7 Planning Contamination Emergency Response Measures for Karst Water Sources

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In karst areas, underground water mainly flows through conduits and fissures due to the solubility of carbonate rocks (Palmer 2007). In contrast to non-karst aquifers, water immediately infiltrates into the karst underground. Surface water from neighbouring non-karst areas also sinks underground at contact points with the karst. Because of their highly heterogeneous structure with a multitude of shapes and sizes of underground pores, karst conduits are characterised by their high flow velocities (up to several hundred metres per hour) and multidirectional drainage, which can extend to areas several dozen kilometres away. However, in less permeable zones with lower flow velocities, water can retain underground for a longer time (Bakalowicz 2005; Goldscheider and Drew 2007).

Because of these characteristics, karst aquifers are highly vulnerable in the case of water, surface or underground contamination (Daly et al. 2002; Hartmann et al. 2014). Due to mostly rapid infiltration, poor filtration capacity and high flow velocities and self-cleaning processes in karst are less efficient; high concentrations of contaminants can pass through the unsaturated zone in a matter of hours and reach a spring over several days (White 2002). Contaminants can partially remain in the less permeable zones and stay underground for days, weeks, months or years (Williams 2008a, b; Kogovšek 2010; Kogovšek and Petrič 2014).

Safeguarding water sources in the case of emergencies demand a good understanding of the hydrogeological characteristics of their catchments and that they are taken into account when planning measures. The spread direction and velocity of potential contamination can only be predicted by understanding the characteristics of the geological structure and hydrogeological conditions. This calls for appropriate hydrogeological research to be carried out in advance. A well-maintained database with general information and relevant knowledge about the function of a hydrological system is an essential tool in planning response measures and quality monitoring in cases of emergency (Vižintin et al. 2018).

This chapter presents the use of several methods of hydrogeological and spatial research for planning appropriate contamination emergency response measures. It is based on the results of tracer tests for determining catchments and groundwater flow velocities, and on the concept of vulnerability mapping and assessment, which is increasingly employed for effective protection of karst water sources (Vrba and Zaporozec 1994; Goldscheider 2010; Turpaud et al. 2018). Vulnerability mapping and assessment makes it possible to differentiate areas of different vulnerability levels and self-cleaning capacities; in combination with data on known groundwater flow directions and travel times, it makes possible a uniform determination of the time it takes water to flow from the point of contamination to an at-risk karst water source.

In the case of contamination, the approach can be used for a first assessment of the threatened water source and the time when contaminants can first be expected to appear there. Based on this, detailed monitoring of water quality and a number of preliminary protection measures can be initiated in due time. This approach was used in the case of the Trnovo–Banjšice high karst plateau in western Slovenia, which has important freshwater resources and headwater catchments.

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7.1 Hydrogeological Characteristics of the Trnovo–Banjšice Plateau

The Trnovo–Banjšice area is a high karst plateau ranging at an elevation of 300–1,500 m a.s.l. and surrounded by the Soča, Idrijca and Vipava valleys. It consists of carbonate rocks from the Late Triassic, Jurassic and Cretaceous (Janež et al. 1997). The oldest outcrops along the northern edge of the area are Norian–Rhaetian dolomite, which southwards passes to Dachstein limestone, and, in a continuous transition, to Jurassic rocks. These are between 1,000 and 1,500 m thick and developed in the central part of the plateau as limestones and dolomites with all transitions. Cretaceous rocks, for the most part limestones, with dolomite inclusions in places, are between 2,500 and 3,000 m thick. In the western part of the plateau, the Upper Cretaceous series is developed as platy limestone overlain by limestone breccias, marlstones, and sandstones. Cretaceous rocks are overlain first by Palaeocene, then Eocene flysch rocks. The coarse-grained breccias covering the flysch rocks on the southwestern slope of the plateau are of Quaternary age, whereas the scree on its southern edge belongs to the Holocene. The dominant tectonic element is Lower Tertiary overthrusts cut by a dense system of subvertical neotectonic faults (Placer 1981; Janež et al. 1997). Between these faults, numerous crushed zones of various width run in the N–S, E–W or NNW–SSE directions, which have provided the genetic base for the development of karst and related hydrogeological phenomena. The thrust structure of the area is characterised by repeated sequences of Palaeocene–Eocene flysch in the overthrust and underthrust structural units (Janež et al. 1997; Turk et al. 2013).

Mesozoic carbonate rocks build the central part of the karst aquifer, which is delimited by highly impermeable flysch beds acting as basal and lateral barriers (Fig. 7.1). The shape and incline of these barriers direct the karst groundwater flow towards springs at the plateau edges (Janež et al. 1997). The main springs are Divje Jezero (elevation 330 m a.s.l.; a periodic spring with flow rates of several dozen m^3/s) and Podroteja (elevation 329 m a.s.l., flow rates between 0.2 and several m^3/s) to the northeast, Hubelj (elevation 240 m a.s.l., flow rates between 0.2 and 59 m^3/s) to the south, Mrzlek (elevation 77 m a.s.l., flow rates between 0.6 and 40 m^3/s) and Lijak (elevation 105 m a.s.l., a periodic spring with flow rates up to 32 m^3/s) to the southwest, Kajža (elevation 191 m a.s.l., flow rates between 0.007 and 2 m^3/s) to the west and Hotešk (elevation 270 m a.s.l., flow rates between 0.03 and 6 m^3/s) to the northwest. The northern border of the karst aquifer is built of Upper Triassic dolomites, in which locally important aquifers with fissured porosity have developed. Breccias and scree on the southern edge of the plateau collect and transport small quantities of groundwater, which feed numerous smaller springs. The karst aquifer of the Trnovo–Banjšice Plateau is a very important groundwater reservoir, and most of the aforementioned springs are used to supply drinking water.

