ARTICLES

LATEST RESEARCH ON KARST WATERS IN SLOVENIA AND THEIR SIGNIFICANCE

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ABSTRACT
Latest research on karst waters in Slovenia and their significance
In this paper an overview on recent research on karst waters in Slovenia is presented. In recent years a great emphasis was given to the investigation of water flow and transport in karst aquifers and questions regarding the protection of karst water. In paper, the results of a series of studies, such as tracer tests, GIS methods, hydrological time series analysis are discussed, as well as their contribution to the scientific knowledge. The results of the studies show that only continuous research of karst waters with the use of different investigation techniques is a guarantee for efficient protection of karst water, which is becoming strategically important natural resource.

KEY WORDS
karst, karst aquifer, tracer test, time series analysis, water sources, vulnerability, protection of karst water, Slovenia

IZVLEČEK
Novejše študije voda na krasu in njihov pomen
V prispevku je predstavljen pregled raziskav kraških voda v Sloveniji v zadnjih nekaj letih. V tem obdobju izstopajo preučevanje toka in transporta snovi v kraških vodonosnikih ter vprašanja povezana z varovanjem kraških voda. V članku so predstavljeni rezultati raziskav, ki zajemajo sledilne poizkuse, uporabo GIS-ov in analize hidroloških časovnih vrst. Rezultati predstavljenih raziskav kažejo, da je zgolj zvezno preučevanje kraških voda z uporabo različnih raziskovalnih tehnik zagotovilo za učinkovito varovanje kraške podtalnice, ki postaja strateško pomembna naravna dobrina.

KLJUČNE BESEDE
kras, kraški vodonosnik, sledilni poizkus, analiza časovnih vrst, vodni viri, ranljivost, varovanje kraške podtalnice, Slovenija

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1 Introduction

In Slovenia karst areas mostly consist of thick carbonate rock sequences of Mesozoic age forming large karst massifs and plateaus that are intersected by lower karst areas, poljes and valleys. Karst areas cover about 44% of the state (Gams 2003) and contain large amounts of quality groundwater. Half of the country's needs for the drinking water supply are abstracted from karst aquifers. These areas are, however, very permeable and enable immediate infiltration of water into the system. In the underground a three dimensional flow net of underground conduits and voids is developed (White 2002; Ford and Williams 2007). Due to some other specific characteristics (absence of protective layers, concentrated recharge, high flow velocities through underground channels, absence of organisms that usually take nutrients on the surface, etc.), karst aquifers are extremely vulnerable to pollution.

Considering both, the importance of karst aquifers and their susceptibility to pollution, many studies focused on topics such as assessments of vulnerability, investigations of water flow and transport, as well as the protection of water sources. Studies included different field and other investigation techniques, such as tracer tests, GIS methods, hydrological time series analysis, etc. In this paper recent research achievements in Slovenia, performed mainly by the associates of the Karst Research Institute of Scientific Research Centre of the Slovenian Academy of Sciences and Arts and associates of Faculty of Humanities Koper University of Primorska are presented.

2 Water flow and transport of soluble substances in the Unica river basin

For efficient protection of karst waters against pollution it is essential to understand and consider the characteristics of water flow and transport of soluble substances in the underground and processes of their exchange with surface waters. The tracer tests were proved as one of the most suitable methods for such studies. Tracing with natural tracers involves detailed monitoring of natural parameters of karst waters in longer periods. In tracing with artificial tracers different substances are injected into the water system and their appearance is observed at selected points within the system (e.g., water caves, springs). In recent years, tracer tests were applied in several research projects on Slovene karst. Beside Rižana springs catchment area, the recharge area of the Malenščica (regionally important drinking water source) and Unica springs at the rim of the Planina polje has been most intensively studied (Fig. 1).

The study area is located in SW Slovenia. The springs are recharged by three hydrologically connected parts. The central part is the karst massif of Javorniki and Snežnik. At the western side it borders the Pivka river valley and at the eastern and northern side a string of karst poljes (the biggest among them is the Cerknica polje). In the Javorniki-Snežnik part, the underground flow is dominant, and in other two parts surface streams are present also. Surface streams are mainly recharged by karst waters, and after a certain distance of surface flow they sink again. To complement the already existing knowledge about the relations between these contribution areas (Gams 1965; Habič 1987; Kogovšek 1998; 1999; 2001a; 2001b), a monitoring net was installed in 2007 (3 rain-gauges and 9 data loggers for recording discharge, temperature – T, and electrical conductivity – EC). Additionally, two multi-tracer tests with artificial tracers were carried out.

