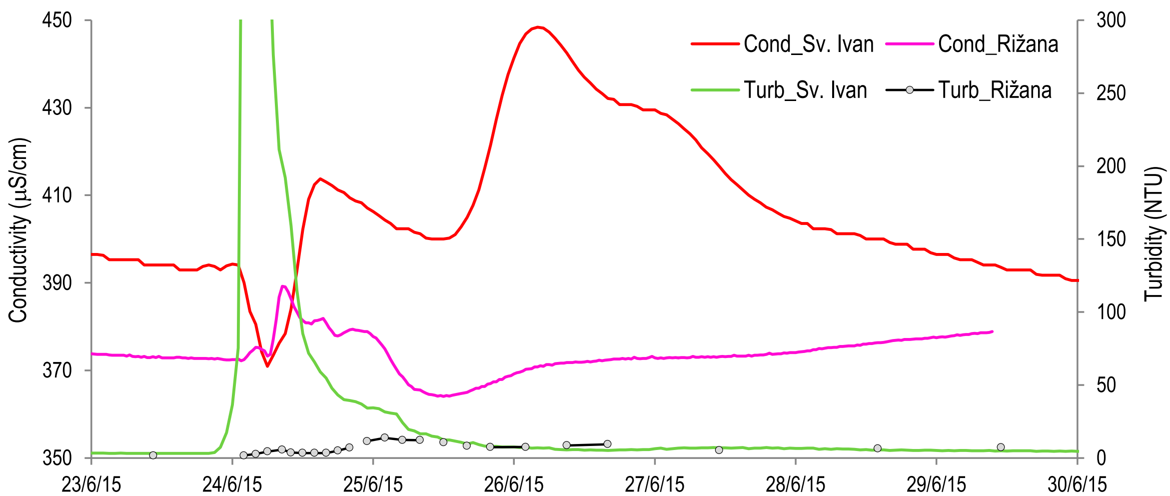

Figure 12.11: Electrical conductivity and turbidity in the Sv. Ivan and Rižana springs during the second flood pulse. Owing to the large differences in turbidity, the selected scale does not show the peak value for Sv. Ivan (1,812 NTU in automatic measuring and 731 NTU in the samples taken).

The analysed chemical parameters in the two observed springs also show different variation. Values for TOC (measured in unfiltered samples) are given by way of example (Fig. 12.12). In the case of Sv. Ivan, the influx of newly infiltrated water and the subsequent reduction in its percentage are mirrored by TOC, which first grows and then gradually decreases. In the Rižana, the mixing of different recharge components is reflected by a more variable shape of the TOC curve. Besides the differences in the structure and functioning of the karst aquifers in the catchment area of the spring, the reason for this lies in the different intensity of the precipitation events that triggered the flood pulse.

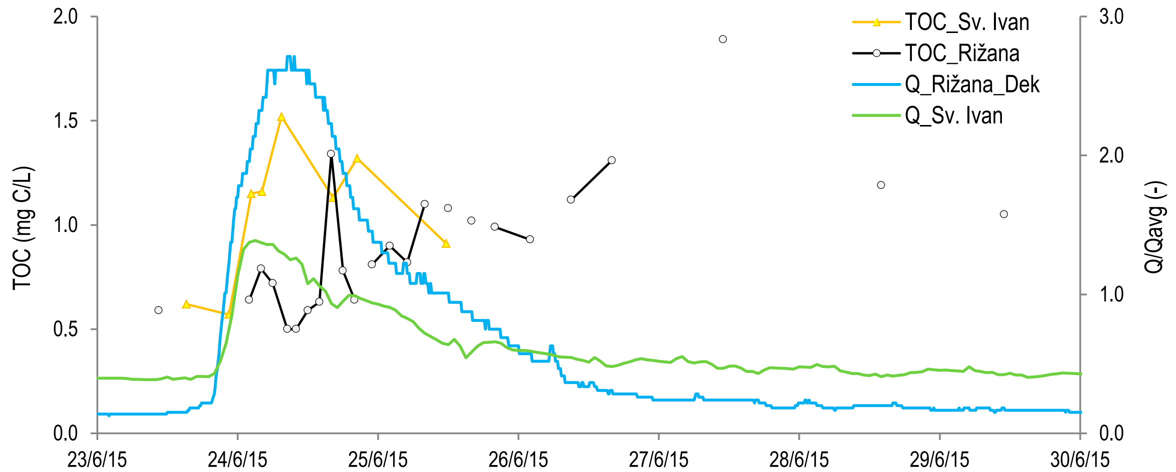

Figure 12.12: Changing TOC values in the Sv. Ivan and Rižana springs during the second flood pulse.

A comparison of turbidity and heavy metals content gives interesting results (Fig. 12.13). In the case of the Sv. Ivan spring, a very high turbidity of 731 NTU was measured in the sample taken at 4.10 a.m. on 24 June 2015. The highest turbidity recorded by automatic measurement was 1,812 NTU at 3.26 a.m. on 24 June 2015. The values in the Rižana were significantly lower, with turbidity first increasing to 5.8 NTU at 8.30 a.m. on 24 June 2015 and then in the second part of the pulse to 13.9 NTU at 2.00 a.m. on 25 June 2015. Turbidity in the Sv. Ivan spring began to increase in parallel with the start of the increase in flow. We concluded that the increase in flow triggered the transport of particles deposited in karst conduits and fissures. A similar explanation is suggested for the first peak of turbidity in the Rižana spring, while the second peak is the consequence of allogenic recharge by sinking streams from the flysch margin. In both springs the increase in turbidity was shown to coincide with higher concentrations of metals. This points to the transport of these metals by particles suspended in the water.

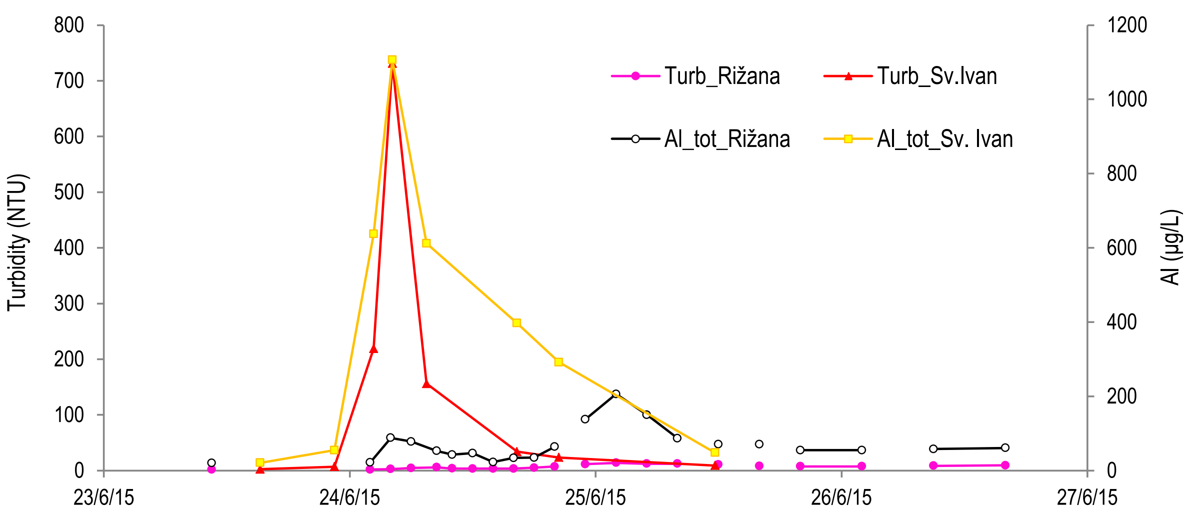

Figure 12.13: Turbidity and total aluminium concentration in analysed samples from the Rižana and Sv. Ivan springs in the second flood pulse.

We were also able to compare the results of isotopic analysis with data from studies conducted between 2001 and 2003 (Biondić et al. 2004). Although these earlier studies focused above all on changes in the isotopic composition of base flow, with samples taken during long dry periods rather than during flood pulses, the results obtained are very similar (Fig. 12.14). Greater changes in the isotopic composition of springs are observed in periods of precipitation, when directly infiltrated precipitation is discharged. The changes thus reflect the greater variability of the isotopic composition of precipitation. In base flow, on the other hand, homogenisation occurs because precipitation is balanced by groundwater stored in various parts of the saturated and unsaturated zones of karst aquifers.

