KRASOSLOVJE V RAZVOJNIH IZZIVIH NA KRASU I **VODA**

KARSTOLOGY AND DEVELOPMENT CHALLENGES ON KARST I **WATER**

UREDNIKI / EDITORS:
MARTIN KNEZ, METKA PETRIČ, TADEJ SLABE

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CIP - Kataložni zapis o publikaciji
Narodna in univerzitetna knjižnica, Ljubljana

911.2(082)

KRASOSLOVJE v razvojnih izzivih na krasu. 1, Voda = Karstology and development challenges on karst. 1, Water / uredniki, editors Martin Knez, Metka Petrič, Tadej Slabe ; [risane predloge Tamara Korošec]. - Ljubljana : Založba ZRC = ZRC Publishing, 2011. - (Carsologica ; 13)

ISBN 978-961-254-334-1
1. Knez, Martin, 1964-
258948608

Carsologica 13

Urednik zbirke
Series editor:
Franci Gabrovšek

Uredniki
Editors:
Martin Knez, Metka Petrič, Tadej Slabe

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Recenzenta
Reviewed by:
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Jezikovni pregled
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Oblikovanje in prelom
Design and typesetting:
Barbara Hiti

Oblikovanje risanih predlog
Drawing:
Tamara Korošec

Izdajatelj
Issued by:
Inštitut za raziskovanje krasa ZRC SAZU
Karst Research Institute ZRC SAZU, Postojna

Zanj
Represented by:
Tadej Slabe

Založnik
Published by:
Založba ZRC
ZRC Publishing, Ljubljana

Za založnika
For the publisher:
Oto Luthar

Glavni urednik
Editor-in-chief:
Aleš Pogačnik

Tisk
Printed by:
Collegium graphicum d.o.o., Ljubljana

Naklada
Printrun:
600

Izdajo knjige je podprla
Subsidized by:
Javna agencija za knjigo RS
Slovenian Book Agency

Postojna-Ljubljana, 2011

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PREDGOVOR

PREFACE

Dobro poznavanje naravne in kulturne dediščine krasa je pogoj za smiselno načrtovanje življenja na njem. Kras pa je moč spoznati in razumeti predvsem s celostnim proučevanjem njegovega površja, jam in voda ter ekoloških značilnosti.

Pri poglabljanju temeljnega znanja na *Inštitutu za raziskovanje krasa Znanstvenoraziskovalnega centra Slovenske akademije znanosti in umetnosti* že več kot šest desetletij razvijamo in interdisciplinarno povezujemo najbolj pomembna področja krasoslovja in jih nadgrajujemo v celostno krasoslovje. Znanje skušamo urediti, da je kar čimbolj uporabno tudi načrtovalcem življenja na krasu. V večje, neposredno uporabne projekte smo vključeni. In izbrani, sveži izsledki so in bodo predstavljeni v knjižni zbirki *Krasoslovje v razvojnih izzivih na krasu.*

Načrtovanje brez dobrega poznavanja okolja in tudi posledično vizije njegovega razvoja, pa čeprav znotraj zakonskih naravovarstvenih omejitev, pač ni dovolj. Z dobrimi krasoslovnimi izsledki, tako na posameznih področjih krasoslovja kot v interdisciplinarni celoti, želimo pripraviti temelj za smiselno načrtovanje življenja na krasu. Za načrtovanje, ki bo upoštevalo naravne in kulturne značilnosti in ranljivost kraških pokrajin, načrtovanje, ki bo presegalo vsakokratne želje po dobičku, načrtovanje okolja pravih družbenoekonomskih razmer, v dobro prebivalcem krasa in njegovega kratko- ter dolgoročnega razvoja. Čeprav je naše poslanstvo predvsem poglabljanje temeljnega znanja o krasu, kraških pojavih in vodah, pa se zavedamo potrebe po stalnem in učinkovitem približevanju krasoslovnih dognanj širši družbeni skupnosti, tudi skozi sodelovanje pri pomembnejših neposredno uporabnih projektih.

Pred desetimi leti smo ustanovili podiplomski študij krasoslovja in s krasoslovnimi predmeti sodelujemo pri geografskih študijih. Ustanovili smo tudi *Krasoslovno akademijo – mednarodno združenje krasoslovcev*, znotraj katere bomo še bolj učinkovito mednarodno povezovali znanje in izkušnje ter poiskali najboljše podlage za smiselno načrtovanje življenja v raznovrstnih kraških pokrajinah.

Vključeni smo v posamezne projekte razvoja in varovanja naravne in kulturne dediščine krasa, regionalnega načrtovanja, oskrbe z vodo, gradnje prome-

A good knowledge of the natural and cultural heritage of karst is a precondition for the rational planning of life on it. The karst can be known and understood primarily through the comprehensive study of its surface, caves, waters, and ecological characteristics.

The *Karst Research Institute* of the *Scientific Research Centre* of the *Slovenian Academy of Sciences and Arts* has been involved in developing this basic knowledge, establishing interdisciplinary connections among the most important fields of karstology, and consolidating them into an integral science of karstology for more than six decades. We try to organize the knowledge to make it as useful as possible for planning life in karst regions and are directly involved in larger major projects. Book collection *Karstology and development challenges on karst* will present a selection of completed and new projects.

Planning without a thorough understanding of the environment and consequently a vision of its development—even though within the boundaries of environmental protection legislation—is certainly not sufficient. We wish to build a foundation for the rational planning of activities on karst based on good karstological research, as much in individual fields of karstology as in interdisciplinary studies. Such planning must take the natural and cultural characteristics and the vulnerability of karst landscapes into consideration and overcome the inevitable pursuit of profit. Environmental planning must realistically consider the socioeconomic conditions for the benefit of local karst populations and the short- and long-term development of karst regions. While the mission of the *Karst Research Institute* is primarily to expand the basic knowledge of karst, karst phenomena, and karst waters, we are also aware of the need for the continuous and effective communication of karstological knowledge to the wider social community, including through our participation in the more important and directly useful projects.

Ten years ago, the *Karst Research Institute* established a postgraduate karstology program and incorporated karstology courses in the undergraduate geography curriculum. The *International Academy of Karst Sciences,* an international association of karstolotnic, zapiranja odlagališč na krasu, zbiranja podatkov o kraških jamah in njihovega varovanja, kraške ekologije in ugotavljanja naših vplivov na kraško podzemlje ter načrtovanja in uporabe kraških pojavov v turistične namene.

V prvi knjigi združujemo izbrane neposredno uporabne študije o kraških vodah, v drugi pa izsledke našega sodelovanja pri načrtovanju in gradnji avtocest na krasu, urejanju jam za turistične namene ter ekologiji in zaščiti podzemlja. Zavedamo se, da to še niso zaključene enote o posameznih delih oziroma celoti krasoslovnega načrtovanja življenja na krasu, so pa, upamo, pomemben korak v to smer in izziv za prihodnost.

Uredniki

gists, was established to link international knowledge and experience more effectively and to find the best foundations for the rational planning of life in various karst regions around the world.

The *Karst Research Institute* is involved in individual projects related to the development and protection of the natural and cultural heritage of karst areas, regional planning, water supply systems, the construction of transportation infrastructure, the closure of dump sites in karst areas, the collection of data on karst caves and their protection, karst ecology and determining the extent of human influence on the karst underground, and planning and monitoring the exploitation of karst phenomena for tourism.

The first book in the series will contain selected directly applicable research studies on karst waters, and the second will present the results of our participation in the planning and construction of expressways on karst, the management of caves for tourist purposes, and the ecology and protection of the underground. We recognize that this does not include certain individual topics or the total contribution of karstology to planning life on karst, but we hope they are a step in the right direction and a challenge for the future.