High oscillations of water temperature at the springs indicate a significant share of secondary recharge from the surface water bodies (Fig. 2). By comparison of the occurrence of the peaks (maximum) or saddles (minimum) of the T curves of the Kotliči and Malenščica springs, the flow velocity in the karst system between them was estimated to 145–215 m/h (Kogovšek and Petrič 2010b). Similar values were calculated as a result of five tracer tests performed previously in this area. The T and EC curves of the Unica spring show an important influence of the recharge from the Pivka sinking stream, which is not characteristic for the Malenščica spring. In all springs the extreme T values are detected during high

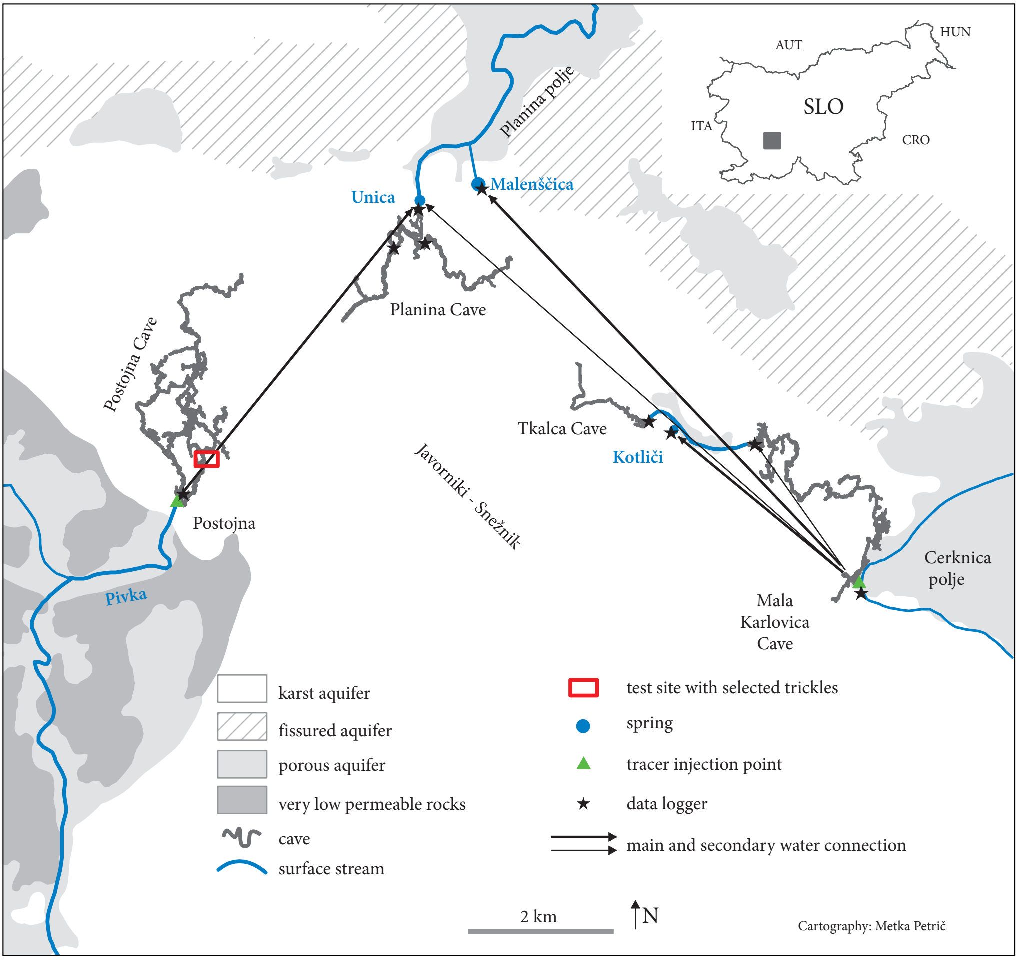


Figure 1: Hydrogeological map of the part of the Unica River catchment area.

waters as a reflection of a dominant recharge from the surface water bodies, while during low waters the recharge is slower and the retention time of water in the karst underground longer. At such conditions the share of primary recharge from the Javorniki-Snežnik karst aquifer is larger.