Analyses of oxygen isotopes in the Rižana spring indicate a slightly greater variability of isotopic composition in comparison to older data and in comparison to variability in the Sv. Ivan and Bulaž springs. This can be explained by the greater variability of isotopic composition during the flood pulse, and also by the considerably more intense precipitation event in the catchment area of the Rižana in comparison to precipitation in the catchments of the Sv. Ivan and Bulaž springs.

In June 2015 only 4 analyses of δO^{18} were carried out in the Mlini spring and changes in the isotopic composition were not observed, probably because of the smaller quantity of precipitation in the catchment area. During this flood pulse, in fact, the water level increased by just 4 cm, which is significantly less than the increase of 50 cm recorded in January 2015. No samples were taken for isotopic analysis in the Mlini spring between 2001 and 2003.

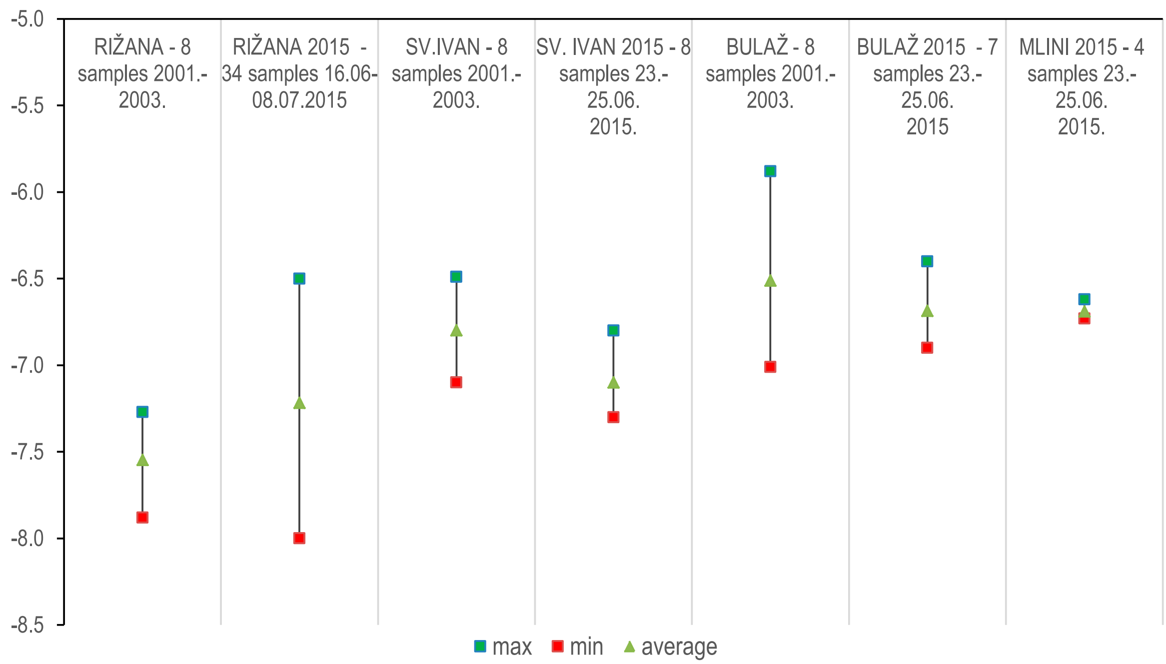

Figure 12.14: Comparison of the results of isotopic analysis of oxygen in the observed springs during the flood pulse in June 2015 and in the period 2001–2003.

Conclusions

The findings of the study are important for understanding flow dynamics and solute transport in karst aquifers, which is essential for the appropriate planning of monitoring of the quality of karst water sources. Monitoring of physical, chemical and microbiological parameters in the same spring during two flood pulses of differing intensity pointed to significant differences in the ways in which these parameters change. Besides the intensity of precipitation events, an important part is played by previous precipitation conditions, since springs react differently in dry and wet periods. Monitoring of the quality of the first flood pulse triggered by intense precipitation following a long dry period is important. As we observed in the case of the samples from the Rižana, this precipitation causes contaminants stored in the unsaturated zone to be flushed out, while at the same time the dynamics of contaminant transport are greatest during heavier rainfall.

The results confirmed the suitability of sampling at brief intervals, especially in flood pulses caused by intense precipitation events following a long dry period. Only in this way it is possible to detect rapid changes in the observed parameters and individual extreme values that are not detected by infrequent sampling without considering hydrological conditions. The highest sampling frequency is necessary in periods of the clearest changes in physical parameters, which can be measured relatively simply using appropriate measuring devices.

Monitoring of a large number of different parameters has pointed to significant differences in their transport through the karst aquifer. Analogously, different types of contaminants are transported differently, a factor that must be taken into account when planning monitoring.

A further advantage of this study is that we observed several different springs simultaneously. This showed us that every spring is specific and that even in a small area its functioning is affected differently by the local distribution and intensity of rainfall. It is therefore extremely important to carry out adequate research during the planning phase of monitoring in order to better understand the functioning of karst aquifers in the catchment area of a karst water source.

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Photo from "Water - Life!" in Istria competition; author: Kristian Macinić

Photo from "Water - Life!" in Istria competition; author: Aleksandar Tumulić

MICROBIOLOGICAL CHARACTERISTICS OF SELECTED KARST SPRINGS

Gorazd Pretnar

Introduction

Karst springs have for years been the subject of various studies by researchers from various scientific disciplines. Different interests meet in this vulnerable area. The most important anthropogenic interest is meeting people's needs for drinking water at the same time as conserving biodiversity. Dinaric karst area, icluding Northern Istria, is exclusively tied to capturing water from karst springs.

The common denominator of karst waters is the short retention period during which water remains in cave systems following rainfall. This may be recognised by changes in the quantity of water in springs. Varying intensities and quantities of precipitation cause flood pulses which change the microbiological and chemical properties of karst springs.

Microorganisms and karst

Microorganisms colonise various environments in caves, from cave walls to puddles, percolation water and condensate. The microbiologist Franc Megušar and the speleobiologist Boris Sket were among the first Slovene researchers to focus their attention on cave bacteria in Planinska jama cave (1977). The majority of the bacteria were Gram-negative. The following bacteria were grown from cave samples in laboratory conditions: *Bacillus subtilis, Bacillus cereus, Bacterium brevi, Proactinomyces polychromogenes (*Mulec 2008).

Figure 13.1: Condensation droplets in caves are full of various bacteria and glisten like silver or gold when lit by artificial light (Photo: Nadja Zupan Hajna).

Their work is being continued by younger colleagues. The findings of Janez Mulec are attracting particular attention. On the basis of morphological and biochemical tests, he and his colleagues identified various bacterial groups in gold and silver droplets on cave walls (Figs. 13.1 and 13.2). The dominant species of bacteria in them was *Pseudomonas florescens* (Mulec et al. 2002; Mulec 2008).

Figure 13.2: »Golden« bacteria in which the fluorescent pseudomonads group predominates (Photo: Nadja Zupan Hajna).

It may be that this phenomenon and the predominant presence of *Pseudomonas f.* can be connected with its ability to release surfactants (Ahern et al. 2007). Researchers have, in fact, found that surfactants in clouds play a very important role in lowering supersaturation. In the atmosphere, the process of activation of aerosol condensation around nuclei is in fact accelerated by the presence of *Pseudomonas f.* through the release of surfactants. Cloud and rain samples collected from two mountains in the Outer Hebrides, NW Scotland, UK displayed significant biosurfactant activity. *Pseudomonas f.*, which has the property of synthesising and releasing surfactants, was found in all samples. It is known that surfactants influence cloud droplet size and increase cloud lifetime and albedo (Ahern et al. 2007). By logically connecting the findings of Mulec and Ahern, not only do we identify the properties of *Pseudomonas f.*, but we can connect these findings to the water cycle and, above all, explain the formation of the silver droplets described by Mulec. It is very probable that this is yet another evolutionary adaptation in which *Pseudomonas f.* actively obtains nutrients through the combination of aerosols. There is no doubt that it creates an ecological niche for itself and the other bacteria found by Mulec in the droplets.

It will be interesting to wait for future studies that promise to shed light on the collective action of *Pseudomonas f.* and *Pseudomonas syringae*. Be that as it may, the invisible network of interdependence and interconnection with incredibly fragile bonds extending into hitherto unsuspected dimensions such as the creation of weather in connection with the biodiversity of the terrestrial world, the oceans and karst areas, is gradually being revealed to us.