The Editors

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ZNAČILNOSTI KRAŠKIH VODONOSNIKOV, NJIHOVA RANLJIVOST IN OGROŽENOST

CHARACTERISTICS OF KARST AQUIFERS, THEIR VULNERABILITY AND ENDANGERMENT

METKA PETRIČ, NATAŠA RAVBAR, JANJA KOGOVŠEK

Čeprav pokrivajo kraške kamnine le 7–12 % zemeljskega površja, se s pitno vodo iz kraških vodonosnikov oskrbuje skoraj četrtina svetovnega prebivalstva (*Ford* in *Williams* 2007). V Sloveniji je ta delež še večji, saj obsegajo karbonatne kamnine približno 43 odstotkov njenega ozemlja. Prevladujejo predvsem v zahodnem in južnem delu države, kjer gradijo obsežne kraške in razpoklinske vodonosnike. Ti zagotavljajo pitno vodo za več kot polovico prebivalcev Slovenije.

Zaradi posebnih značilnosti so kraški vodonosniki izjemno ranljivi za posledice različnih virov onesnaževanja. Dobra prepustnost kraških kamnin omogoča hitro infiltracijo vode v podzemlje, znotraj tega pa zelo hitro pretakanje na velikih razdaljah in po navadno neznanih poteh. Z vodo se naglo širi tudi onesnaženje, ki ogroža vodne vire. Zaradi heterogene zgradbe kraških vodonosnikov je zelo težko predvideti režim pretakanja podzemne vode in prenosa škodljivih snovi, dodatno težavo pa predstavlja velika spremenljivost njihovih značilnosti v različnih hidroloških razmerah. Odziv na razne negativne dejavnike je zato specifičen in se bistveno razlikuje od drugih okolij. Pri oceni vpliva človekovih dejavnosti na kraške vode je treba te posebnosti upoštevati. Dobro poznavanje značilnosti kraških vodonosnikov je predpogoj za njihovo ustrezno varovanje.

1.1 Značilnosti kraških vodonosnikov

Kraški vodonosniki so območja karbonatnih kamnin (predvsem apnenca in dolomita), ki so bila izpostavljena zakrasevanju. V njih kraški kanali in razpoke različnih velikosti hranijo razmeroma velike količine podzemne vode. Od drugih tipov vodonosnikov se razlikujejo zlasti po visoki stopnji topnosti kamnin, kar povzroča značilno oblikovanost površja in podzemne pojave ter vpliva na posebnosti pretakanja voda v podzemlju (*Gams* 2004; *Ford* in *Williams* 2007).

Kraški vodonosniki so navadno več deset do več sto km² obsežna območja, ki jih pogosto prepredajo močno zakraseli razpoklinski in prelomni predeli. Zaradi razpokanosti in pretrtosti kamnin deževnica

Although karst rocks cover only 7–12 % of land surface, drinking water from karst aquifers supply almost a quarter of world population (*Ford* and *Williams* 2007). In Slovenia this share is even larger, as carbonate rocks cover approximately 43 % of its territory. These rocks mostly prevail in western and southern part of the country, where they build vast karst and fissured aquifers. They ensure drinking water to more than half of Slovene population.

Due to special characteristics karst aquifers are extremely vulnerable to consequences of different sources of pollution. High permeability of carbonate rocks enables quick infiltration of water into underground, and very fast flow over large distances in the underground, usually through unknown flow paths. With the water flow also contamination is rapidly spread that endangers water sources. The regime of groundwater flow and contaminant transport is very hard to predict due to heterogeneous structure of karst aquifers. Great variability of transport characteristics in different hydrologic circumstances represents an additional problem. Response to various negative factors is therefore very specific and differs from other environments. These peculiarities need to be taken into consideration when estimating influences of human activities on karst waters. Good knowledge of karst aquifers characteristics is a prerequisite for their proper protection.

1.1 Characteristics of karst aquifers

Karst aquifers are areas of carbonate rocks (mainly limestone and dolomite) that have been exposed to karstification. They are significant for underground karst channels and fissures of different sizes that hold relatively big quantities of underground water. They differ from the other types of aquifers concerning mainly high degree of rocks solubility that induce characteristic relief forms and underground phenomena, and influences special water flow in the underground (*Gams* 2004; *Ford* and *Williams* 2007).

Karst aquifers are usually several ten to several hundred of km² vast areas, that are often criss-crossed with highly karstified fissured and fault zones. Due hitro pronica skozi golo površje ali skromni prsteni pokrov v podzemlje. Na stiku s krasom poniknejo tudi površinski vodotoki z nekraškega obrobja.

V podzemlju se infiltrirana voda s površja pretaka večinoma v navpični smeri proti gladini podzemne vode. Na svoji poti s kemičnim delovanjem razpoke korozijsko širi in veča. Tako ustvarja sistem različno velikih in med seboj povezanih podzemnih poti. Zato se struktura in delovanje kraških vodonosnikov močno razlikujeta od nekraških (npr. medzrnskih), saj ju določajo predvsem izjemno visoka prepustnost in velike hitrosti pretakanja voda v podzemlju, raznovrstnost načina pretakanja in običajno neznane smeri odtekanja vode, ki segajo tudi do več deset kilometrov oddaljenih predelov. V krasu se pogosto meša voda z različnih območij napajanja (*Gunn* 1981, 1983; *White* 1988; *Worthington* 2009).

Glede na značilnosti pretakanja in procese uskladiščenja vode v podzemlju ločimo več delov vodonosnika (1). Zgornji del vodonosnega sistema, v katerem se prepletata hitro vertikalno pretakanje po primarnih drenažnih poteh in počasno precejanje skozi slabše razpokano osnovo, sestavlja nezasičeno ali vadozno cono. To je suhi del vodonosnika in je lahko debel tudi do več sto metrov. V spodnjem delu vodonosnika pa je zasičena ali freatična cona, ki je ves čas zalita z vodo. Pretakanje v tej coni poteka po kanalih, razpokah in porozni osnovi. Tok je pogosto turbulenten in navadno poteka sub-horizontalno v smeri proti izvirom, skozi katere se podzemne vode spet vračajo na površje (2).

Prehodno območje med nezasičeno in zasičeno cono imenujemo poplavna ali epifreatična cona, določa pa jo gladina podzemne vode. Ta je mnogokrat nezvezna in njeno višino je zelo težko določiti, ker se nenehno spreminja in je močno odvisna od trenutnih hidroloških stanj. Človeku je dostopna le v posameznih, redkih vodnih jamah ali vrtinah, zato nam je višina kraške podzemne vode pogosto neznana (*White* 1988; *Ford* in *Williams* 2007).

Pomembno vlogo pri pretakanju in uskladiščenju infiltrirane vode ima epikraška cona (*Mangin* 1975; *Király* idr. 1995; *Petrič* 2002; *Trček* 2003) v zgornjem delu nezasičene cone. Lahko je različno debela (do

to fissuring and crushing of the rock, precipitation water infiltrates through the bare surface or thin soil. Consolidated streams that gather water on non-karst surfaces also sink into the karst subsurface.