Artificial tracers were used in May and November 2008 to prove the main groundwater flow from the Mala Karlovica Cave at the Cerknica polje to the Kotliči spring and further on toward the Malenščica and Unica springs. The results are presented in Figs. 1 and 3 (Gabrovšek et al. 2010). During the second tracer test, the tracer was also injected into an oil collector which collects drainage water from the highway Ljubljana–Postojna to provide us with the characteristics of the contaminant flow from the karst surface.

Outflow from the collector infiltrates into the vadose zone (upper, unsaturated part of the aquifer). In the period without rainfall the flow towards the observed springs was slow and tracer was appearing in very low concentrations. Only the intensive rain pushed it more efficiently out of the system. At given hydrological conditions, the main direction of flow was toward the Unica spring and only low concentrations of tracer were recorded at the Malenščica spring.

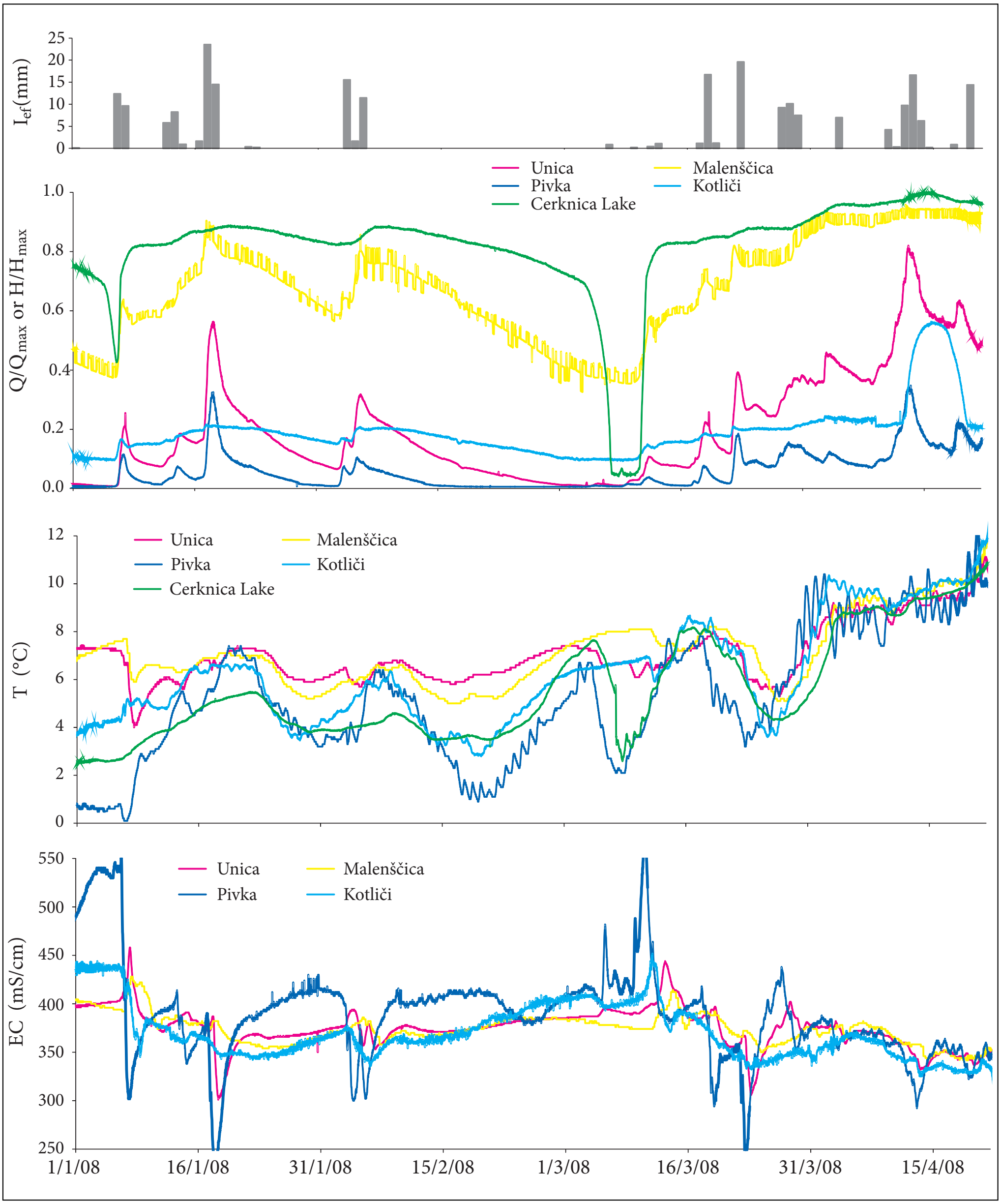


Figure 2: Effective infiltration and discharges or water levels (presented relatively to the maximum value for the two hydrological years), T and EC at selected monitoring points.

Percolation through the vadose zone is significantly slower than groundwater flow through karst conduits and it depends on various factors. These were studied by the monitoring of precipitation and discharge of selected trickles in the Postojna cave (Fig. 1) over successive hydrological years. It was established that the dynamics of percolation through the vadose zone is directly related to the quantity and