It was long believed that karst aquifers do not have self-cleaning mechanisms such as those found in nature above other types of aquifers. Today we know that the areas of karst aquifers above and below the water surface are covered by a biofilm. This is a specific structure created by bacteria. It is a three-dimensional structure that is connected with the formation of various adhesins. Biofilms are created by various types of bacteria that are symbiotically connected. Among these bacteria there is regulation of growth, with the result that the three-dimensional structures do not change their shape. Under a microscope they are most reminiscent of a densely populated city with tower blocks. Biochemical processes and metabolic pathways in 90% of karst aquifers take place in the biofilm. And finally, in research conducted in the last 10 years, they have been given the common name of autochthonous bacteria of karst aquifers. Owing to its inaccessibility this autochthonous group of bacteria is still poorly researched.

It is, however, significant that we know of its existence and of its function in the self-cleaning process. In the process of multiplication within the biofilm, bacteria undergo planktonisation. This means that we find them moving freely in the water body of a karst aquifer. These bacteria are more or less metabolically dormant. We find them when taking samples in karst springs. Many of these bacteria can be cultivated in laboratory conditions, while there are also many in which cell division does not occur under laboratory conditions. Their presence can be traced in the total measurement of ATP (*adenosine triphosphate*). We can only create an indirect picture of the autochthonous population of karst aquifers. When taking samples from karst springs, from the microbiological point of view we actually see the planktonic part of autochthonous bacteria, which are joined, in different weather conditions, by groups of bacteria washed from the surface and those present in precipitation. The picture becomes even less clear if we also take into account the activity of bacteriophages.

Microbiology of flood pulses in karst springs

One of the characteristics of karst aquifers is that the flow rate of their springs changes in proportion to the intensity of precipitation. Intense precipitation causes a flood pulse in karst aquifers. We expected to find substances and microorganisms that could represent a threat to human health in flood pulse samples.

For this reason, we decided to use microbiological methods in our study in order to establish the presence of potentially pathogenic microorganisms. These analyses include detection of the total number of coliform bacteria, *E. cooli*, enterococci and *Clostridium perfringens* and the presence of a number of heterotrophic bacteria incubated at 22 and 37 °C.

In springs that we judged to be important, we also carried out tests for the presence of the parasites *Giardia lamblia* and *Cryptosporidium* spp. In order to ensure the reliability of our results, we did not expand the range of tests beyond accredited methods.

The above microorganisms are indicators of individual groups of microorganisms which represent a potential threat to human health. We use identification of their presence in drinking water in order to prevent potential hydric epidemics.

Coliform bacteria and *E. cooli* are considered the main indicators of faecal contamination. Taking into account the chemical parameters measured in this project, and on the basis of reciprocal communication, the results do not indicate faecal contamination of karst aquifers.

The microbiological indicators – the presence of coliform bacteria and *E. cooli* – appear to contradict the chemical analyses. This divergence is one of the surprises of the measurements carried out in this project.

These contradictory results pose the following interesting question: can the presence of coliform bacteria and *E. cooli* be attributed to natural background conditions rather than to faecal contamination?

An anthropogenic view of the karst landscape above and below the ground can quickly persuade us that this is an extreme region, particularly that below the ground. The view of a microbiologist, on the other hand, can be entirely different. If we merely consider temperature changes, we can state that temperatures are almost constant in caves and karst aquifers. They are by no means as extreme as on the surface, which is exposed to temperature fluctuations ranging from around -10 °C in winter and over 30 °C in summer. Another limiting factor for the growth of bacteria, besides temperature, is the presence of water, which is another constant of the cave environment. The only question that occurs to us here is to ask whether coliform bacteria and *E. cooli* are sufficiently adaptable to survive for a longer period outside the digestive tract of warm-blooded vertebrates. And, whether conditions in karst aquifers are such as to enable not only their survival but their adaptation to life among autochthonous bacterial flora. There is little literature available to confirm this hypothesis.

There is, however, an interesting example worth citing, on the basis of which it is possible to continue this line of thought, namely that the probability exists that coliform bacteria and *E. cooli* are part of the autochthonous bacterial flora of the karst aquifers in which we have carried out analyses as part of this project.

Researchers in New Mexico have found coliform bacteria in the pools of Lechuguilla Cave, part of the Carlsbad Caverns National Park, which have persisted there for years. This cave has numerous pools with their own specific bacterial community, which has been influenced by visiting cavers. Lechuguilla Cave is the 5th largest cave in the world. Its total length is 170 kilometres and it lies at a depth of 475 metres. Coliform bacteria were first discovered in the cave in 1995. Since that time, they have been found not only in the pools but also on the ground. Researchers have concluded that they either entered the cave system via the percolation of water from the surface or with the help of contamination from human activity in the caves. It is interesting to note here that chemical analyses of the water in the pools indicate a very low total carbon content, which points to the oligotrophic nature of the Lechuguilla Cave pools and the low energy value of the nutrients in them (Hunter et al. 2004). This situation is very similar to our findings, in that our chemical analyses also point to a low total carbon content. The group led by Andrea J. Hunter (2004) directed their research above all towards discovering different possibilities of bioremediation and tried to find a solution that would reduce the presence of coliform bacteria in the pools of Lechuguilla Cave.

They suspected the existence of a connection between the growth of coliform bacteria and biofilm in various cave features. They found that coliform bacteria grew significantly better in laboratory conditions in water taken from pools where a biofilm was present (Hunter et al. 2004). Given the findings on the existence of biofilms referred to in the introduction, this in itself offers an explanation of the persistence of coliform bacteria in karst aquifers. Naturally, this assumption does not exclude the possibility of simultaneous faecal contamination during a flood pulse in karst aquifers. If coliform bacteria have become part of the autochthonous bacterial population of karst aquifers, they lose their function as indicators of faecal contamination. The same would apply in this case to the presence of *E. cooli*.

Microbiological analyses of the flood pulse of the Rižana spring

The long drought in the spring of 2015 dragged on into the beginning of the summer. Since there was no rainfall worth mentioning, an interesting situation arose, at least from the microbiological point of view. Our colleagues state that their chemical measurements indicate that the flood pulse which we describe in this work caused dilutions in all the karst aquifers covered by the study. The same applies to the bacterial population of the karst aquifers, where we have to take into account influx via sinking streams and planktonisation of the biofilm. On 17 February 2015 we carried out the control measurements shown in Table 13.1.

Table 13.1: The table shows the presence of coliform bacteria, E. cooli, enterococci, Clostridium perfringens and a number of heterotrophic bacteria incubated at 22 and 37 °C. Samples were taken in eight locations.

	Coliform bacteria	**E. cooli**	**Enterococci**	**C. perfringens**	**No. at 22°C**	**No. at 37°C**
	CFU/100 ml	CFU/100 ml	CFU/100 ml	CFU/100 ml	CFU/ml	CFU/ml
Sv. Ivan sec.	20	10	2	5		41
Tombazin	30	30	2	1	110	45
Podgaće	5	2	1	4	>300	73
Bulaž	12	11	4	0	>300	35
Butori	22	22	2	0	260	20
Rižana	5	4	4	1	>300	30
Marušići	73	73	9	0	>300	38
Filarija	1	0	6	0	>300	15

The results shown in Table 13.1 are the average standard microbiological picture of karst springs. Coliform bacteria are present in low numbers, as is *E. cooli*. The number of both is for the most part in mutual correlation, with the result that we can say that *E. cooli* predominates. The results for enterococci and *Clostridium perfringens* merely indicate their presence. The most interesting figure is the number of heterotrophic bacteria incubated at 22 and 37 °C. Those heterotrophic bacteria incubated at 22 °C represent the population of the natural background. The majority of them do not survive at higher temperatures. And they are not a potential health threat as long as the number remains below 100/100 ml. Heterotrophs that survive incubation at 37 °C are representatives of the group of bacteria that could potentially survive in the human body and are an indicator group expressed merely as a number of potential pathogenic bacteria.

A situation showing a high number of heterotrophs (22 °C) is expected in all karst springs. The results are mutually comparable and are a relevant indicator of natural background conditions. Assuming that not all species can be cultivated in laboratory conditions, their number is slightly higher than shown. Heterotrophs (37 °C) are numerically significantly fewer than heterotrophs (22 °C).

Microbiological measurements carried out in all locations in January 2015, in a period with no notable precipitation, are mutually comparable and no location deviates significantly.