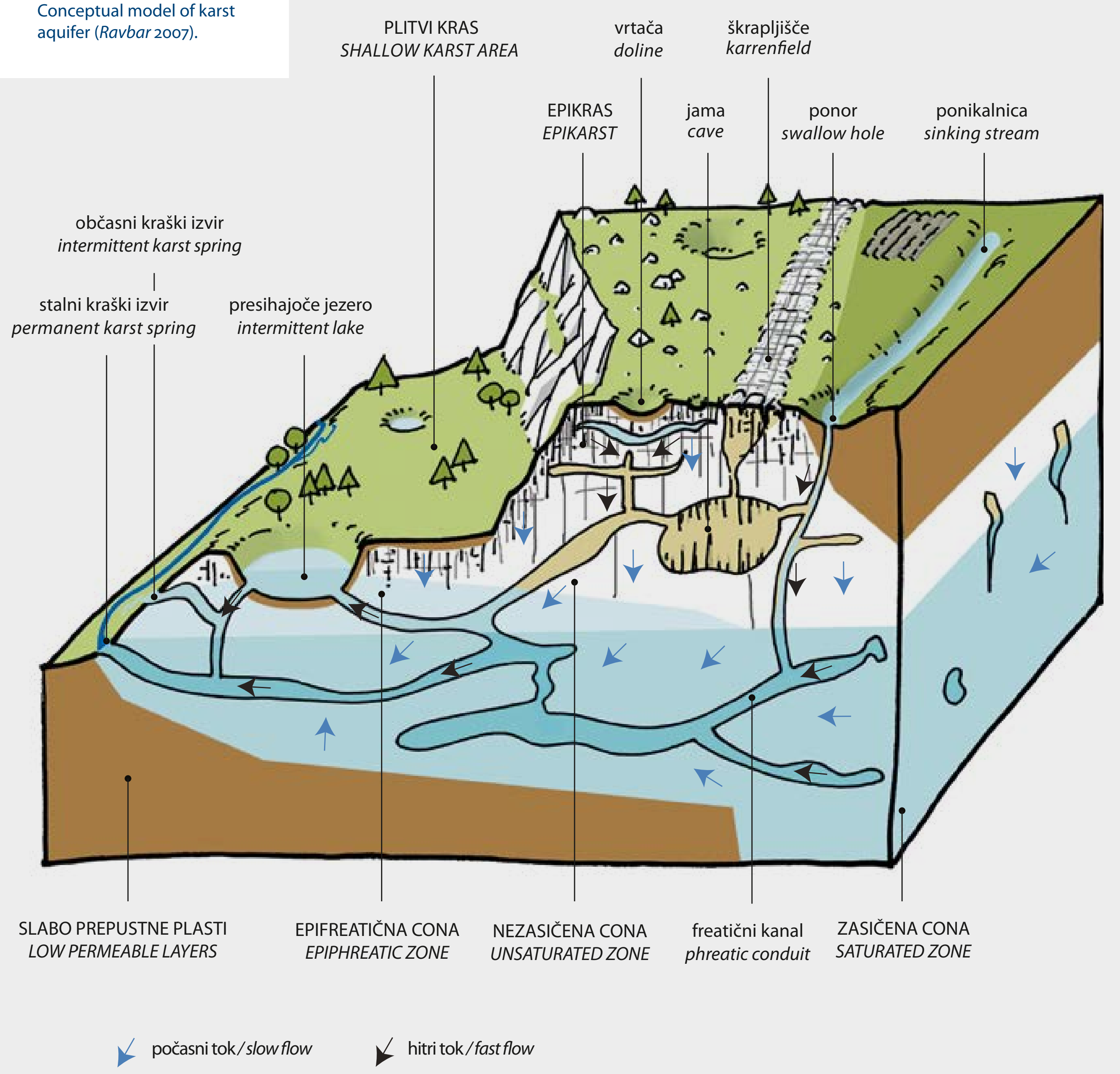
In the underground the infiltrated water from the surface flows mainly vertically towards the groundwater. On its way it chemically widens and enlarges the cracks. In this manner it creates a system of differently big and interconnected underground paths. Therefore the structure and functioning of karst aquifers strongly differs from the non-karst (e.g. porous) ones. They are determined above all by exceptional permeability, and high groundwater flow velocities, variety of flow manner and usually unknown flow pathways that reach even several tens of kilometres distant areas. In karst there are frequent connections and intersections of water paths from different recharge areas (*Gunn* 1981, 1983; *White* 1988; *Worthington* 2009).

According to characteristics of water flow and processes of water storage in the underground, several parts of the aquifer can be differentiated (1). The upper part of the aquifer system, with combined fast vertical flow through the primary drainage pathways and slow seepage through the weakly cracked matrix, composes the unsaturated or vadose zone. This is a dry part of the aquifer and can be up to several hundred metres thick. In the lower part of the aquifer there is the saturated or phreatic zone that is permanently filled with water. Water flow in this zone is through the channels, cracks and through the porous matrix. The flow is often turbulent and in a sub-horizontal manner towards the springs through which the groundwater comes back to the surface (2).

Transitional area between unsaturated and saturated zones is the flooding or epiphreatic zone determined by the groundwater surface. This is often interrupted and its height is very hard to determine, as it constantly changes and is highly dependent on temporary hydrologic conditions. It is reachable by human only in individual and scarce water caves or boreholes, therefore the groundwater surface in karst often remains unknown (*White* 1988; *Ford* and *Williams* 2007).

Important role in groundwater flow and storage of

1 Konceptualni model kraškega vodonosnika (*Ravbar* 2007).
Conceptual model of karst aquifer (*Ravbar* 2007).



več deset metrov) in različno zakrasela. Razpokanost in zakraselost epikraške cone, ki se z globino manjšata, pogojujeta hitrost vertikalnega pronicanja vode. Po razširjenih glavnih prevodnikih se infiltrirana voda pretaka zelo hitro, pronicanje po stranskih, slabše prepustnih razpokah pa je precej ovirano. Voda se tudi z lateralnim pretakanjem steka proti primarnim drenažnim conam vertikalnega prenikanja.

infiltrated water is played by an epikarst zone (*Mangin* 1975; *Király* et al. 1995; *Petrič* 2002; *Trček* 2003) in the upper part of the unsaturated zone. It can be differently thick (up to several tens metres) and differently karstified. The fissuring and karstification of the epikarst zone that lower with depth condition the velocity of vertical seepage of water. Through the widened main conduits the infiltrated water flows very

2 Kraški izviri, skozi katere iztekajo podzemne vode na površje, so izjemno pomemben vir za oskrbo s pitno vodo.
Karst springs through which underground waters flow onto surface are exceptionally important for drinking water supply.

Skladiščenje vode in koncentracija toka sta odvisna od velikosti, odprtosti in povezanosti razpok, por in kanalov v epikraški coni, pa tudi od stopnje prejšnje zapolnjenosti sistema z vodo (*Klimchouk* 2000). Ob padavinah se del infiltrirane vode hitro prenese v vertikalno mrežo kanalov glavnih prevodnikov, presežek pa se uskladišči in se po stranskih prevodnih kanalih počasi preceja v spodnjo nezasičeno cono. Dotok vode ohranja stalnost kraških izvirov v dolgih sušnih obdobjih (*Kogovšek* 2010).

1.2 Ranljivost kraških vodonosnikov

Ranljivost kraških vodonosnikov opisuje verjetnost njihovega onesnaženja in jo uporabljamo za oceno občutljivosti za posledice morebitnih človekovih vplivov. Je naravna lastnost sistemov podzemne vode in je odvisna od geoloških, hidrogeoloških, hidroloških, klimatskih in vegetacijskih značilnosti, neodvisna pa

fast, whereas the flow through lateral and less permeable cracks is mainly hindered. In this way water also flows laterally towards the primary draining zones of vertical seepage.

Storage of water and concentration of the flow are dependent on size, openness and connectivity of fissures, pores and channels in the epikarst zone, as well as on the degree of previous saturation of the system with water (*Klimchouk* 2000). With precipitation part of the infiltrated water is quickly transported in the vertical net of channels of the main conduits, while the surplus of the water is stored and is transported via lateral channels slowly towards the lower lying unsaturated zone. Such inflow preserves permanent water in karst springs even in long lasting dry periods (*Kogovšek* 2010).

od lastnosti onesnaževal (*Vrba* in *Zaporozec* 1994). Osnovna procesa, ki vplivata na ranljivost, sta napajanje z infiltracijo padavin ali površinskih tokov skozi nezasičeno cono ter tok in transport snovi v zasičeni coni vodonosnika. Prvega določajo predvsem efektivna infiltracija padavin s površja v kamninski sistem, stopnja razvitosti epikraške cone pri razpršenem napajanju ter položaj in značilnosti ponorov, skozi katere se v podzemlje koncentrirano stekajo površinske vode in na ta način neposredno vnašajo tudi onesnaženje. Značilnosti pretežno horizontalnega toka vode in transporta snovi v zasičeni coni pa so

3 Infiltracija padavin je zaradi majhne debeline prsti in zakraselosti kraškega površja zelo hitra.
Infiltration of precipitation is due to thin cover of soil and high karstification of the surface very rapid.