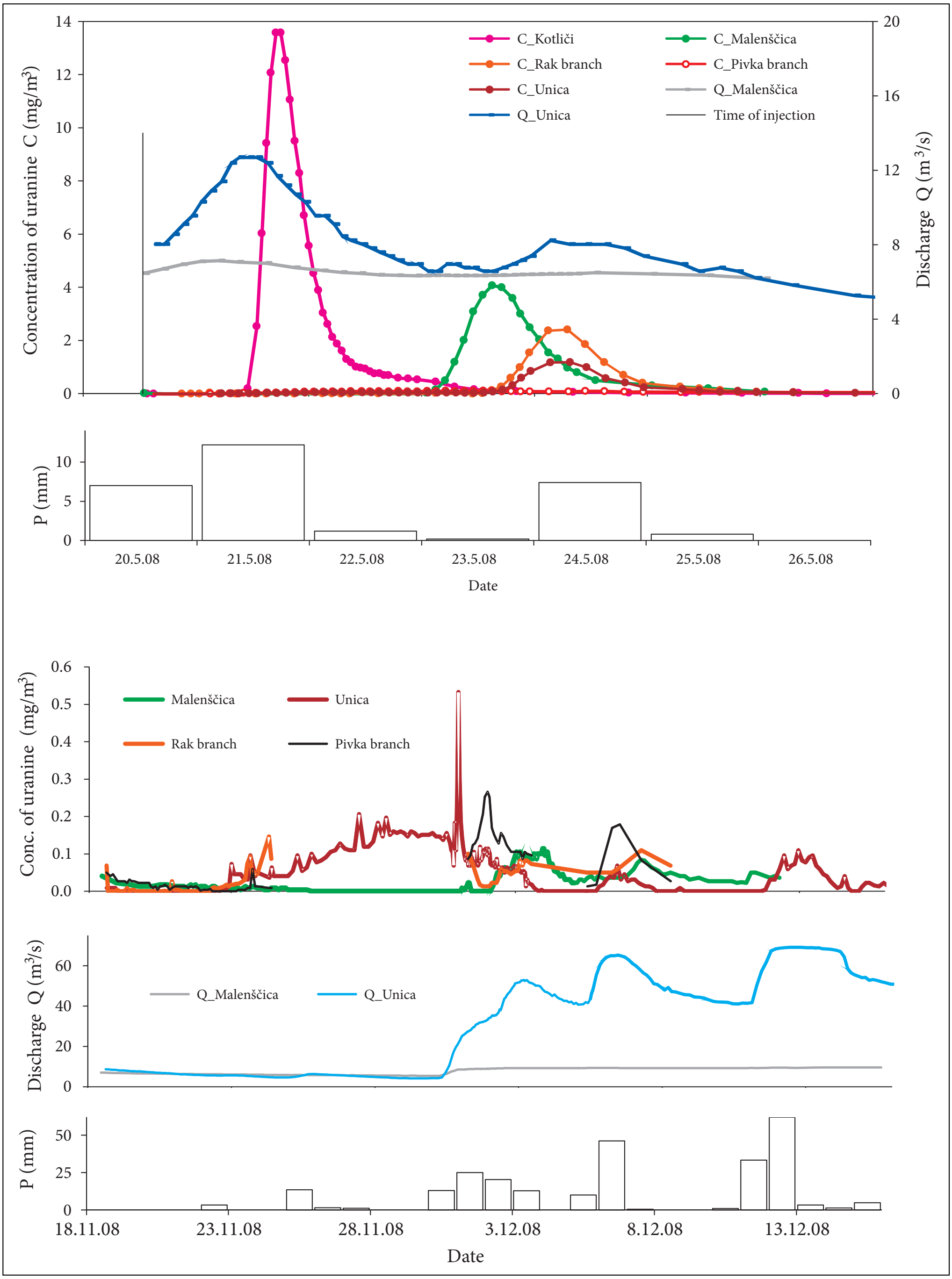


Figure 3: Uranine breakthrough curves, discharges and precipitation for tracer tests conducted (after Gabrovšek et al. 2010).

intensity of precipitation. The study also showed that continuous percolation occurs only with good saturation of soil and vadose zone (Kogovšek 2010).

The calculations of the annual volumes in three consecutive hydrological years show substantially different ratios between the annual quantity of water that infiltrates the vadose zone and the quantity of water that flows through it and supplies the deeper parts of the aquifer. This indicates that the process of recharging and discharging the vadose zone occurs in a longer period of several successive hydrological years. This was proven also by the results of isotopic analyses of oxygen that reflected residence-times from several months to one year and more (Kogovšek 2010). Therefore also the transfer of contaminants through the vadose zone is directly related to the dynamics of infiltrated precipitation. It is less intense in dry periods when discharges are minimal, and the most intense during the flood waves that follow longer dry periods. Artificial tracers additionally proved different retention times of infiltrated precipitation and contaminants in the variously permeable parts of the vadose zone (Kogovšek and Šebela 2004) and that even thin layer of soil and sediments on the surface are an important filter in the transfer of soluble substances (Kogovšek 2010).

3 Hydrological time series analysis as a tool for the study of karst aquifers: example of the Unica river basin

A monitoring net installed in the catchment of the Unica and Malenščica springs was also used for a detailed statistical analysis of the daily and hourly hydrological time series. Data were acquired and measured in hydrological years 1975 and 2008. Study comprised an univariate (r_x – correlation coefficient) and bivariate correlation (r_{xy} – cross-correlation coefficient) and spectral analysis of discharges, precipitation and the physical-chemical parameters of the Malenščica spring as well as other springs in its catchment (Kovačič 2010). The results confirmed the current knowledge and revealed some new information about the hydrogeological functioning of the Unica and Malenščica springs. The results bring also important methodological novelties.