The first flood pulse (between 16 and 21 June 2015) is accompanied by growth in the number of coliform bacteria, which decline in number with the decrease of the flood pulse (Fig. 13.3). If we were to make conclusions merely on the basis of this flood pulse, we would undoubtedly conclude that we were looking at faecal contamination as a consequence of precipitation washing coliform bacteria from the land. Or faecal contamination carried by sinking streams. This assertion would be correct if the same picture had appeared in the second flood pulse, which followed a few days after the first. However, notwithstanding the strength of the second flood pulse, the number of coliform bacteria fell consistently until 26 June. We may therefore state, as our colleagues noted, that the first and second flood pulses were characterised more by dilution than by influx. The second peak in the appearance of coliform bacteria is only noted when the water level falls, something which could be more plausibly explained by the flushing of the higher-lying water basins of the karst aquifer.

The behaviour of *E. cooli* during the flood pulses in the karst aquifer of the Rižana is identical to the description of coliform bacteria shown graphically in Graph 1.

Clostridium perfringens is one of the most common bacteria and is found in nature in decomposing organic matter of animal and plant origin. We find it in the digestive tract of both vertebrates and insects. Throughout the first flood pulse and until the start of the decrease of the second flood pulse on 25 June, the number recalls our base measurements in January 2015. The number remains low throughout this period. This means that during the first pulse *Clostridium perfringens* was not the subject of dilution, as was found for coliform bacteria. If this had been a case of rapid flushing from the surface, we would have seen this in both pulses, either at the beginning or in the middle. The shift in the appearance of an increased number of *Clostridium perfringens* is the surprise of this project. It is highly likely that this is a case of the percolation of water on the surface through the soil and fissures filled with organic material. *Clostridium perfringens* is always an indicator of old contamination or of a long-lasting natural process of demineralisation. A few other conclusions may be drawn from the results of the measurements of the presence of *Clostridium perfringens* in the two flood pulses. We may conclude that there is very little likelihood that *Clostridium perfringens* is a representative of the biofilm of karst aquifers. While this is, of course, a hypothetical assertion – one that it will be possible to prove through other studies involving sampling of the biofilm – it is certainly probable, since despite reciprocal contact inhibition of growth, representatives of the biofilm ensure their own reproduction through planktonisation. In the specific case of *Clostridium perfringens* this would be a process of sporulation. And the number, following a lengthy dry period, would in this case be greater and at least comparable to coliform bacteria in terms of the time of appearance. The measurements are not only interesting as a new scientific finding, but also as the basis for advice to hydrologists on what to expect when a flood pulse decreases. *Clostridium perfringens* infections are very common in some European countries, particularly in the United Kingdom. Such infections are very unpleasant. It would therefore be logical to note that reservoirs should be filled before major precipitation events and that the flood pulse should be allowed to pass until complete stabilisation is re-established. Such a contingency would make it possible to avoid a potential hydric epidemic caused by *Clostridium perfringens*. This advice is particularly relevant to smaller water supply systems connected to karst aquifers. It would also be useful to take samples following a flood pulse and to carry out microbiological analyses to test for the presence of *Clostridium perfringens*.

Table 13.1 (the Rižana spring) shows a numerical value of >300 CFU/ml. This value is the product of an accredited method, which we preferred not to change by increasing dilution. The second reason is that a value of >300 CFU/ml already exceeds the permitted limit for drinking water.

This does not make the results any less valuable, since even in this context they clearly point to a process of flushing of the planktonic part of the bacteria from the karst aquifer. The results of the second pulse are not as homogeneous as those of the first. There is a fluctuation of the presence of heterotrophs (22 °C). These fluctuations following the first pulse may be attributed to particular features of the internal structure of the karst aquifer, including the diversity of the surface and the hydrology of the sinking streams.

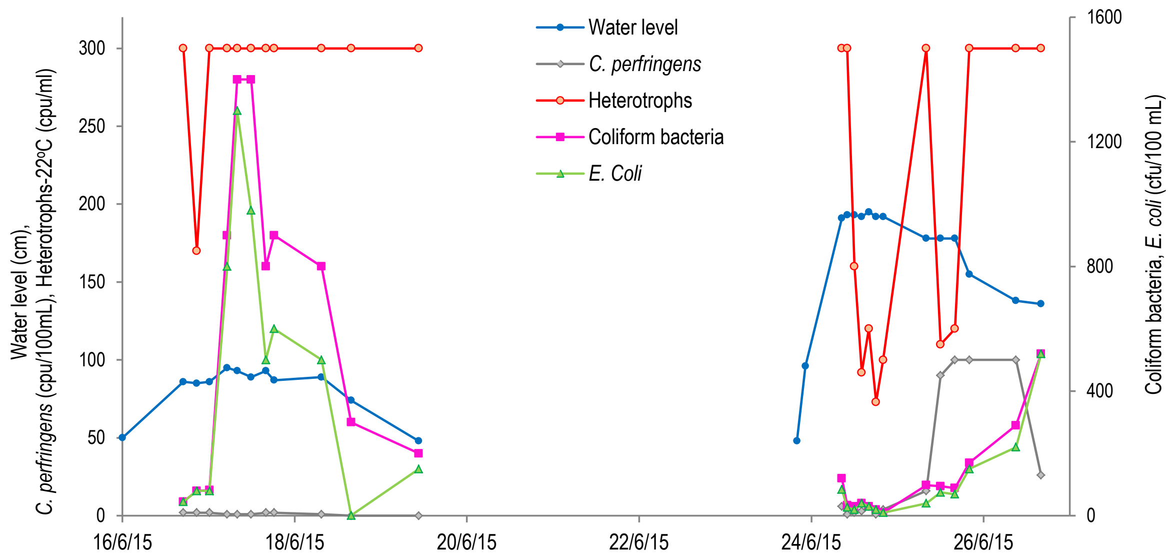

Figure 13.3: The graph shows the presence of coliform bacteria, E. cooli, Clostridium perfringens *and heterotrophs (22 °C) during the two flood pulses at the Rižana spring.*

Microbiological analyses of the flood pulse of the Sv. Ivan spring

The flood pulse in the Sv. Ivan spring was not as pronounced as in the Rižana spring but still sufficiently strong to allow observation of microbiological changes. While the sampling frequency was lower, it was nevertheless high enough to enable a comparison. In this case, too, coliform bacteria corresponded numerically with the number of *E. cooli*. Likewise, we may point to the effect of flushing, as seen in the case of the Rižana spring.

The flood pulse in the Sv. Ivan spring began on 23 June and reached its peak on 24 June, coinciding with the second pulse in the Rižana spring. Since in the case of the Sv. Ivan spring we do not have two pulses of at least approximately equal intensity, comparison is difficult but nevertheless possible. The only logical comparison is that of the first pulse in the Rižana spring and the pulse in the Sv. Ivan spring (Fig. 13.4).

Owing to the previous flushing, the second pulse in the Rižana spring is not comparable at all.In both springs the number of coliform bacteria and *E. cooli* grew steeply. In both cases this was very probably a consequence of the flushing out of the karst aquifer following a long dry period.

The first difference appears with regard to *Clostridium perfringens*. *Clostridium perfringens* is barely detected in the first pulse in the Rižana spring, and is not observed until the last part of the second pulse. In the Sv. Ivan spring we detect it immediately, on 24 June, during the peak of coliform bacteria, *E. cooli* and enterococci. This is followed by a fall in the number and a new peak on 25 June when the pulse is already abating. In between, a further lower peak is detected. We attribute the difference to the different structure of the karst aquifer and the different landscape of the recharge area.

Heterotrophic bacteria (22 °C) reach their peak in the flood pulse in the Sv. Ivan spring on 24 June. The peak continues despite the fact that the flood pulse is abating. On 7 July the number of heterotrophic bacteria (22 °C) decreases to 105. In terms of a comparison of the number of heterotrophic bacteria (22 °C), both karst springs – Sv. Ivan and Rižana – are comparable. When the flood pulse occurs, the number of heterotrophic bacteria (22 °C) increases rapidly and persists long after the water level falls.

We may conclude that tracking the number of heterotrophic bacteria (22 °C) is the factor that indicates that microbiological stability has returned to the springs following a flood pulse.