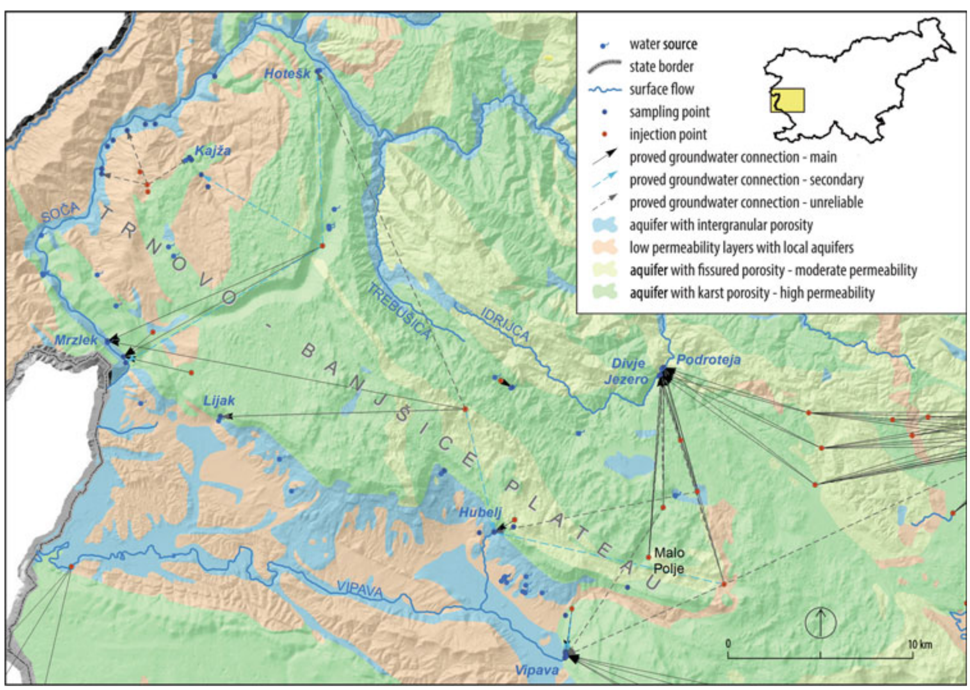

Fig. 7.1 Hydrogeological map of the Trnovo–Banjšice Plateau area

7.2 Basic Considerations for Planning Contamination Emergency Response Measures

The basic aim of preparing the emergency response plan was to assess the velocity of potential contamination spreading in an individual water source catchment and thus estimate the travel time of contamination to a water source. We chose the worst-case scenario of high water levels and heavy precipitation, during which groundwater flow and solute transport rates in the karst are at their highest and the time for effective measures at its shortest (Daly et al. 2002). The established model can be used in the case of emergencies to immediately determine which water source is threatened and when contaminants can first be expected to appear there.

To estimate groundwater flow velocities, we used the results of all the tracer tests conducted with artificial and natural tracers. Analysis of the results took into account that the velocities identified depend on the injection method and location, as well as the precipitation and hydrological conditions at the time of testing. With regard to factors affecting solute transport from the surface to springs (meteorological, geological, geomorphological, speleological and hydrogeological factors and soil and vegetation types), we chose one of the parametric methods of vulnerability mapping that combines all these characteristics. With respect to natural conditions, we drew up a vulnerability map with three vulnerability levels identifying areas of varying likelihood of groundwater contamination. For all tracer tests, the flow velocities identified were analysed with regard to the vulnerability level of the injection site, as well as the precipitation and hydrological conditions during the tests. In this way, we determined the maximum flow velocities within the catchments of water sources (with regard to the straight-line distance to the water source and the first appearance of tracer) for each of the three vulnerability levels. We used these velocities to map isochrones for each point within its catchment area with respect to its distance to the water source, thus showing the shortest time a potential contamination would need to travel from any surface point to a water source.

7.3 Past and Recent Research in the Selected Study Area

Over the past years, various geological, geomorphological, speleological, hydrogeological, meteorological and hydrological studies were carried out as part of a number of projects, which determined the basic characteristics of the Trnovo–Banjšice Plateau aquifer and the adjacent water sources. Geological, geomorphological and speleological maps of various scales (Placer and Čar 1974; Čar and Gospodarič 1988; Janež and Čar 1990; Janež et al. 1997) improved our understanding of the lithological and structural characteristics that play a significant part in the modes of groundwater flow in the karst underground. Combined tracer tests carried out in changing hydrological conditions, using a range of artificial and natural tracers, at various locations and with different tracer injection methods (Habič 1982, 1987; Kranjc 1997; Janež et al. 1997; Trček 2003) have provided in-depth knowledge of water flow directions and characteristics at various points of the karst aquifer. On the basis of data collected with the KARSYS method (Jeannin et al. 2013), assessments of the groundwater storage were made and the catchments of the main springs were delineated (Turk et al. 2013).

The hydrogeological map shows general characteristics of the water flows and the main water sources in the Trnovo–Banjšice Plateau area (Fig. 7.1). It indicates the identified groundwater flow directions and catchments of the major water sources.