1.2 Vulnerability of karst aquifers

Vulnerability of karst aquifers is defined by the probability of their contamination. It is used to assess the sensibility of the aquifer systems to the consequences of eventual human influences. It is a natural characteristic of the groundwater systems and is dependent on geological, hydrogeological, hydrological, climatic and vegetational circumstances and independent from the nature of the contaminants (*Vrba* and *Zaporozec* 1994). Two principal processes that influence the vulnerability are the recharge with the infiltration of the precipitation or surface waters through the unsaturated zone, and the flow and transport of substances through the saturated zone of the aquifer. The diffuse infiltration of water is determined by the effective infiltration from the surface into the rock system and by the degree of the epikarst zone development. The concentrated infiltration is determined by the location and characteristics of the swallow holes through which underground is directly connected with the surface and in this way any contamination rapidly enters the aquifer. The characteristics of the predominant horizontal flow in the saturated zone are determined by the distinction between the karstified, fissured and porous aquifers with different degrees of porosity and permeability (*Zwahlen* 2004).

For protection of karst aquifers thin soil cover overlying carbonate rocks represents an unfavourable characteristic (3). In many places this cover is entirely removed. The effect of filtration and retardation of noxious matter in the upper layer is therefore negligible. The lower lying bedrock is usually very crushed and infiltration is possible practically everywhere.

Due to the very well developed net of karst fissures and voids the velocity of the groundwater flow in the unsaturated zone is relatively high. However, it is significantly influenced by the intensity and distribution of the precipitation. Many studies have shown that intensive and abundant rain may flow through the well permeable conduits of the 150 m thick ceiling in even six hours, while through the most permeable ones that resemble shafts it may flow even quicker. Beside the well permeable voids there is a net of less permeable cracks that much slower conduct smaller quantities opredeljene predvsem na osnovi ločevanja kamnin na kraške, razpoklinske in medzrnske vodonosnike z različnimi stopnjami poroznosti in prepustnosti (*Zwahlen* 2004).

Pri zaščiti kraških vodonosnikov predstavlja neugodno lastnost majhna debelina preperinskega pokrova, ki prekriva karbonatne kamnine (3). Na številnih mestih je ta pokrov celo povsem odstranjen. Učinek filtracije in zadrževanja škodljivih snovi v vrhnji plasti je zato majhen. Poleg tega je osnovna kamnina pod preperinsko plastjo večinoma zelo razpokana in infiltracija je možna praktično povsod.

Zaradi razvite mreže kraških razpok in kanalov je hitrost pretakanja podzemne vode v nezasičeni coni relativno velika. Pomemben vpliv nanjo imata tudi izdatnost in razporeditev padavin. Raziskave so pokazale, da intenzivne in izdatne padavine preidejo 150 m debele apnence po bolj prepustnih prevodnikih že v šestih urah, po tistih najbolj prepustnih, ki so že začetki brezen, pa še znatno hitreje. Bolj prepustne razpoke spremlja mreža slabo prepustnih razpok, ki bistveno počasneje prevajajo manjše količine vode, kar pa v primeru onesnaženja pomeni akumulacijo in velike zakasnitve dotoka onesnaževal do izvira. Tako je hitrost pretakanja vode in v vodi topnih snovi s površja do sklenjenih vodnih tokov globlje v kras od 25 m/h do manj kot 1 cm/h (*Kogovšek* 2010). Po onesnaženju na kraškem površju lahko torej pričakujemo zelo različne hitrosti prenosa škodljivih snovi globlje v kras do sklenjenih vodnih tokov, s temi pa običajno zelo hitro proti kraškim izvirom.

Različne hidrološke razmere pomembno vplivajo na smeri in potovalni čas vode ter na možnost razredčevanja in uskladiščenja onesnaževal v podzemlju. Ob točkovnih izlitjih na kraškem površju (npr. ob raznih nesrečah) izlite tekočine v sušnih razmerah zelo hitro prodirajo po razpoložljivih dobro prepustnih prevodnikih, v slabo prepustnem delu nezasičene cone pa se začasno uskladiščijo. Nadaljnji prenos je odvisen od padavin, ki sledijo. Ob razpršenem in manj intenzivnem vnosu snovi prihaja v sušnih razmerah le do uskladiščenja, tudi za več mesecev (*Kogovšek* 1995a). V takih primerih ne zaznamo onesnaženja takoj, zato lahko ob nepoznavanju razmer zmotno sklepamo, da

of water. In case of contamination the pollution is accumulated and retarded there and reaches the springs with a delay. Therefore the velocities of the water flow and soluable matter from the surface to the water courses in karst may range from 25 m/h to less than 1 cm/h (*Kogovšek* 2010). After the contamination on the karst surface very different velocities of noxious matter transport deeper into the subsurface to the underground water resources can therefore be expected. Once contaminants reach consolidated water courses, they rapidly flow towards the karst springs.

Different hydrological conditions importantly influence the way and travel time of water, as well as the possibilities of contaminant dilution and storage in the underground. In case of the point outflow on the karst surface (e.g. in case of accidents) in low-water conditions the liquid rapidly penetrates the well permeable conduits, while it is temporarily stored in the less permeable matrix of the unsaturated zone. Further transport depends on the subsequent precipitation intensity. In case of diffuse and less intensive pollution in low-water conditions the contaminant may be stored even for several months (*Kogovšek* 1995a). In such cases the contamination is not detected immediately. Therefore we can incorrectly deduce that the contamination did not affect the spring. When the unsaturated zone is well saturated with water, due to the previous precipitation, the differences of travel time between the well permeable and less permeable conduits are much smaller (*Kogovšek* 2000; *Gabrovšek* et al. 2010).

Due to the described characteristics the vulnerability of karst aquifers is very high. Rapid infiltration, small filtration, very high velocities of water flow in the underground and quick transport of contamination far away from the recharge point with it, are the reasons of the usually less efficient processes of self-purification in karst.

1.3 Endangerment of karst water

The most frequent sources of contamination are urban settlements, industry, agriculture and traffic. We differ diffuse contamination of karst, as is onesnaženja sploh ni bilo. Kadar je nezasičena cona zaradi predhodnih padavin dobro namočena z vodo, so razlike v hitrostih pretakanja po dobro prepustnih in slabo prepustnih prevodnikih veliko manjše (*Kogovšek* 2000; *Gabrovšek* idr. 2010).

Zaradi vseh opisanih značilnosti je ranljivost kraških vodonosnikov zelo velika. Hitra infiltracija, manjša filtracija, visoke hitrosti pretakanja voda v podzemlju in s tem hiter prenos onesnaženja daleč stran od točke vnosa so razlogi, da so procesi samoočiščevanja v krasu običajno manj učinkoviti.

1.3 Ogroženost kraške vode

Najpogostejši viri onesnaženja so mestna naselja, industrija, kmetijstvo in promet. Ločimo razpršeno onesnaževanje krasa, kot je onesnaževanje s kmetijskih površin zaradi gnojenja in uporabe zaščitnih snovi, linijsko (npr. prometnice) in točkovno onesnaževanje (*De Ketelaere* idr. 2004). Slednje so predvsem izpusti mestne kanalizacije in razlitja nevarnih snovi ob različnih nesrečah, ko lahko v kras stečejo večje količine nevarnih ali celo strupenih snovi. V naseljih so največkrat problem neurejena kanalizacija in neustrezna odlagališča odpadkov, iz katerih padavine spirajo tudi nevarne snovi. Prenašajo se v tekoči fazi, zato je njihova mobilnost zelo velika. V odpadnih vodah je koncentracija škodljivih snovi pogosto visoka. Med njimi so organske snovi, fosfati, amoniak, nitrati, nitriti, kovine, detergenti, bakterije in virusi, ki zaradi neučinkovitosti filtracije, adsorpcije ali biodegradacije v krasu pomenijo zelo veliko nevarnost za vodne vire. Reševanje tega problema je v prvi vrsti povezano z gradnjo novih ali z izboljšanjem že zgrajenih kanalizacijskih sistemov in njihovo povezavo z ustreznimi čistilnimi napravami. Naselja v kanalizacijo odvajajo odpadne vode, ki so pogosto komunalno-industrijske in se večinoma še ne čistijo v bioloških čistilnih napravah s predčiščenjem industrijskih voda. Ponekod imajo le mehansko stopnjo čiščenja, v številnih primerih pa neočiščena odpadna voda odteka v kraške vodotoke ali pa kar neposredno v kras (*Kogovšek* idr. 2008).