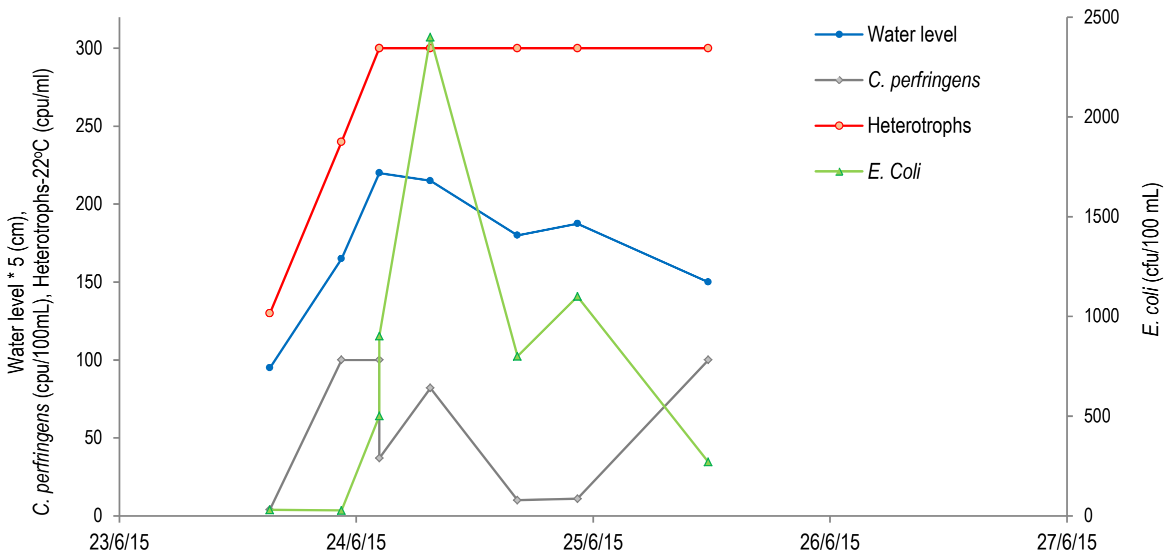

Figure 13.4: The graph shows the presence of E. cooli, Clostridium perfringens *and heterotrophic bacteria (22 °C) during the flood pulse at the Sv. Ivan spring.*

Conclusions

Our measurements demonstrated and confirmed the claims of our peers that karst aquifers differ from each other, with the result that it is difficult to arrive at a common denominator. This means that every manager of a water supply system that is fed by karst aquifer needs to know it well. And it is only possible to know it well through a sufficient number of microbiological analyses and familiarity with its individual specific characteristics.

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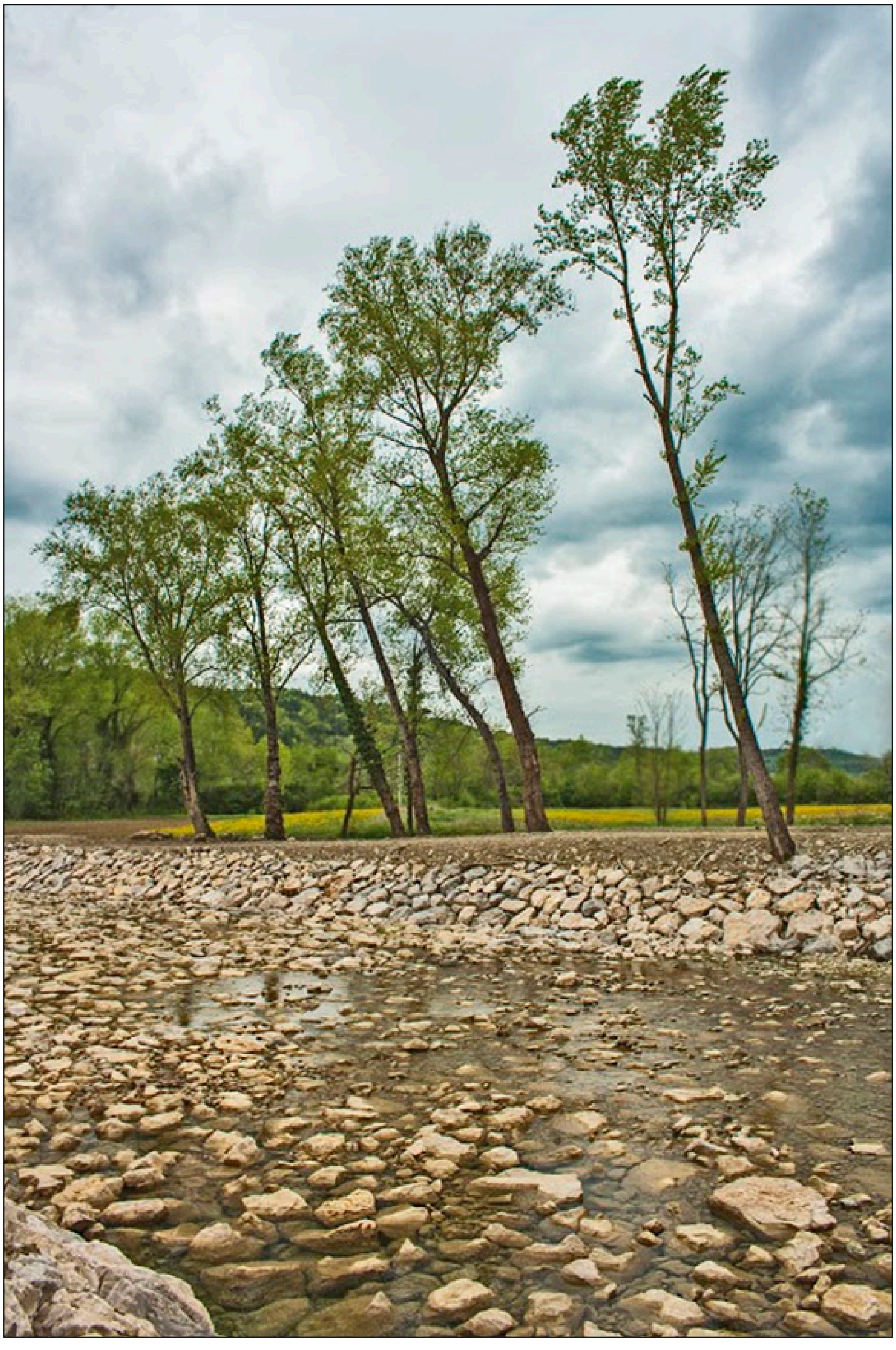

Photo from "Water - Life!" in Istria competition; author: Mirna Bartolić

MONITORING THE QUANTITATIVE STATUS AND QUALITY OF KARST WATER SOURCES

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Introduction

Establishing the quantitative and qualitative status of waters and detecting exceptional situations requires regular monitoring of climatic, hydrological, physical, chemical, biological and bacteriological parameters. The characteristics of the monitoring through which this is done are defined in the national regulations of each country. The specific characteristics of karst waters are not adequately taken into account by legislation either in Slovenia or Croatia, and for the most part the same method is used for monitoring of groundwater from karst aquifers as is used for intergranular aquifers, which, however, typically differ in terms of their hydrological dynamics.

For this reason one of the objectives of the research forming part of the ŽIVO! project was to carry out monitoring of the quantity and quality of water in selected karst water sources in the Northern Istria in conditions of changeable hydrological conditions with the appearance of a flood pulse following a long dry period, when usually critical values of individual water quality parameters are recorded. Analysis and interpretation of data obtained in this way represent the basis for the recommendations submitted here for an improvement to the existing model of monitoring the quantity and quality of karst waters.

Monitoring in the national regulations of Croatia and Slovenia

In EU Member States, national regulations (laws, decrees, rules, etc.) relating to monitoring must take into account the requirements of the Water Framework Directive (2000/60/EC) and the Directive on the protection of groundwater against pollution and deterioration (2006/118/EC). The umbrella laws that regulate the legal status of waters and numerous other measures and activities related to water and water resources (e.g. management of water quality and quantity, public water supply activities) are, in Slovenia, the *Zakon o vodah* (Waters Act) and its amendments (Official Gazette RS 67/2002) and, in Croatia, the *Zakon o vodama* (Waters Act; Official Gazette RH 153/2009, 130/2011, 53/2011, 14/2014).