7.3.1 Tracer Test

Tracer tests are one of the best methods for determining the directions and characteristics of groundwater flow and solute transport in karst areas. The results of tracer tests are highly useful in developing emergency response plans. If these data are not available or if specific underground connections remain undefined despite tracer testing, the existing database must be improved with new research. In the case at hand, the watershed between Hubelj and Podroteja springs in the eastern part of the aquifer could not be reliably identified on the basis of existing data, and therefore we decided to carry out a new tracer test at the Malo Polje location. On 24 April 2014 at 10.00 am, we injected a solution of 6 kg of fluorescent dye uranine into the karst fissure and irrigated the area with 6 m^3 of water from a tank (Fig. 7.2).

We closely monitored Hubelj and Podroteja springs using ISCO 6700 automatic samplers; initially, sampling was carried out twice a day, and once a day after the first wave of the tracer had passed through. In parallel, we measured the fluorescence at thirty-minute intervals using LLF-M Gotschy Optotechnik field fluorometers; the measurements were carried out until 10 October 2014 at Podroteja spring and until 14 September 2014 at Hubelj spring (Fig. 7.3). Sampling at Divje Jezero spring was done manually during increased flow rates between 24 April and 10 October 2014. Control sampling took place once a day at Vipava and Mrzlek springs using ISCO 6700 automatic samplers; sampling at Vipava lasted until 8 August 2014 and at Mrzlek until 20 October 2014.

Fig. 7.2 Injection of uranine solution into the fissure at Malo Polje, 24 April 2014

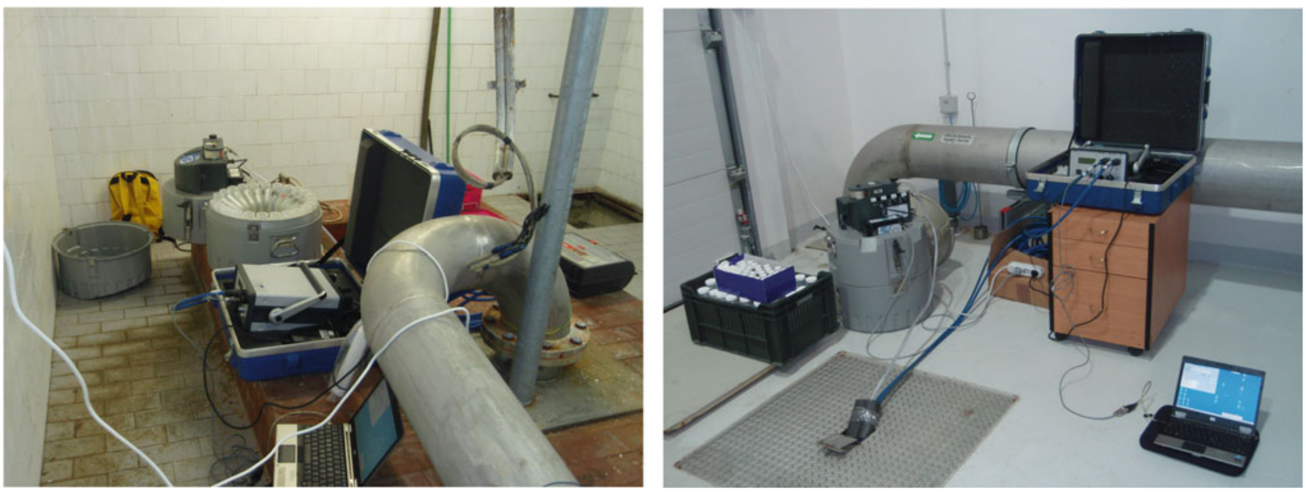

Fig. 7.3 ISCO 6700 automatic samplers and LLF-M field fluorometers at Podroteja (left) and Hubelj (right) springs

Samples of water were analysed at the Karst Research Institute laboratory in Postojna using a Perkin Elmer LS 45 fluorescence spectrometer (E_{ex} = 491 nm, E_{em} = 512 nm). Analysis was carried out directly from the samples soon after collection and repeated later, when any solid particles suspended in the samples had settled.

During the tracer tests, we also measured precipitation using the Hobo Onset RG2-M rain gauge installed near the injection point. The Slovenian Environment Agency (Hydrological Data Archive 2014) provided thirty-minute-interval data on water levels at Podroteja spring and the flow rate of the Idrijca River below the spring. While collecting samples at Divje Jezero, we also measured the water level of the spring.

At different water levels during the tracer testing, we used a WTW 330i conductivity meter to manually measure electrical conductivity and water temperature in the Idrijca River before the inflow from Divje Jezero spring, between the inflows from Divje Jezero and Podroteja springs, below the confluence with Podroteja spring, and in both springs (Podroteja and Divje Jezero). With regard to the data on flow rates of the Idrijca River below Podroteja (Hydrological Data Archive 2014) and differences in measured electrical conductivity and temperature at all measurement points, we estimated the flow rates of Podroteja and Divje Jezero springs using a linear mixture equation. On the basis of comparison with data collected on water levels, we developed an equation describing the dependence of flow rates on water levels. This equation allowed us to estimate flow rate values for all water levels measured in both springs, which were in turn used to estimate the percentage of recovered tracer.

7.3.2 Vulnerability Mapping

The vulnerability map was drawn up using the Slovenian Approach method (Ravbar and Goldscheider 2007), which has already proven useful on several occasions. Using ArcGIS 10.1. software, vulnerability was assessed on the basis of factors that affect the flow of infiltrated water from the surface to springs. These factors include geological maps (Janež et al. 1997 and references therein), geomorphological-topographic maps and digital elevation models (Topographic and Cartographic Data 2014), and the speleological (Cave Registry 2014), hydrogeological (Hydrogeological Map 2014), pedological and vegetation characteristics of the Trnovo–Banjšice Plateau. We also took into account the meteorological conditions of the area and land use.