The study has shown that the size of a catchment area can influence the memory effect of individual karst springs; typically, the memory effect of larger karst aquifers (e.g. Unica, Malenščica, Pivka, etc.) is greater and vice versa. In comparison with larger systems, the response of smaller karst springs to precipitation events is faster and more intense; however the duration of their pulse is shorter. The study has shown that in the karst aquifers with quick responses to precipitation events (fast and simultaneous recharge) via ponors the EC data sets can provide valuable information about hydrogeological behaviour of karst aquifers. On the other hand, the applicability of T time series is rather limited, because the T of water is not a conservative tracer and the interpretation of these time series is delicate in karst systems. Methodologically important is that the results of the cross-correlation analysis (r_{xy}) of hourly EC values between ponors and springs were in line with the results (underground tracer velocities) of the tracer test conducted in May 2008 (Gabrovšek et al. 2010; Kovačič 2010), which shows the usefulness of EC time series analyses as an alternative method to water tracing between ponors and related springs.

A comparative analysis of the time series analysis performed for the Malenščica and Unica springs in the successive hydrological years 1997–2002 reveals that the selection of the hydrological year can have strong effects on the results (e.g. different decorrelation lags, correlation and cross-correlation coefficients, etc). In this regard, in order to obtain a more general image of the functioning of a karst system in absolute terms, it is important to consider longer hydrological data sets.

Furthermore, not all karst aquifers characterized by a higher memory effect should be considered as poorly karstified. In this regard, caution needs to be used when classifying karst aquifers into groups only on the basis of the results of a time series analysis. It is essential that the results of time series analysis must be interpreted together with the results of other methods used in karst hydrology (Kovačič 2010).