In Slovenia the quantitative and qualitative status of karst groundwater is assessed on the basis of groundwater monitoring, which is regulated by the Rules on Groundwater Monitoring (Official Gazette RS 31/2009) in accordance with the EU directives. The Rules set out the method and scope of groundwater monitoring and the frequency of sampling, analyses and measurements. Groundwater monitoring includes monitoring of chemical status and monitoring of hydrological phenomena. The parameters of the chemical and quantitative status, the values of the quality threshold of groundwater, the criteria and method of assessment of quantitative and qualitative status and action to be taken, where necessary, are laid down by the Decree on Groundwater Status (Official Gazette RS 25/2009, 68/2012). The network of monitoring sites, measured parameters and sampling frequency, and sampling and analysis methods are laid down by the Water Status Monitoring Programme prepared for the period 2010–2015 (2011). In the context of national monitoring, sampling in shallow aquifers is envisaged, in the case of karst-fissured aquifers, in boreholes or springs up to twice a year at each sampling location. Groundwater monitoring under this Decree is carried out by the Ministry of the Environment and Spatial Planning of the Republic of Slovenia.

The Rules on the Definition of Bodies of Groundwater (Official Gazette RS 63/2005) include karst springs in groundwater monitoring. Monitoring of the quantitative status of groundwater in bodies of water with predominantly karst and fissured porosity will take place in the period 2010–2015 in 21 springs and four boreholes (Water Status Monitoring Programme for 2010–2015, 2011). These include the spring of the Rižana, which is part of the groundwater body »Coast and Karst with the Brkini«.

National monitoring of water status for 2010–2015 does not envisage biological analysis and identification of the ecological status of groundwater. Biological analyses of water quality assessment are analyses of a consequent state, where we analyse the effects left by allochthonous substances in the water environment in biotic communities, populations and organisms, and are an appropriate complement to chemical analyses. Ecological analyses (biological and microbiological) are carried out in the natural environment and used to establish the state of biotic communities in a given environment (in situ). A biotic assessment is a summary assessment in that it takes into account abiotic and biotic factors. This type of monitoring would mean regular (at least two or three times a year) monitoring of biotic parameters.

Natural waters in Croatia fall within the purview of the Ministry of Agriculture's Water Management Department. The Decree on Water Quality Standards (Official Gazette RH 73/2013, 151/2014 and 78/2015) transposes the European water directives into Croatian law. This Decree prescribes quality standards not only for groundwater but also for surface waters, including coastal waters and territorial waters. It prescribes special water protection targets, criteria for setting water protection targets, conditions for extending the deadlines for the achievement of these targets and elements for water status assessment, water status monitoring and water status reporting. No special legislation exists for groundwater.

Groundwater status monitoring is carried out according to a monitoring plan of Croatian Waters at a network of measuring stations as control and operational monitoring and, where necessary, investigative monitoring. It includes the taking of samples and the analysis of groundwater with regards to parameters indicative of the quantitative and chemical status of each prescribed element of quality. This provides a comprehensive overview of the chemical status of groundwater in a river basin district and identifies a perceptible and constantly increasing trend of pollution of this water.

In both countries the different purposes of monitoring the qualitative and quantitative status of groundwater also require different types of monitoring, which can be divided into control monitoring, operational monitoring and investigative monitoring. Control monitoring complements and evaluates pollution assessment procedures and provides information for the assessment of significant and constantly growing trends which are the result of changes in natural conditions and the impact of human activities.

Operational monitoring is carried out in order to determine the chemical status of all bodies of groundwater for which a danger of failure to achieve water protection targets has been identified by a study of the characteristics of the river basin district and in which changes in status are monitored during implementation of the programme of measures and identification of significant and steadily worsening trends in terms of concentrations of contaminants as a consequence of human activities.

Investigative monitoring is carried out when the causes of exceedance of limit values of water status assessment parameters are unknown, when control monitoring indicates a low probability that a specific body of groundwater will achieve water protection targets and operational monitoring to determine these causes has not yet been established, in order to determine the extent and impact of sudden pollution and obtain information necessary for the establishment of a programme of measures to achieve water protection targets and the definition of a programme of special measures to eliminate the consequences of sudden pollution.

Monitoring of the quantitative status of groundwater must enable a reliable estimate of the quantitative status of a body of groundwater, including an estimate of available groundwater reserves. The spatial distribution of stations and the frequency of measurement of quantitative status must enable an estimate of groundwater levels in each groundwater body, taking into account short-term and long-term changes in the recharge of these bodies. Groundwater bodies identified as being at risk and transboundary aquifers require additional measuring locations, which are essential for estimating the direction and rate of flow of groundwater.

In Slovenia the possible presence of pollutants in drinking water sources is additionally verified through monitoring of quality and conformity with limit values on the basis of the Drinking Water Monitoring Programme (2015) prescribed by the Rules on Drinking Water (Official Gazette RS 19/2004, 35/2004, 26/2006, 92/2006 and 25/2009) and implemented under the aegis of the Ministry of Health. The purpose of this monitoring is to verify the conformity of drinking water with the requirements that must be met by drinking water and to protect human health from the harmful effects of any form of pollution in drinking water. The Rules lay down a set of parameters and limit values, monitoring procedures, requirements for sampling and testing methods, internal control procedures for operators, and the required number of samples, which varies depending on the quantity of water distributed in the supply area. The Programme defines sampling locations, sampling frequency and sampling methodology and lays down requirements for personnel and the laboratories that perform the analyses. The number of samples is evenly distributed in time and space, so a weekly schedule is drawn up of drinking water monitoring for regular and periodic testing (Drinking Water Monitoring Programme 2015).

Regular testing provides basic information on drinking water such as organoleptic properties (odour, taste, turbidity, colour), electrical conductivity and consequent mineralisation of water, turbidity and microbiological safety, and also information on the effectiveness of treatment of drinking water (particularly disinfection) where this is used. Periodic testing is carried out in order to obtain information on the conformity of drinking water with specific pollution parameters. The Programme includes consumers' taps as sampling locations, while internal controls from source to consumer are carried out by the operator of water supply system.

In Croatia the Decree on Water Quality Standards does not apply to water intended for human consumption, which instead falls under the Water for Human Consumption Act (Official Gazette RH 56/2013, 64/2015). Just as in Slovenia, the Act prescribes regular monitoring and audit monitoring of the water supply system and monitoring of springs as the entry points of these systems. The Rules on Conformity Parameters and Methods of Analysis of Water Intended for Human Consumption (Official Gazette RH 125/2013, 141/2013) prescribe the scope of analyses (mandatory parameters for regular monitoring, microbiological and chemical parameters of the wholesomeness of water and indicator parameters in audit monitoring and monitoring of springs). The frequency of measurement and the number of measuring stations are defined with regard to the quantity of water delivered within the water supplies, expressed in m^3/day. Monitoring of springs takes place once a year and covers all wholesomeness parameters and indicator parameters, with the exception of those parameters that are characteristic of the polymer materials of water supply pipes in the water distribution system.

Monitoring of springs observed within the ŽIVO! project

In the course of the regular internal controls carried out by Rižanski vodovod Koper d.o.o, which provides the mandatory local public service of drinking water supply within the three coastal municipalities (Koper, Izola and Piran), between 7 and 12 tests of untreated water are carried out each year in the Rižana spring, including at least two tests covering an expanded set of parameters in accordance with the Rules on Drinking water. The water in the spring is untreated and, owing to frequent microbiological contamination, is unsuitable for drinking water supply. For this reason it is appropriately treated at the Cepki waterworks.

In 2013 and 2014, only one set of samples per year was taken from the Rižana-Zvroček spring as part of groundwater monitoring. On this basis water quality for the groundwater body »Coast and Karst with the Brkini« was assessed as good.

The Sv. Ivan, Bulaž and Mlini springs are monitored within the context of the control monitoring carried out by Hrvatske vode d.o.o., and also as part of the monitoring of springs under legal requirements for water intended for human consumption. The other measuring locations included in the ŽIVO! project are not included in any kind of monitoring. In 2014 four analyses of chemical and microbiological parameters were carried out under the Decree on Water Quality Standards at the Sv. Ivan and Bulaž springs, while a single analysis was carried out at each spring under requirements for water intended for human consumption (Rules on Conformity Parameters and Methods of Analysis of Water Intended for Human Consumption) as part of the monitoring of springs for all parameters contained in the Rules. The assessment of the chemical status is good, while regarding microbiological parameters the water does not meet requirements and needs to be disinfected before use.