Vulnerability mapping was based on the data on the geological characteristics of the area, the 3D hydrogeological model of the karst aquifer (Turk et al. 2013) created using the KARSYS approach, and the results of the tracer tests with natural and artificial tracers. Using additional hydrogeological data (e.g. the position and characteristics of springs, flooded caves and ponors), the underground water bodies within the karst aquifer were defined, groundwater flow directions determined and the catchments of the major karst springs delineated. On this basis, we could determine the thickness of the unsaturated zone with regard to the elevation data in the digital relief model.

Soil thickness and texture were obtained from the soil maps (Grčman et al. 2015), and vegetation cover was deduced from land-use maps (Land use data 2013). The surface morphological features and slope declination were deduced from geomorphological studies and the digital relief model. Data on precipitation amount and intensity was obtained from twelve pluviometers over a thirty-year period, and the mean annual precipitation distribution was provided by the Slovenian Environment Agency (Meteorological Data Archive 2014).

By analysing changes in the physical parameters of the springs (flow rate, temperature and electrical conductivity), we were able to assess the velocities and characteristics of their reaction to precipitation events; based on this, we could also draw conclusions regarding the mode of solute transport in the karst aquifer.

7.3.3 Isochrones Mapping

In all the tests carried out, the determined flow velocities were compared with the hydrological conditions at the time of the tests. With analysis of the data collected, we identified the maximum possible velocities of water flow and solute transport towards the water sources for all vulnerability levels on the vulnerability map. This data was then combined in an isochrone map. The isolines represent the shortest travel times of potential contaminants from the emergency area to individual water sources. To facilitate the planning of effective response measures, the map models the worst-case scenario of high water levels and heavy precipitation, during which groundwater flow and solute transport rates in the karst are at their highest and the time for effective measures at its shortest.

7.4 Results of Recent Studies

7.4.1 Tracer Test

The injected uranine appeared over a month later, on 28 May 2014, in Podroteja spring 10 km away, and two days later in the neighbouring overflow spring at Divje Jezero as well (Fig. 7.4). At Podroteja, the first increase in tracer concentration (of 0.43 mg/m^3) was recorded on 5 June 2014 at 12.00 pm, and peak concentration (of 0.52 mg/m^3) was recorded on 25 June at 12.00 am. With respect to the straight-line distance between the injection site and the spring, and the time period between injection and the first tracer appearance, the linear maximum groundwater flow velocity was estimated at 12.7 m/h whereas the linear dominant flow velocity, with respect to the onset of peak tracer concentration, was estimated at 7 m/h. The injected uranine discharged uniformly and in average concentrations through Podroteja spring until the end of August 2014, three months in total. At Divje Jezero, larger changes in concentration were observed in accordance with flow fluctuations and the overflow character of the spring. Peak concentration was recorded on 30 June 2014 at 4.10 pm, and the identified linear maximum and dominant velocities were 11.5 m/h and 5.8 m/h, respectively.

We used estimated flow rates of both springs to calculate the tracer recovery rates. During the observation period, a little more than 3 kg, or approximately 51%, of the injected tracer was discharged through Podroteja spring (Fig. 7.4). Because sampling at Divje Jezero was only carried out occasionally, the concentrations were roughly estimated by comparison with Podroteja spring. The estimated percentage of recovered tracer—approximately 33% (a little less than 2 kg)—is thus less conclusive. During the observation period, a total of approximately 84% of the injected uranine was discharged through both springs, and lower tracer concentrations undoubtedly continued to flush after observations were concluded. At other observation points, we did not record tracer concentrations that would reliably confirm potential underground connections. The tracer test confirmed that the groundwater from the Malo Polje area flows towards Podroteja and Divje Jezero springs, rather than Hubelj