V primerih, ko se odpadne vode stekajo v kraške ponikalnice (4), je predvsem ob višjem vodostaju ugodna okoliščina razredčitev in ob površinskem

the contamination from the agriculture due to the manuring and usage of fertilizers, line contamination (e.g. transport routes) and point contamination (*De Ketelaere* et al. 2004). The latter are mainly outflows from sewage network and outflows of dangerous substances in case of accidents when larger quantities of dangerous or noxious substances may leak into karst. In the settlements there are usually problematic unregulated sewage systems and illegal garbage dumps, from which precipitation wash away dangerous substances. They are transported in a liquid manner, and therefore their mobility is very high. In waste waters the concentration of harmful substances is often very high, too. There are organic matter, phosphates, ammonia, nitrates, nitrites, metals, detergents, bacteria and viruses that are very threatful for karst springs due to limited possibilities of filtration, adsorption and biodegradation within the karst aquifer. Solving this problem is primarily linked to building of sewage systems or renovation of the old ones and their connection to the waste water treatment plants. Settlements usually draw off waste water that are of communal and industrial origin and are usually not yet cleaned in the biological waste water treatment plants with the industrial water pretreatment. In places they only have mechanical level of treatment, but in many cases the uncleansed waste water flows into karst rivers or directly into karst (*Kogovšek* et al. 2008).

In cases when waste water flows into sinking rivers (4), there is usually a positive effect of dilution at high-water conditions and a certain degree of self-purification at the surface flow across the karst poljes. However, contamination of sinking rivers is usually very high. In Slovene karst sinking rivers sink several times and reappear in springs on the lower-lying karst poljes. Karst poljes are densely populated and contribute with additional inflows of waste waters. The conditions become critical often in summer and autumn times, as well as in early spring, when level of water is the lowest and when the dilution effect is minimal or even absent. If in such circumstances higher quantities of waste waters are released or the environment is polluted with dangerous matter due to the accidents, the consequences may be catastrophic (dying of living beings in waters or contamination of captured drinking water supplies, pretakanju po kraških poljih tudi določena stopnja naravnega samoočiščevanja. Obremenjenost ponikalnic pa je običajno velika. Na slovenskem krasu te pogosto večkrat poniknejo in se nato pojavijo v izviru na nižje ležečem kraškem polju. Kraška polja so gosteje poseljena, zato se vanje stekajo dodatni dotoki odpadnih voda in dodatno onesnaženje. Razmere postanejo kritične običajno poleti in jeseni, a tudi zgodaj spomladi, ob najnižjih vodostajih, ko je razredčevalni učinek minimalen ali celo izostane. Če so v takih razmerah izpuščene večje količine odplak ali pa je okolje onesnaženo z nevarnimi snovmi ob različnih nesrečah, so lahko posledice katastrofalne (pomor življenja v vodotoku ali onesnaženje zajetih vodnih virov, če se nesreča zgodi v njihovem zaledju).

Naselja so tudi vir večjih količin odpadkov, ki jih zbiramo na komunalnih odlagališčih. Njihov vpliv na kraške vode je bolj podrobno predstavljen v poglavju »Načrtovanje monitoringa podzemne vode v vplivnem območju odlagališč odpadkov na krasu na podlagi rezultatov sledilnih poskusov« v tej knjigi. Še dodatno nevarnost pomenijo divja odlagališča odpadkov.

Na naseljenih območjih je običajno zelo obsežna tudi industrijska dejavnost, ki glede na vrsto povzroča specifično onesnaževanje, predvsem z neustrezno

if the accident happens in their catchment).

Settlements are also sources of bigger quantities of waste material that is being collected in waste disposal dumps. Their influence to karst waters is in more detail described in the chapter »Planning of the groundwater monitoring in the impact areas of landfills in karst based on the results of tracer tests« of this book. Additional danger is represented by the illegal waste disposal.

4 Iztok iz čistilne naprave v občasni površinski vodotok, ki na stiku s krasom ponika v podzemlje.
Outflow from the waste water treatment plant into the periodical surface stream that in contact with karst sinks underground.

In settled areas the industrial activity is often very intensive, too. As for the type of industry it usually produces very specific contamination, mainly by the unsuitably treated industrial waste waters or unsuitable storage of dangerous substances. Usually industries contaminate air and the contaminants are later rinsed with precipitation and threaten karst waters. Also in this case suitable treatment plants that reduce the possibilities of negative impacts have an important role beside usual safety measures. Beside constant emissions accidents with spillage of harmful substances are also very dangerous. Therefore it is very important to implement severe measures for accidents prevention. However, if the accidents happen, quick action is needed—to inform the competent services and undertake immediate and professional measures.

obdelanimi industrijskimi odplakami ali neprimernim skladiščenjem nevarnih snovi; zelo pogosto pa je tudi onesnaževanje zraka, ki nato z infiltracijo padavin prav tako ogroža kraške vode. Tudi v tem primeru imajo poleg splošnih varnostnih ukrepov pomembno vlogo ustrezne čistilne naprave, ki zmanjšujejo možnost negativnih vplivov. Poleg stalne emisije so zelo nevarne še nesreče z enkratnim izpustom škodljivih snovi. Zaradi tega je zelo pomembno izvajanje strogih ukrepov za preprečitev teh nesreč, če pa se nesreča že zgodi, je nujna hitra akcija – tako informiranje ustreznih služb kot takojšnje in strokovno premišljeno ukrepanje.

Zaradi goste prepredenosti krasa s prometnicami in njihove velike prometne obremenjenosti so kraške vode pogosto onesnažene z organskimi snovmi, ogljikovodiki, olji in težkimi kovinami, ki jih padavine spirajo s cest. Podrobneje o možnih negativnih vplivih govori poglavje pričujoče knjige z naslovom »Ogroženost kraških vodnih virov zaradi prometa v rednih razmerah«. Dodatno nevarnost pomeni izlitje nevarnih snovi ob nesrečah, tako ob prevažanju po cestah, pretakanju v skladiščih ali zaradi puščanja naftnih rezervoarjev. Primeri tovrstnih nesreč so obravnavani v poglavju »Izlitja nevarnih snovi ogrožajo kraške vode« v tej knjigi.

Na slovenskem krasu prevladujejo ekstenzivne in tradicionalne oblike kmetovanja, zato je nevarnost onesnaževanja nekoliko manjša. Kljub temu pa varstvo voda zahteva omejitve uporabe in pravilno ravnanje s škodljivimi snovmi, ki jih uporabljajo v kmetijstvu. Kmetije bi morale imeti primerno urejene objekte za rejo živine in gnojišča. Gnojenje z naravnimi in umetnimi gnojili je treba prilagoditi naravnim samoprečiščevalnim zmožnostim okolja, to je uporabljati ustrezne količine in izbrati primeren čas gnojenja (ne tik pred deževnim vremenom ali med njim, ne na zamrznjena ali zasnežena tla ipd.). Podobne omejitve veljajo tudi za uporabljanje škropiv. Nepravilna raba težko razgradljivih pesticidov je povzročila že več onesnaženj kraških vodnih virov. Posebno pozornost je treba posvetiti tudi ustreznemu skladiščenju nevarnih snovi.

Posledica neustrezne uporabe umetnih gnojil in zaščitnih sredstev je razpršen vnos onesnaževalcev. Navadno se zaradi tega zveča vsebnost nitratov in drugih kemičnih snovi v vodi. Najbolj nevarne so

Due to dense transport routes that criss-cross karst areas and their high traffic burdening, karst waters are frequently contaminated with organic matter, hydrocarbons, oils and heavy metals that are rinsed from the roads by precipitation. Possible negative impacts are in detail presented in the chapter »Threats to the karst water sources from traffic in normal conditions« of this book. Additional danger is the spillage of dangerous substances in case of accidents, when transported, decanted in repositories or due to leakage in oil reservoirs. Cases of such accidents are presented in the chapter »Spillages of hazardous substances endanger karst waters« of this book.