Weaknesses of existing monitoring

The quantitative status of water in karst aquifers is determined by the level of groundwater and the quantity of water discharged by springs. The Water Framework Directive (2000/60/EC) provides that the basic indicator for an estimate of quantitative status should be the level of groundwater. However, unlike in non-karst areas, where piezometer boreholes enable a relatively good generalisation of the spatial distribution of water levels on the basis of point data, in karst aquifers the lack of homogeneity means that this is not usually possible. For this reason, monitoring of the dynamics of fluctuation of the groundwater level in order to estimate quantitative status is extremely rare, and for the most part quantitative status is monitored in locations where groundwater is most accessible and dynamics are greatest – i.e. at karst springs. It is of course also necessary to develop monitoring of the fluctuation of groundwater levels in the active parts of a karst aquifer, where speleological structures – ponors and caves – which have a contact with the base water flow are highly suitable measuring locations in that they reflect the situation in these most active parts of karst aquifers.

Establishing the qualitative status of groundwater is conceived in such a way that analyses of samples only show the current status at the time the samples were taken. The hydrological circumstances at the time of taking untreated samples of water are not precisely laid down in existing national monitoring programmes. In cases where a spring is not simultaneously a water source, the planned density of sampling is too low. Furthermore, the existing national monitoring programmes do not take sufficient account of the fact that in karst areas current conditions are to a large extent influenced by the specific characteristics of water flow. Since conditions in karst aquifers change rapidly, the results of the planned monitoring do not necessarily show representative values of the qualitative and quantitative status.

Owing to the specific characteristics of groundwater flow, the quality of karst water sources typically changes in different hydrological conditions. The most intensive flushing and transport of contaminants usually takes place in periods of more intensive rainfall, particularly after rainfall following a long dry period. In such situations, the quality of karst waters can deteriorate very quickly. Fluctuations in the values of individual parameters are particularly significant in karst springs which have a complex catchment and are not only fed by diffuse infiltration of precipitation but also by sinking streams.

In karst areas, knowledge of water flow dynamics in the catchment is therefore important for good monitoring of quality. When planning a sampling programme, it is also sensible to take into account the characteristics of water flow and the transport of contaminants in karst, since periodic sampling – usually monthly or quarterly – which is independent of hydrological conditions cannot give an insight into short-term climaxes of flood pulses at a spring, which are not measured in days but in hours and are dependent not so much on the season as on current hydrological conditions in the catchment. Individual detailed research of flood pulses points to different reactions in individual springs, meaning that in the case of karst springs there are more exceptions than rules. In the case of karst springs, it would therefore make sense to supplement basic monitoring of groundwater quality with accurate monitoring of water quality during flood pulses. At present, monitoring of this type is only carried out rarely, usually as part of research projects.

The situation is different when it comes to biological assessment of water quality, where in periods of greatly changed hydrological conditions, e.g. in the case of increased rate of flow, we do not usually carry out sampling, since a specific organism may only be present as a result of floating matter. Sampling is carried out in periods of stable hydrological conditions. Underground, just as in surface waters, the presence or absence of organisms is a criterion for the evaluation of water quality and changes to the environment. Indicator species (or bioindicators) are therefore species that indicate specific characteristics of an environment without the need to use instruments to measure pollution variables. An indicator organism is one that is chosen for quality evaluation because of its sensitivity or tolerance to different sources of pollution or consequences of pollution (e.g. pollution with heavy metals, reduced oxygen concentration, etc.). The best indicators are those with a narrow ecological tolerance, since their presence best reflects conditions in the water environment.

A frequent problem in groundwater is the accumulation of organic matter. Since primary production is absent underground and the circulation of matter does not take place in the same way as in surface waters, subterranean organisms use surplus organic matter as a source of food. This results in changes to the composition, biodiversity and numerical size of subterranean biotic communities.

The recommended European directives on a common water policy envisage biological methods that are mutually comparable, particularly when it comes to determining the borderline between good and poor quality. At the same time, however, they recommend that each country should use its own, already established method. It is important to realise that the majority of biological methods used in a given region or country require modifications when transferred to new environments. This is necessary above all because of species specificity, particularly among macroinvertebrates.

Results of the ŽIVO! project study

The weaknesses described above were our starting point when planning activities in the ŽIVO! project. We conducted a study of the dynamics of changes in water quality in selected karst water sources managed by Rižanski vodovod d.o.o. (Slovenia) and Istarski vodovod d.o.o. (Croatia) and related water flows in the wider area of influence. Detailed monitoring of rainfall and hydrological conditions, measurement of physical parameters at 30-minute intervals and the taking of samples for chemical and microbiological analysis every few hours took place in June 2015 in a period of flood pulses following a long dry period. The results of the monitoring, during which we observed several different springs in parallel, showed that every spring is specific and that even within a small area its activity is affected in different ways by the local distribution and intensity of rainfall. It is therefore extremely important to carry out adequate research during the planning phase of monitoring in order to better understand the functioning of the karst aquifer in the catchment areas of individual karst water sources.

The results confirmed the suitability of sampling at brief intervals, since only in this way is it possible to detect rapid changes in the observed parameters and individual extreme values that are not detected by infrequent sampling. The highest sampling frequency is necessary in periods of the rapid changes in physical parameters, which can be measured relatively simply using appropriate measuring devices. The establishing of online monitoring of characteristic parameters such as electrical conductivity and turbidity guarantees the timely acquisition of information on the need for temporary exclusion of a spring from the water supply system, to avoid overburdening the water treatment system with harmful substances that would prevent it from functioning correctly. Though these parameters are not directly determining the contamination.

Additionally acquiring information on the occurrence of such extreme states is equally important purpose of such monitoring, so as to allow the preparation of background documentation for the drawing up of prognosis models of such states. With models of this kind, we would be able to foresee critical situations involving extreme turbidity or the appearance of the contaminants even before they occur and take appropriate measures (e.g. abstracting larger stocks of water from a spring before deterioration of its quality and storing it in reservoirs in order to be able to use it to bridge periods of extremely poor quality).

Observation of two successive flood pulses in the spring of the Rižana confirmed that it is important to monitor the quality of the first flood pulse triggered by heavy rainfall following a long dry period. Such rainfall causes contaminants stored in the unsaturated zone to be flushed out, while at the same time the dynamics of contaminant transport are greatest during heavier rainfall.

Monitoring of a large number of different parameters has pointed to characteristic differences in their transport through the karst aquifer. Analogously, different types of contaminants are transported differently, a factor that must be taken into account when planning monitoring.

On the basis of analysis of collected results and our knowledge of the characteristics of water flow and contaminant transport in karst, obtained through numerous previous studies, we have drawn up some proposed guidelines for the monitoring of the quantitative and qualitative status of karst water sources.

Guidelines for monitoring the quantitative status of karst waters

It is recommended that all important springs, and in particular all springs connected to the public drinking water supply system, be included in a monitoring programme that includes monitoring of water levels at the spring, the quantity of captured water and overflow water and the total water flow in these springs. The data obtained need to be used to allow an estimate of the water balance at various levels – from an estimate of the current flow value at the spring to an estimate of the average balance of discharge and quantities abstracted for water supply over a number of years.

In order for the status of a water body to be assessed as good, the mean annual quantities of abstraction from this water body must not exceed the mean annual recharge quantities, less environmental flow, over a longer period. As well as monitoring the overall water balance of discharge, it is essential to carry out hydrological monitoring of the quantities entering the system, i.e. meteorological parameters (above all rainfall) and concentrated inflows in the catchment area, i.e. watercourses, which most often end in ponors. This monitoring of quantitative status includes monitoring of water levels in surface flows before their infiltration underground or into a ponor and an estimate of flow from data on recorded levels and the consumption curve for this profile. Hydrological stations should be set up in such a way as not to slow the drainage of water underground.

In addition to providing hydrological information for control, operational and investigative monitoring of the qualitative status of water, monitoring of the quantitative status should also provide a basis for adequate active management and use of water sources in karst areas. In this sense, it is also essential to ensure the remote transmission of data on water levels from measuring points to the water supply company's administrative centre, since this would enable optimisation of water use. Also important, alongside the monitoring of water levels, is the parallel monitoring of specific physical and chemical parameters (e.g. water temperature, electrical conductivity), while in springs where problems of increased turbidity are more frequent, this parameter should also be measured.

The interval for reading hydrological data depends on the size of the aquifer and the spring through which the aquifer discharges, and also on the speed with which the spring reacts to changes in its catchment area. The recommended interval is a maximum of 1 hour under stable hydrological conditions and a maximum of 10 minutes when monitoring changes during flood pulses.