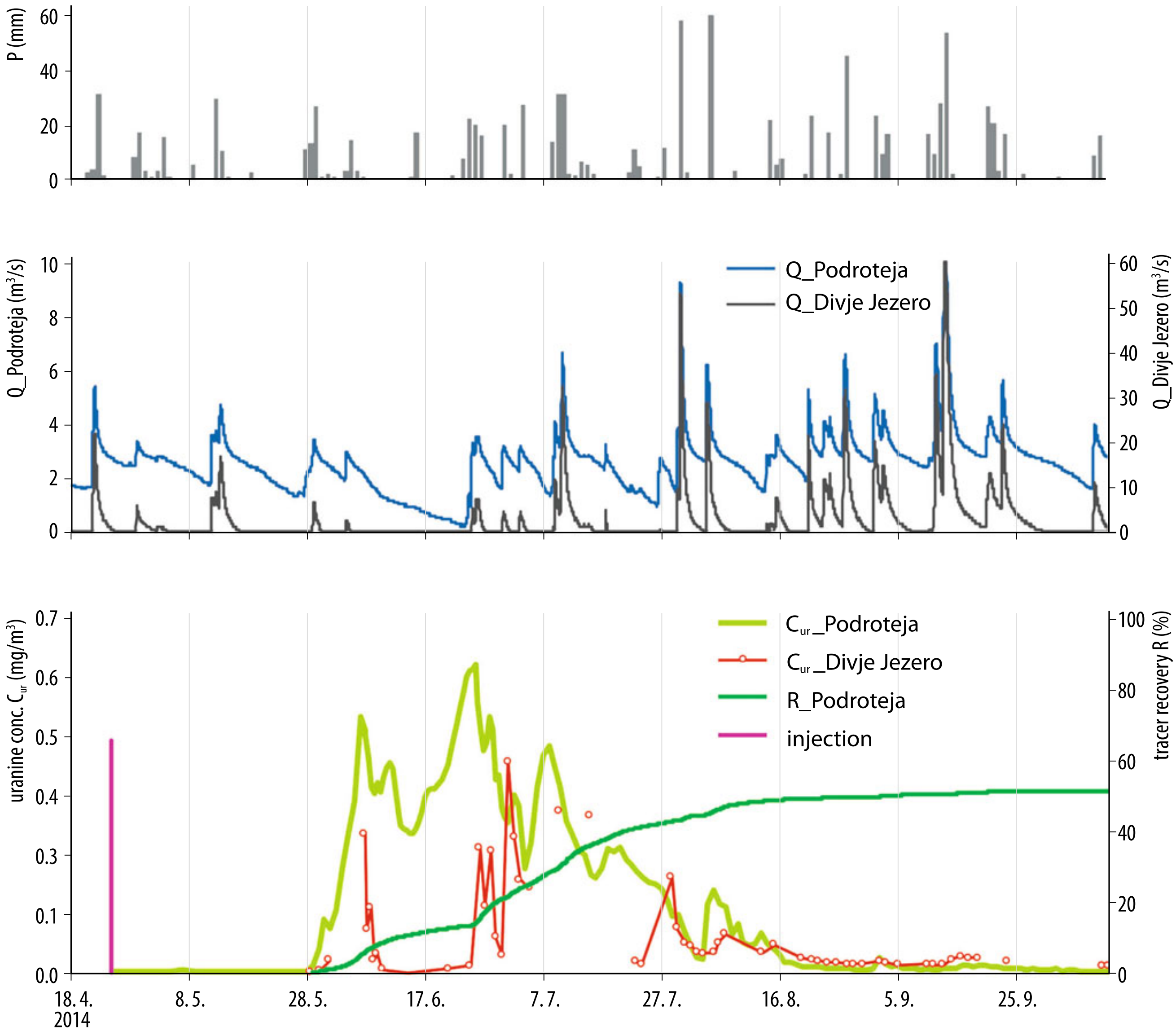

Fig. 7.4 Daily precipitation at Malo Polje (*P*), flow rates of Podroteja and Divje Jezero springs (*Q*), uranine concentrations (C_{ur}) and the percentages of recovered tracer in Podroteja and Divje Jezero springs (*R*)

spring. We reviewed the catchment areas of these springs accordingly and used the determined maximum velocities for isochrones mapping.

7.4.2 Vulnerability Mapping

The vulnerability map of the selected Trnovo–Banjšice Plateau area covers the catchments of five major karst springs: Mrzlek, Kajža, Hotešk, Hubelj and Podroteja (Fig. 7.5).

The map uses colour coding to represent different vulnerability levels. Within the catchments of individual karst water sources three vulnerability levels were determined, ranging from areas of high vulnerability, from which contaminants can reach a spring rapidly and in less diluted form, to areas of low vulnerability, from which contaminants take longer to reach the springs and might degrade en route.

The most vulnerable are the bare karst areas at the heart of the Trnovo–Banjšice Plateau, and those in the immediate catchments of the sinking streams. Moderately vulnerable areas include areas of carbonate rocks covered by a thin soil layer, while the least vulnerable areas are those of carbonate rocks covered by thicker layers of soil and sediments, as well as non-karst areas.

The vulnerability map represents the basis for analysing the spreading of potential contaminants towards major drinking water sources.