In Slovene karst extensive and traditional farming prevails, therefore the contamination is less possible. Nevertheless, protection of waters requests usage restriction and proper handling with dangerous substances that are used in agriculture. Farms should have well-regulated stables and dungheaps. Manuring with natural or artificial fertilizers need to be adjusted to the natural self-purification capabilities of the environment. When manuring, suitable quantities need to be used and in convenient time (i.e. not before or during the rain, not on frozen areas or areas covered with snow). Similar measures need to be taken when fertilizing. Incorrect usage of difficultly decompositive pesticides has caused several contaminations of karst springs already. Special care need to be taken when storing dangerous substances.

Consequences of incorrect usage of artificial fertilizers mean diffuse contamination. Usually it causes higher concentrations of nitrates and other chemical matters in water. The most dangerous are substances that are toxic even in small concentrations (e.g. cancerogenous, mutagenic substances) and that only slowly degrade in the environment. This usually means more durable contamination and accumulation of contaminants.

Karst waters are very vulnerable to contamination with microorganisms (bacteria, viruses) as the fast inflow from the point of release to the spring does not assure their die off. Therefore many karst springs are bacteriologically contaminated and the water is without proper pre-treatment not drinkable. The most frequent treatment is chlorination. If the tiste snovi, ki že v majhnih koncentracijah delujejo škodljivo (npr. karcenogene, mutagene snovi) in se v okolju le počasi razgrajujejo, kar pomeni trajnejše onesnaženje in akumuliranje.

Kraške vode so zelo ranljive za posledice onesnaževanja z mikroorganizmi (bakterijami, virusi), saj hiter tok od točke izvora do izvirov ne zagotavlja njihovega odmrtja. Zato je bakteriološko oporečna večina kraških izvirov, ki brez ustrezne razkužitve niso primerni za pitje. Vodo se še vedno najpogosteje razkužuje s kloriranjem. Če so v njej organske snovi (mineralna olja, plinsko olje itd.), je to lahko nevarno za zdravje, saj nastanejo klorirani ogljikovodiki, ki so karcenogeni. Primernejši so drugi načini dezinfekcije, npr. UV-dezinfekcija in filtracija z membranskimi filtri, ki pa sta dražja postopka in zato žal tudi manj uporabljana.

1.4 Pomen predhodnih raziskav krasa

Dobro poznavanje značilnosti kraških vodonosnikov je predpogoj za njihovo ustrezno varovanje (*Ravbar* in *Kovačič* 2006). Kam in kako hitro se onesnaženje s kraškega površja širi v kraški notranjosti in v katerih izvirih ga lahko pričakujemo, lahko uspešno napovemo le, če zadosti dobro poznamo značilnosti kamninske zgradbe in hidrogeološke razmere na obravnavanem območju. Za to so potrebne ustrezne raziskave. Ob nesrečah v industriji ali prometu se je pokazalo, da smo le na območjih, kjer so že bile opravljene predhodne celostne hidrogeološke raziskave, lahko sklepali, na katerih izvirih in kdaj naj bi se onesnaženje pojavilo. Zaradi tega je bilo možno stalno vzporedno spremljanje kakovosti vode in ob zaznavi škodljivih snovi je bil izvir pravočasno izključen iz sistema vodooskrbe.

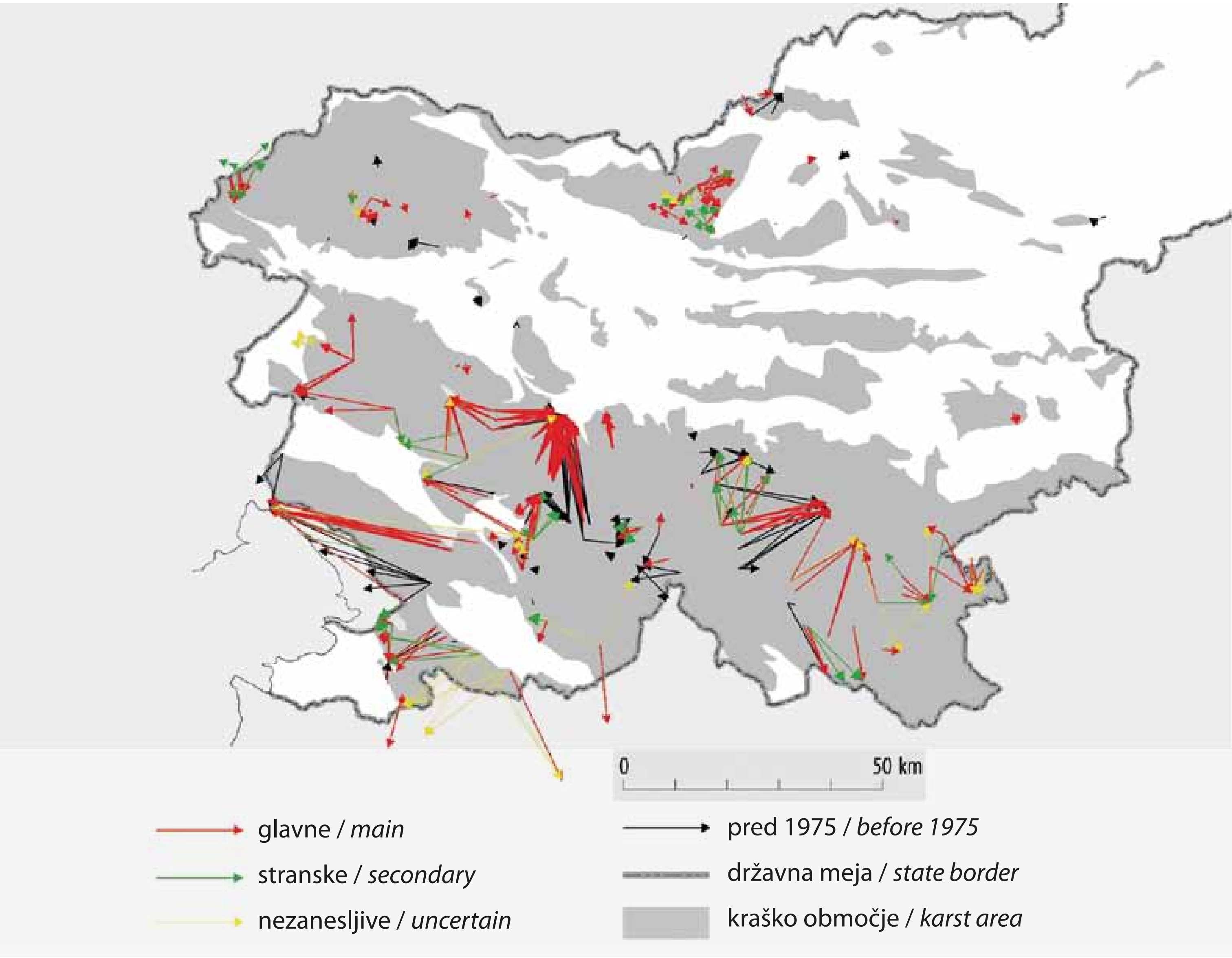
Za hitro in ustrezno ukrepanje je torej pomembno, da lahko na osnovi že obstoječih predhodnih raziskav za izbrano lokacijo predvidimo smeri in značilnosti podzemnega pretakanja vode. V preteklosti so bile opravljene številne hidrogeološke raziskave, ki so dale potrebne podatke za določena območja. Kot zelo primerne za raziskovanje kraških voda so se pokazale metode sledenja z naravnimi in umetnimi sledili. Pri sledenju z naravnimi sledili v daljšem obdobju po-

water contains organic matter (mineral oils, gas oil, etc.), chlorination can be dangerous for health due to the formation of chlorinated hydrocarbons that are cancerogenous. Therefore more appropriate are other ways of water treatment, e.g. UV-disinfection or filtration with membrane filters. These procedures are, however, more expensive and therefore unfortunately less frequently used.