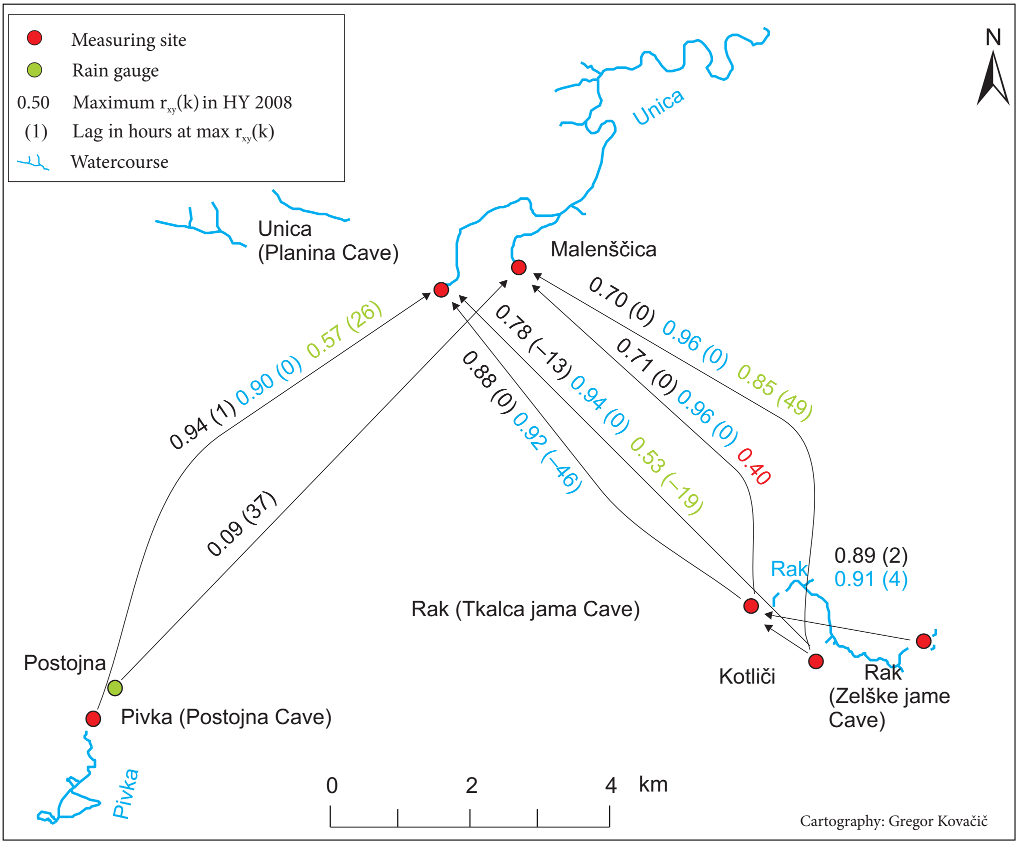


Figure 4: Cross-correlation coefficients for the hourly discharge (black), T (blue) and EC (green) time series in the hydrological year 2008 (after Kovačič 2010).

4 Drinking water sources and their protection

Generally, karst water sources quality and quantity are satisfactory, but they may be organically polluted or threatened by human activities. Due to inappropriately built roads and dumping sites the protection against chemical contamination is usually not assured.

Dumping is a serious threat to karst groundwater, due to the washing out of waste substances by precipitation and fast percolation of wastewater into the underground. This is explicitly uttered in case of landfills located on karst areas with very high intrinsic vulnerability (Zwahlen 2004; Ravbar and Kovačič 2006). A well-planned, long-term monitoring of negative influences on groundwater quality in their impact areas is therefore necessary to efficiently define and implement the protection measures. Additional to basic hydrogeological mapping, the tracer tests are a very useful method for selecting representative monitoring points and preparing a monitoring plan. In recent years, such approach was used for several landfills on Slovene karst (Petrič and Šebela 2005; Kogovšek and Petrič 2006; 2007; 2010a).

The tracer tests were carried out at the Mala Gora, Sežana and Mozelj landfills in the period 2004–2006. By tracer tests the main groundwater flow connections were defined and for each of them the maximal (regarding the first appearance of tracer) and dominant apparent flow velocities (regarding the first peak of the breakthrough curve) were calculated. Additionally, the recovery of injected tracers was assessed.