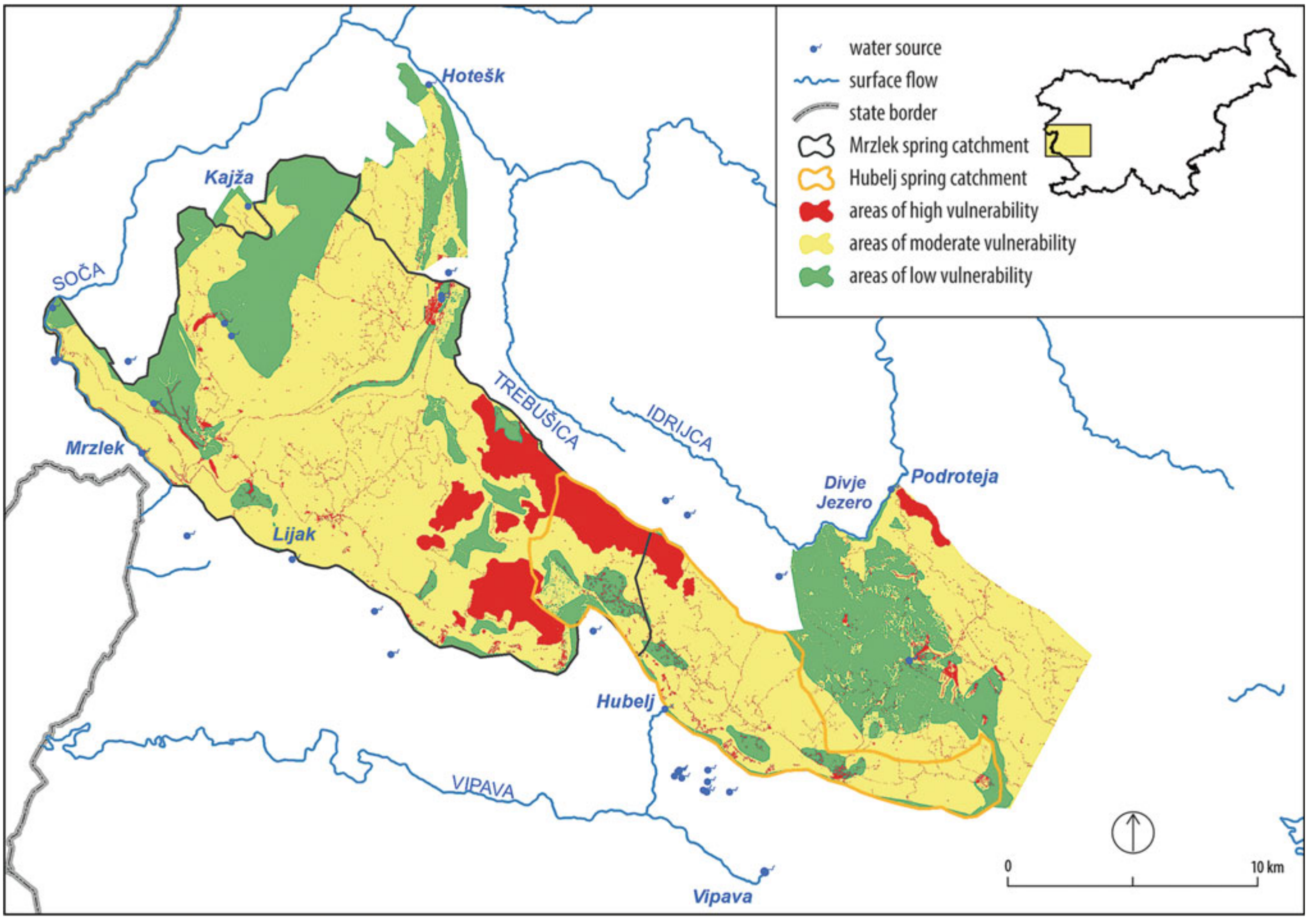

Fig. 7.5 Vulnerability map of the selected Trnovo–Banjšice Plateau area

7.4.3 Isochrone Map

The flow velocities—identified in both past and recent tracer tests—were adjusted for the delay in the appearance of precipitation and the flood pulse following tracer injection in such a way as to estimate the highest possible velocities under conditions most favourable for water flow and its solute transport. Through comparison of the results obtained, and taking into account the vulnerability level of the injection points, a linear maximum velocity of groundwater flow towards a spring was determined for each of the three vulnerability levels: for the most vulnerable area 95 m/h, for the moderately vulnerable area 60 m/h and for the least vulnerable area 10 m/h (Vižintin et al. 2018). Taking into account these velocities and the distance from the karst water sources, an isochrone map was drawn up within their catchment areas showing the distribution of the shortest predicted travel times of potential contamination from a selected point on the map to an individual water source.

For clarity, Fig. 7.6 is limited to the major water sources of Mrzlek and Hubelj, which jointly supply water to around 54,000 people, and their catchments. The travel time differences between the isochrones are 6 h for the most vulnerable areas, 24 h for moderately vulnerable areas and 48 h for the least vulnerable areas. From the most vulnerable areas that are closer to the water sources, contaminants can appear in Mrzlek and Hubelj springs within a single day, whereas their travel time from more distant areas is under one week. The flow from less vulnerable areas is typically slower, and several months can pass before contaminants appear in water sources.