Guidelines for monitoring the quality of karst water sources

Accurate monitoring of water quality at different water levels in karst areas significantly increases our ability to detect contamination. We are most likely to detect poor water by carrying out detailed monitoring of a flood pulse. This is a period in which water flow grows, peaks and falls. It is triggered by heavy rainfall and accompanied by changes in physical, chemical and microbiological parameters. Periods of rainfall following a long dry period usually result first in a flushing-out of contaminants stored in the unsaturated zone. If rainfall is particularly heavy, the movement of these contaminants towards springs can be very fast.

In order to plan monitoring logically, it is first necessary to draw up a monitoring plan (Fig. 14.1). This requires the collaboration of an expert in karst hydrology who understands water flow dynamics and contaminant transport in the catchment area of karst water sources. After an appropriate period, the suitability of the plan needs to be verified on the basis of analysis of the results collected and, if necessary, the plan should be adapted to the identified characteristics of the source or to new research findings.

Since every karst aquifer system is unique, an individual monitoring plan is required for each individual water source. The strategy below merely offers guidelines for such a plan:

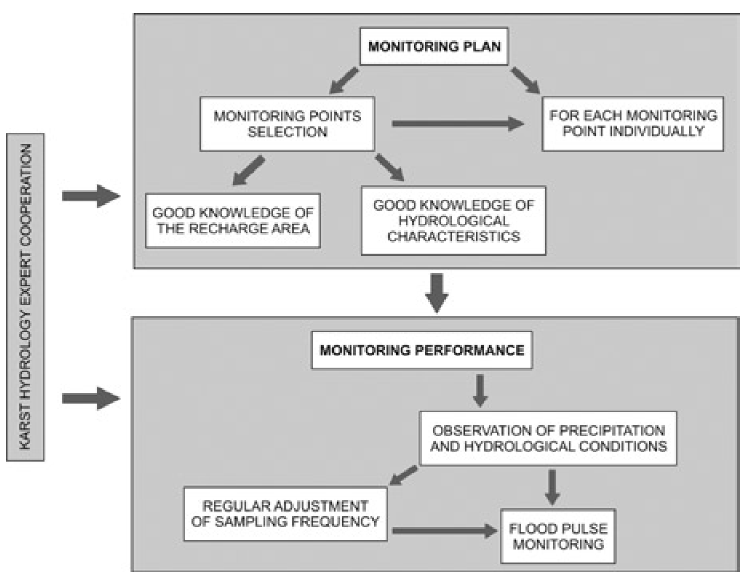

Figure 14.1: Schematic diagram of a monitoring plan and monitoring performance.

Because many karst springs have large and complex catchment areas in which autogenic recharge (rainfall) combines with allogenic recharge (sinking streams), the combination of negative impacts from various sources of contamination is possible. In order to adequately plan quality monitoring, good knowledge of the functioning of karst aquifers, the area in question and the hydrological characteristics of the water source is necessary. A variety of geological, hydrogeological, hydrological, geomorphological, speleological and other data can be of use here.

Sampling locations in karst areas are usually springs, which represent the discharge of karst groundwater onto the surface. Occasionally, boreholes are also used. After choosing the monitoring location, the reaction of the water source to rainfall needs to be evaluated. A reaction of the water source to rainfall and the transport of contaminants through the karst is only triggered by sufficiently abundant effective rainfall. Flow data and simultaneous measurements of temperature, electrical conductivity and turbidity are very useful. Changes in the values of the latter parameters also indicate the possibility of changes in water quality. Earlier hydrological studies or tracer tests carried out in the area under observation can serve as an additional basis for an estimate of how much rainfall and what conditions are sufficient to result in the transport of contaminants. In cases where sufficient data are available, we can use special technological equipment and knowledge to model the reaction of a water source to rainfall.

When sufficient quantities of rainfall are forecast, frequent monitoring of precipitation and hydrological conditions is essential. Sampling is carried out in the period from the initial low rate of flow, during the growth phase and after the peak has been reached, and during the decrease in the flow rate until conditions before the precipitation event are restored (Fig. 14.2). Since changes are very rapid during a flood pulse, sampling needs to be carried out at intervals of every few hours at the start of the precipitation event and during the increase in the rate of flow. Sampling frequency should be greater during the growth phase until the middle of the decrease in the flow rate, since this is also when the dynamics of contaminant transport are greatest. Sampling frequency should be adjusted on an ongoing basis with regard to the reaction of the water source and ongoing meteorological and hydrological conditions.

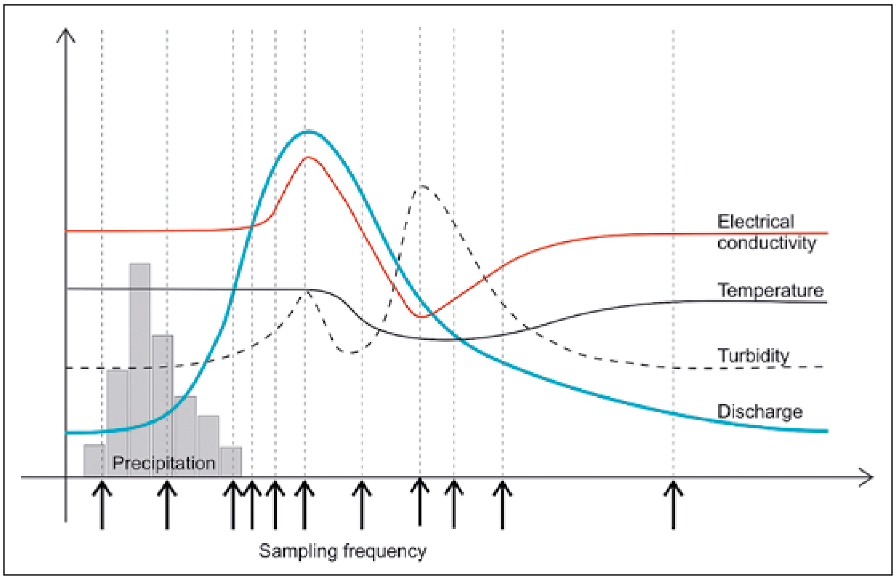

Figure 14.2: Proposed sampling during a flood pulse. Sampling frequency should be adapted to the reaction of the water source and ongoing meteorological and hydrological conditions.

In order to identify the actual qualitative status of karst springs, additional monitoring is necessary of the quality of ponor waters in their catchment area, in order to provide a complete picture of the flushing and dilution of contaminants.

It is recommended that biological monitoring and monitoring of the ecological status of groundwater should include seasonal (or at least twice- to thrice-yearly) sampling of subterranean aquatic fauna, in order to identify any changes to communities of organisms and their vitality or eventual threatened status. Subterranean fauna is specialised for life under specific conditions, and the species composition is entirely different from that of surface fauna.

For this reason professionally trained personnel are required.

Since the subterranean environment is closely connected to the surface environment, monitoring of the fauna in water that percolates underground (»epikarst fauna«) is also recommended. The epikarst zone lies a few metres or less below the surface, and inappropriate or uncontrolled activities on the surface can endanger the epikarst population. Epikarst fauna is frequently also the main source of organisms in underground water flow. Safeguarding and protection must include, as well as the cave habitat itself, the wider catchment area, which also includes the epikarst zone and the land above it. Seasonal sampling of subterranean aquatic fauna is recommended. This should include as many sampling locations as possible, from ponor to spring and along the underground watercourse, and the same time sampling of fauna in percolation water.

Conclusions

Despite the high percentage of carbonate rocks and the economic importance of karst areas, particularly of water sources in Slovenia and Croatia, current standards for their protection and rational use are too loosely defined. Numerous examples of poor management of karst water sources in the local environment and more widely, on the global scale, show that existing findings regarding the characteristics of water flow and solute transport in karst areas also need to be taken into account in practice.

The studies we have carried out as part of the ŽIVO! project are therefore an excellent basis for amendments to national regulations governing monitoring of the quantitative and qualitative status of waters. These regulations are not only written for the countries in question, but can be adopted and adapted to national water quality regulations by other countries with abundant karst water sources. The proposed guidelines represent a general basis which can be adapted to the search for solutions to specific problems (e.g. detecting pollution, planning safe water supply, etc.) and which opens up new possibilities for addressing the issues highlighted.

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Photo from "Water - Life!" in Istria competition; author: Josip Madračević

REPUBLIC OF SLOVENIA
GOVERNMENT OFFICE FOR DEVELOPMENT AND EUROPEAN COHESION POLICY

Naložba v vašo prihodnost
Operacijo delno financira Evropska unija
Evropski sklad za regionalni razvoj

Ulaganje u vašu budućnost
Operaciju djelomično financira Europska unija
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