The springs with the main underground water connections should be selected as the monitoring points. High apparent velocities of flow toward the main springs and large shares of recovered tracers indicate very high vulnerability and a serious danger of pollution with harmful substances from the landfill. To increase the possibility of detecting the sources of pollution, it is sensible to adjust the time and frequency of sampling to hydrological conditions.

Twenty years long monitoring of pollutant transport through the vadose zone confirmed that the leaching even of minor contamination from the surface may take several decades before the original conditions are restored (Kogovšek 1997; 2010). This knowledge is the basis for the protection of springs, which can be influenced by different activities on karst surface (e.g., landfills, military training areas, petrochemical depot, roads and highways, railways, agriculture, petrol stations, illegal waste disposal dumps, etc.) Similarly, the water quality at karst springs can change a lot during different hydrological conditions. Abundant precipitation that follows dry periods flushes accumulated pollution through the recharge areas of karst springs, leading to the most intense transfer of contaminants (Kogovšek 2001b).

Numerous socio-economic processes increase the drinking water demand and thus enhance its utilization. The attitude towards water is extremely careless and wasteful, as it has been confirmed by the detailed research on individual's behavior towards drinking water (Veljanovski and Ravbar 2005). The study showed that an average inhabitant in SW Slovenia uses 130–150 L/day, the average monthly consumption of water in households was 12 m^3. The biggest quantities of water (i.e., 1.4 m^3/month) were used for splashing. For hygienic purposes, a household used 2.6 m^3/month and for washing the dishes and laundry 2.2 m^3/month. Unfortunately, drinking water is in addition used for cleaning cars and streets, and for irrigation.

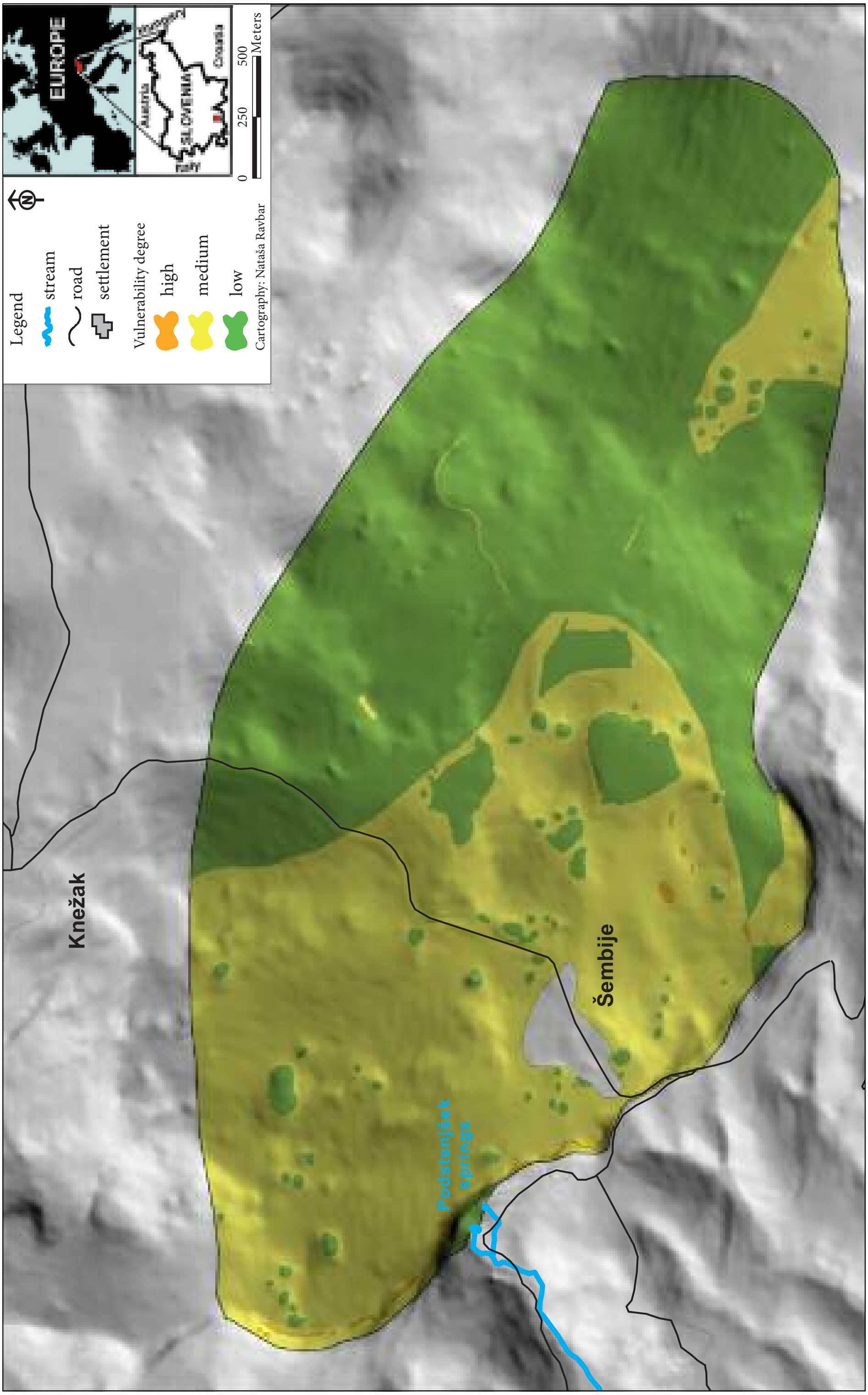
The study also showed (Veljanovski and Ravbar 2005) show that 60% of the asked thinks that the water consumption in their household is not big. Furthermore, the prices of water do not crucially impact the individual's attitude towards water. Even if the price of the water would rise for a quarter, 66% of the asked would not change their consumption attitude. However, two thirds of the asked is willing to pay more, if the protection of water sources would be higher.