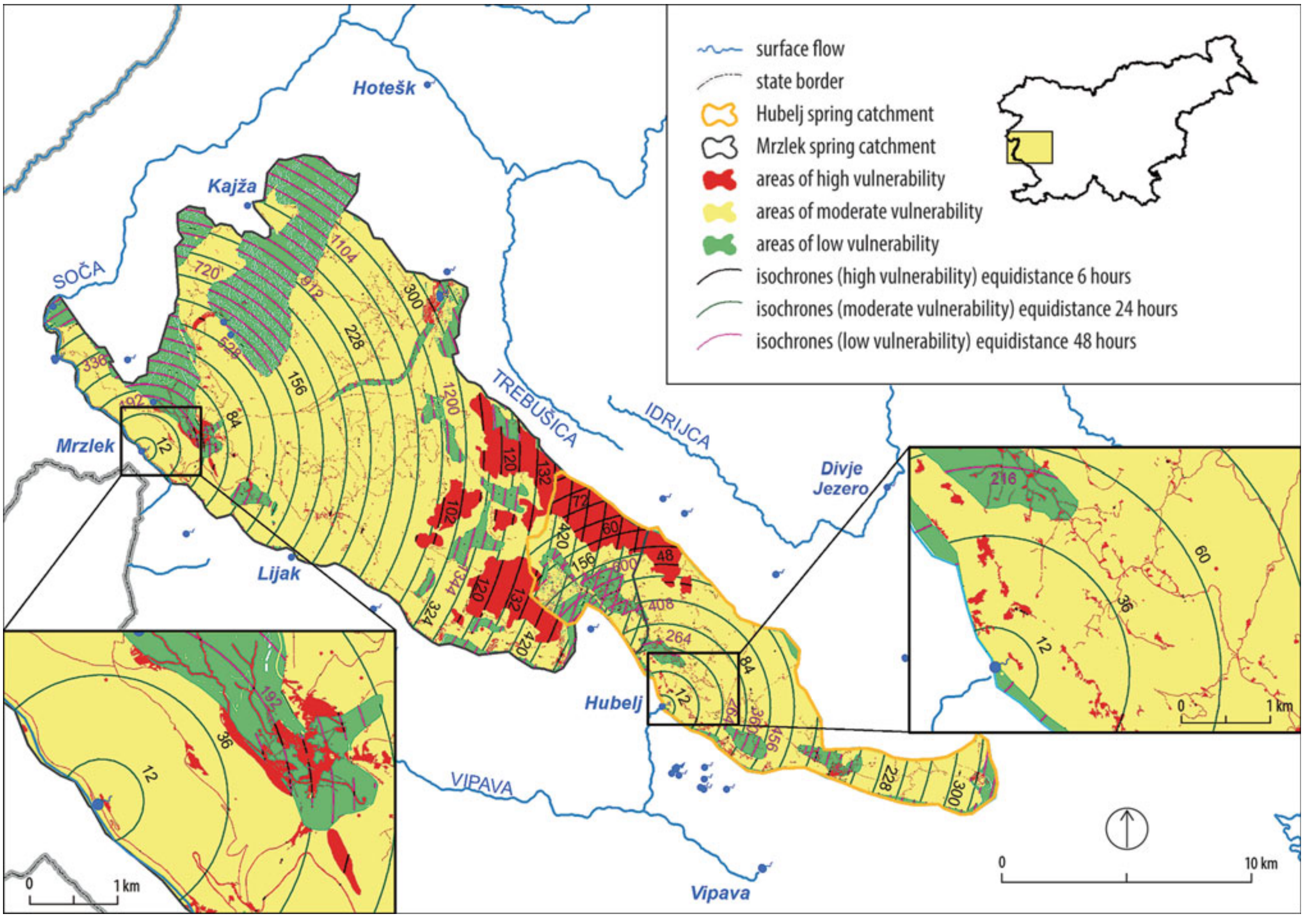

Fig. 7.6 Isochrone map of different vulnerability levels for the Mrzlek and Hubelj water sources (adapted from Vižintin et al. 2018)

7.5 Planning Contamination Emergency Response Measures for the Trnovo–Banjšice Plateau Area

Owing to their nature, karst aquifers are highly susceptible to contamination. Sustainable and efficient freshwater management in karst requires consideration of the characteristics of groundwater flow because they determine the spread mode and scope of potential contamination to water sources, as well as the threat it presents.

However, modelling solute transport in karst aquifers is far more complex than the simulation of transport processes in a porous medium. This is due to the high heterogeneity of flow, as well as the unknown storage in various karst subsystems, such as the epikarst, vadose and phreatic zones. Therefore, solute transport modelling has mainly been performed on synthetic karst systems (Kovacs and Sauter 2007).

More commonly, tracer tests are used to study solute transport in actual karst aquifers and to simulate the transport, fate and attenuation of different types of contaminants in both the unsaturated and saturated zones (Benischke et al. 2007). In recent decades, the concept of vulnerability assessment has proven useful in determining the required level of karst water source protection (Zwahlen 2004). These two methods were also adopted in this study for the purpose of developing a system of emergency measures.

In the Trnovo–Banjšice Plateau area, numerous combined tracer tests were carried out over recent years under various precipitation and hydrological conditions, and therefore our knowledge of groundwater flow directions and characteristics is well above average. Another favourable aspect was the varied methods of injecting tracer (into a sinking stream, shaft or doline, or dispersed on the surface), which allowed us to assess how different injection methods affect the velocities and characteristics of tracer transport. We drew up a vulnerability map for the catchments of all five springs, which also includes the injection sites of the tracer tests. By comparing the vulnerability levels at the injection sites, and with regard to the flow velocities that were identified at these points, three maximum possible velocities were estimated for the three different vulnerability levels throughout the entire area. Using these velocities, an isochrone map of the entire area was then drawn up with respect to the water source distances, showing the distribution of predicted travel times of any contamination from a selected point on the map to individual water sources. To facilitate the planning of effective response measures, the map models the worst-case scenario of high water levels and heavy precipitation, during which groundwater flow and solute transport rates in the karst are at their highest and the time for effective measures at its shortest. In the case of a contamination emergency at any location, the map can be used to determine which water sources are threatened and when contaminants can first be expected to appear there; on this basis, appropriate response measures can be planned by establishing close monitoring of water quality and eventually disconnecting the affected water source from the drinking water supply system.

For the time being, we are in the first phase of developing an emergency response plan because our assessment is focused on the velocity of potential contamination in order to predict its shortest travel time to a water source. Based on this, close monitoring of water quality and a number of preliminary protection measures can be initiated in due time as an emergency response. On the other hand, the worst-case scenario is not the most likely, and it is probable that contamination will take a longer time to appear. Nonetheless, the planning of response measures should involve experts in karst hydrogeology, who will be able to suggest further steps with respect to the precipitation and hydrological conditions, as well as the results of continuous water quality monitoring. As for future research, the focus will be on predicting the duration and maximum concentrations of contamination, which will in turn allow us to determine the objectives and duration of emergency measures in greater detail.