1.4 Significance of preliminary researches in karst

Good knowledge of karst aquifer characteristics is a prerequisite for their proper management (*Ravbar* and *Kovačič* 2006). We can successfully predict where and how fast contamination will spread from the karst surface into the subsurface and in which springs the contamination may be expected only if we sufficiently good know the characteristics of the bedrock and hydrogeological settings in the selected area. Therefore suitable research is needed. It has been proved in case of accidents in industry or traffic that only in areas where previous comprehensive hydrogeological research has been done, we can deduce on which springs and when contamination turns up. In addition constant parallel monitoring of water quality has been possible. When harmful substances have been detected, the water sources have been timely expelled from the drinking water supply system.

For prompt and proper action it is therefore important to predict, on the already existing research, directions and characteristics of the groundwater flow in the selected location. Numerous hydrogeological researches have been done in the past that have provided us with necessary information for certain areas. Tracer tests with natural or artificial tracers have proved to be very suitable for karst water research. When tracing with natural tracers, continuous monitoring of selected natural parameters in karst waters (e.g. temperature, electrical conductivity, Ca and Mg ions, etc.) is conducted. With the comparison of the collected data we can deduce on the karst aquifer characteristics (*Kogovšek* and *Habič* 1981; *Kogovšek* 2001a; *Kogovšek* and *Petrič* 2010b). When tracing with artificial tracers,



5 Podzemne vodne zveze na kraških območjih v Sloveniji, ki so bile ugotovljene s sledilnimi poskusi v obdobju 1907–2010 (*Petrič* 2009).
Groundwater flow connections in karst areas in Slovenia that have been proved by tracer tests in the period 1907–2010 (*Petrič* 2009).

drobno spremljamo spreminjanje različnih naravnih parametrov kraških voda (npr. temperaturo, električno prevodnost, Ca in Mg ione ipd.) in s primerjavo zbranih podatkov sklepamo o značilnostih kraških vodonosnikov (*Kogovšek* in *Habič* 1981; *Kogovšek* 2001a; *Kogovšek* in *Petrič* 2010b). Pri sledenju z umetnimi sledili, npr. fluorescentnimi sledili ali solmi, pa okolju neškodljive snovi injiciramo v vodonosni sistem in potem z opazovanjem na različnih točkah znotraj tega sistema – v vodnih jamah, vrtinah ali na izvirih – spremljamo njihovo pretakanje (*Benischke* idr. 2007; *Kogovšek* in *Petrič* 2004, 2010a).

Žal so izsledki opravljenih raziskav vse prevečkrat predstavljeni le v internih poročilih ali razpršeno objavljeni v strokovnih publikacijah. Šele z njihovim zbiranjem in ureditvijo v informacijsko bazo podatkov (*Petrič* 2009), ki bo enostavno uporabna in lahko dostopna, jih bomo lahko bolj učinkovito uporabili pri praktičnem načrtovanju posegov na krasu in pripravi ukrepov za varovanje kraških voda (5).

Številna pa so kraška območja, za katera tovrstni podatki s predhodnimi raziskavami še niso bili pridobljeni. Pogosto šele nesreče in posledično onesnaženje izvira sprožijo prve podrobnejše raziskave njegovega zaledja, taka zamuda pa močno zmanjša uspešnost varovanja ter preprečevanja onesnaženja in odpravljanja njegovih posledic. Zato je treba pripraviti in izvajati načrt hidrogeoloških raziskav, ki bo sistematično vključeval še neraziskana območja in omogočal pridobivanje podatkov za dopolnitev in izboljšavo baze podatkov o smereh in značilnostih podzemnega pretakanja, pa tudi o količinah in kakovosti vode na območju slovenskega krasa.

e.g. fluorescent tracers or salts, we inject into the aquifer system substances that are harmless for nature and then observe their appearance at the various points within the system—in the water caves, boreholes and at the springs (*Benischke* et al. 2007; *Kogovšek* and *Petrič* 2004, 2010a).

However, the research results are frequently documented in internal reports or diffusely published in professional publications. Only with their collection and arrangement into the information database (*Petrič* 2009) that will be simply applicable and easily accessible we will be able to more efficiently use them for practical planning of encroachments in karst and for preparation of measures for karst waters protection (5).

Numerous are karst areas that lack hydrogeological data and where preliminary studies have not yet been done. Frequently the accidents and consequent contamination of springs launch first detail studies of springs and their catchments. However, such a delay strongly reduces the efficiency of water protection, prevention and the consequences compensation. Therefore it is necessary to prepare and implement a plan of hydrogeological research that will systematically include the less investigated areas and enable acquisition of data to complement and improve database on directions and characteristics of groundwater flow, as well as on quantities and qualities of water in Slovene karst.

2

THE ROLE OF THE VADOSE ZONE IN THE TRANSFER OF POLLUTION THROUGH KARST AQUIFERS TO KARST SPRINGS

JANJA KOGOVŠEK

VLOGA VADOZNE CONE V PRENOSU ONESNAŽENJA S POVRŠJA SKOZI KRAŠKE VODONOSNIKE DO KRAŠKIH IZVIROV

Na kraškem površju padavine razpršeno vstopajo skozi vegetacijski pokrov in prst ter se najprej pretakajo skozi vadozno cono do kraške zalite oz. freatične cone in nato naprej do kraških izvirov. Vadozna cona je debela nekaj deset do nekaj sto metrov in v njenem zgornjem delu se padavine in kontaminanti lahko zadržijo tudi daljši čas. Ker pa je nadaljnje pretakanje po sklenjenih kanalih v zaliti coni vse do kraških izvirov znatno hitrejše, prav v vadozni coni potekajo pomembni fizikalni in kemijski procesi.

Pretekle raziskave vadozne cone so nakazovale, da se padavine, ki se sorazmerno hitro infiltrirajo v vadozno cono, v tem delu vodonosnika zadržujejo različno dolgo (*Mangin* 1973; *Bakalowicz* idr. 1974; *Kogovšek* in *Habič* 1981; *Williams* 1983; *Kogovšek* 1982, 1983, 1984, 1990, 1994a, 1994b, 2000; *Pezdič* idr. 1984; *Smart* in *Friedrich* 1986; *Klimchouk* 1995; *Stichler* idr. 1997; *Jeannin* in *Grasso* 1995; *Maloszewski* idr. 2002; *Perrin* idr. 2003; *Trček* 2003 itd). To znanje je bilo pridobljeno z opazovanjem izvirov in z opazovanji v vadozni coni le krajši čas ali pa dolgotrajnejše raziskave niso zajele sočasnega opazovanja curkov z bistveno različno prepustnostjo zaledja, ki bi bili reprezentativni za celotno vadozno cono.

Meritve padavin na površju in multiparametrske zvezne meritve pretakanja in prenosa v vodi topnih kontaminantov skozi več reprezentativnih curkov v 100 m debeli vadozni coni Postojnske jame (1), ki so potekale sklenjeno več zaporednih let (*Kogovšek* 2010), so razkrile, da je prenos kontaminantov neposredno povezan z dinamiko pretakanja vode in da gre pri tem za procese shranjevanja in spiranja.

Poudarek je bil na prenosu kontaminantov v vodnih valovih po padavinah v obdobju celega hidrološkega leta in na sočasni uporabi številnih različnih metod, ne le sledenj z naravnimi sledili ter meritev fizikalnih in kemijskih parametrov, marveč tudi sledenj z umetnimi sledili in različnim načinom injiciranja, saj vsakokratne razmere, niti na površju niti v vadozni coni ali celotnem vodonosniku, niso ponovljive.

Voda lahko po bolj prepustnih razpokah prenaša tudi trdne delce (*Kogovšek* 1982), delce organskega onesnaženja (*Kogovšek* in *Habič* 1981) in koloide (*Shevenell* in *McCarthy* 2002), še posebej ob hitrem naraščanju pretoka, ko je transportna moč vode najve-

On the karst surface precipitation disperses through the vegetation cover and soil and continues to percolate through the unsaturated vadose zone, which can be some tens to hundreds of metres thick, to the phreatic zone. The upper part of the vadose zone can retain water for a long period of time. Because further flow in the phreatic zone along connected channels is considerably faster, various important processes occur in the upper vadose zone.