Despite very high importance of karst water sources, their protection is frequently insufficient (Ravbar and Kovačič 2006). Due to very high susceptibility of karst aquifers to contamination, their water sources require appropriate managing. Unfortunately, in the acts of Slovene legislation, the special characteristics of water flow within karst regions are not very seriously taken into consideration in determining the criteria for karst water sources protection. In contrast, in some other countries (e.g., Ireland, Switzerland), the concept of groundwater vulnerability mapping has been successfully used for protection zoning and assessment of contamination risk is increasingly important in land use planning. European guidelines for making such assessments (Daly et al. 2002) were elaborated.

The recently proposed Slovene approach (Ravbar and Goldscheider 2007) follows these guidelines most comprehensively. The method includes the assessment of vulnerability and degree of hazard. These two assessments form the basis for calculating the contamination risk to groundwater or water sources. The final result of the vulnerability assessment can be transformed into the water protection zones.

The Slovene approach ranks among extremely sophisticated methods because its application does require a large amount of data, time, financial, and technical sources. It is the only one to offer the possibility of assessing the importance of groundwater or water sources on a basis of which it is possible to predict potential damage and elaborate a priority list of rehabilitation measures. Validity tests on the acquired results showed that compared with simpler methods the use of such a method is quite reasonable because it provides more reliable and less subjective results (Ravbar and Goldscheider 2009).

Figure 5: An example of vulnerability map for a local drinking water source in SW Slovenia. The map represents characteristics of groundwater flow in the saturated zone of the karst aquifer (after Ravbar and Goldscheider 2009). ➤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5 Conclusion

Karst springs are becoming economically more and more important due to its abundance (high flow rate springs up to some tens of m^3/s) and relatively high water quality not only in Slovenia, but also worldwide. However, karst aquifers pose many specific engineering and environmental problems, related to the presence of underground conduits and voids and the specifics of groundwater flow. The position of most of the underground water flow paths is often unknown, which makes the characterization of karst aquifers extremely difficult.

Studying the special character of karst therefore requires particular investigation approaches and techniques (e.g., speleological investigations, tracer tests, etc.; Drew and Goldscheider 2007). In this paper the newest achievements in this respect have been presented that are valuable contributions to further understanding of karst aquifers and their behaviour. The newest findings on the characteristics of water flow and transport of soluble substances, storage capacities etc. are important and should be utilized in further research and considered when monitoring karst water quality, implementing groundwater protection measures and optimizing future water exploitation.

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