References

Bakalowicz M (2005) Karst groundwater: a challenge for new resources. Hydrogeol J 13(1):148–160

Benischke R, Goldscheider N, Smart P (2007) Tracer techniques. In: Goldscheider N, Drew D (eds) Methods in karst hydrogeology. Taylor & Francis, London, pp 147–170

Čar J, Gospodarič R (1988) Geološka zgradba in nekatere hidrološke značilnosti bruhalnika Lijaka. Acta Carsolog 17:3–32

Cave Registry 2014: Speleological Association of Slovenia and Karst Research Institute at Research Centre of the Slovenian Academy of Sciences and Arts

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, Popescu IC, Zwahlen F (2002) Main concepts of the European approach for (karst) groundwater vulnerability assessment and mapping. Hydrogeol J 10:340–345

Goldscheider N (2010) Delineation of spring protection zones. In: Groundwater hydrology of springs. Butterworth-Heinemann, pp 305–338

Goldscheider N, Drew D (eds) (2007) Methods in karst hydrogeology. IAH, International contributions to hydrogeology 26, Taylor & Francis, London, p 264

Grčman H, Vidic NJ, Zupan M, Lobnik F, Jones A, Montanarella L (2015) Soils of Slovenia with soil map 1:250.000. European Commission JRC Institute for Environment and Sustainability, Luxemburg, p 187

Habič P (1982) Kraški izvir Mrzlek, njegovo zaledje in varovalno območje. Acta Carsolog 10:45–73

Habič P (1987) Sledilni poskus na kraškem razvodju med Idrijco, Vipavo in Ljubljanico. Acta Carsolog 16:105–119

Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M (2014) Karst water resources in a changing world: review of hydrological modeling approaches. Rev Geophys 52:218–242

Hydrogeological map (2014) Ministry of the Environment and Spatial Planning, Slovenian Environment Agency. http://gis.arso.gov.si/

Hydrological Data Archive (2014) Ministry of the Environment and Spatial Planning, Slovenian Environment Agency. http://www.arso.gov.si/vode/

Janež J, Čar J (1990) Kraški izvir Kajža in njegovo zaledje. Acta Carsolog 19:101–138

Janež J, Čar J, Habič P, Podobnik R (1997) Vodno bogastvo visokega krasa. Geologija d.o.o., Idrija, p 167

Jeannin P-Y, Eichenberger U, Sinreich M, Vouillamoz J, Malard A, Weber E (2013) KARSYS: a pragmatic approach to karst hydrogeological system conceptualisation. Assessment of groundwater reserves and resources in Switzerland. Environ Earth Sci 69(3):999–1013

Kogovšek J (2010) Characteristics of percolation through the karst vadose zone. ZRC Publishing, Ljubljana, p 168

Kogovšek J, Petrič M (2014) Solute transport processes in a karst vadose zone characterized by long-term tracer tests (the cave system of Postojnska Jama, Slovenia). J Hydrol 519:1205–1213

Kovacs A, Sauter M (2007) Modelling karst hydrodynamics. In: Goldscheider N, Drew D (eds) Methods in karst hydrogeology. Taylor & Francis, London, pp 201–222

Kranjc A (ed) (1997) Karst hydrogeological Investigations in South-Western Slovenia. Acta Carsolog 26(1), p 388

Land use data (2013) Ministry of agriculture, forestry and food. http://rkg.gov.si/GERK/

Meteorological Data Archive (2014) Ministry of the environment and spatial planning. Slovenian Environment Agency. http://www.meteo.si/

Palmer AN (2007) Cave geology. Cave Books, Dayton, Ohio, p 454

Placer L (1981) Geološka zgradba jugozahodne Slovenije (Geologic structure of southwestern Slovenia). Geologija 24(1):27–60

Placer L, Čar J (1974) Problem podzemeljske razvodnice Trnovskega gozda, Križne gore in Črnovrške planote. Acta Carsolog 6:79–93

Ravbar N, Goldscheider N (2007) Proposed methodology of vulnerability and contamination risk mapping for the protection of karst aquifers in Slovenia. Acta Carsolog 36(3):461–475

Topographic and cartographic data (2014) Surveying and Mapping Authority of the Republic of Slovenia. http://www.e-prostor.gov.si/

Trček B (2003) Epikarst zone and the karst aquifer behaviour. A case study of the Hubelj catchment, Slovenia. Geološki zavod Slovenije, Ljubljana, p 100

Turk J, Malard A, Jeannin P-Y, Vouillamoz J, Masini J, Petrič M, Gabrovšek F, Ravbar N, Slabe T (2013) Interpretation of hydrogeological functioning of a high karst plateau using the KARSYS approach: the case of Trnovsko-Banjška planota (Slovenia). Acta Carsolog 42(1):61–74

Turpaud P, Zini L, Ravbar N, Cucchi F, Petrič M, Urbanc J (2018) Development of a protocol for the karst water source protection zoning: application to the Classical Karst Region (NE Italy and SW Slovenia). Water Resour Manage 32(6):1953–1968

Vižintin G, Ravbar N, Janež J, Koren E, Janež N, Zini L, Treu F, Petrič M (2018) Integration of models of various types of aquifers for water quality management in the transboundary area of the Soča/Isonzo river basin (Slovenia/Italy). Sci Total Environ 619–620:1214–1225

Vrba J, Zaporozec A (1994) Guidebook on mapping groundwater vulnerability. International Association of Hydrogeologist (16). Verlag Hienz Heise, Hannover, p 156

White WB (2002) Karst hydrology: recent developments and open questions. Eng Geol 65(2–3):85–105

Williams PW (2008a) World heritage caves and karst: a thematic study. IUCN World Heritage Studies, Gland, Switzerland, p 57

Williams PW (2008b) The role of the epikarst in karst and cave hydrogeology: a review. Int J Speleol 37:1–10

Zwahlen F (2004) Vulnerability and risk mapping for the protection of Carbonate (Karstic) aquifers. Final report COST action 620. European Commission, Directorate-General for Research, Brüssel, Luxemburg