Past research indicated that precipitation rapidly infiltrates the upper vadose zone and can be retained in the vadose zone for a long period of time (*Mangin* 1973; *Bakalowicz* et al. 1974; *Kogovšek* and *Habič* 1981; *Williams* 1983; *Kogovšek* 1982, 1983, 1984, 1990, 1994a, 1994b, 2000; *Pezdič* et al. 1984; *Smart* and *Friedrich* 1986; *Klimchouk* 1995; *Stichler* et al. 1997; *Jeannin* and *Grasso* 1995; *Maloszewski* et al. 2002; *Perrin* et al. 2003; *Trček* 2003, etc.). This knowledge was acquired largely by monitoring and measuring springs, or through observations in the vadose zone that lasted for only short periods and had a small number of measured parameters, or through studies that did not include simultaneous monitoring at a number of trickles that differ significantly relative to the permeability of their catchment areas, and therefore the results acquired are not representative for the entire vadose zone.

The present multiparameter study, based on measurements of precipitation on the surface and of percolation and transfer of water-soluble contaminants through several representative trickles in the 100 m thick vadose zone in the Postojna cave/Postojnska jama (1) over consecutive hydrological years (*Kogovšek* 2010) demonstrates that the transfer of contaminants is directly connected to the dynamics of water percolation and that processes of accumulating and rinsing are going on there.

The emphasis of this study was on the transfer of contaminants in water pulses after precipitation over the period of an entire hydrological year and on simultaneous use of a number of different methods, not only using natural tracers, measuring physical and chemical parameters but also tests with artificial tracers and different methods of injection, since conditions on the surface as well as in the vadose zone and the entire aquifer are unrepeatable at any given time.

čja. Vodne poti s kraškega površja v podzemlje ubirajo tudi izlite netopne tekočine, kot so naftni derivati in podobne snovi (*Kogovšek* 1995b). Značilnosti njihovega prenosa v krasu smo v zadnjih desetletjih lahko spremljali le ob nesrečah, ko je prišlo do razlitij na kraškem površju (*Kogovšek* 1995b, 1996a; *Kogovšek* in *Petrič* 2002a, 2002b, 2004).

2.1 Dolgotrajne raziskave prenosa kontaminantov (1988–2009)

Vidno onesnaženje na stalaktitih v Postojnski jami, na katero so opozorili jamarji na začetku 80. let prejšnjega stoletja, je bilo vzrok za podrobnejše raziskave. Vir onesnaženja je bila odpadna voda iz manjše vojašnice jugoslovanske vojske na površju nad tem delom jame, kjer je bilo nastanjenih okrog 20 vojakov. Po sedimentaciji odpadne vode v sedimentacijskem bazenu je voda odtekala v 4 m globoko izkopano greznico in od tam prenikala skozi 100 m debele apnence do rovov Postojnske jame (1). Spomladi 1991 je vojska to območje zapustila, tako da ni bilo več nadaljnjega onesnaževanja. V naslednjih letih vse do danes so padavine spirale zaostalo onesnaženje iz greznice in jamskega stropa. Prve občasne analize prenikle vode (curkov in kapljanj) na širšem območju v Postojnski jami od leta 1988 naprej so podale njeno sestavo v različnih hidroloških razmerah (*Kogovšek* 1997).

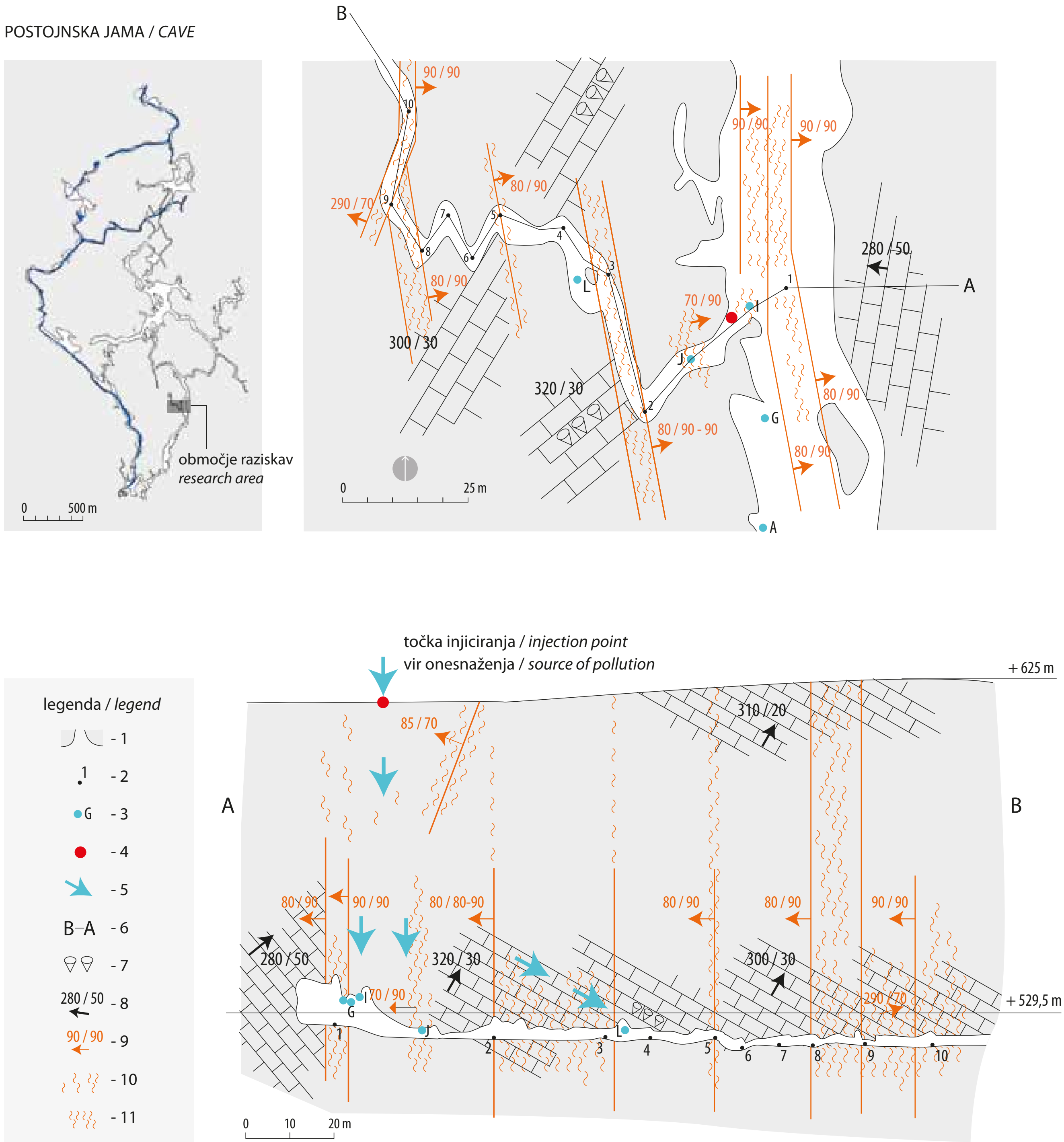
Do pomladi 1991 se je aktivno onesnaževanje na površju pokazalo v povečanih koncentracijah nitratov (do 180 mg NO_3^-/l), kloridov (do 60 mg Cl^-/l), sulfatov (do 50 mg SO_4^{2-}/l) in o-fosfatov (do 2,8 mg PO_4^{3-}/l) v opazovanih curkih I, J in L v jami. Za primerjavo smo vzorčili tudi referenčni curek A izven območja onesnaženja. Večje koncentracije kontaminantov so se odrazile tudi v višji specifični električni prevodnosti (EC) in večjih celokupnih trdotah vode. V sledečih treh letih, ko je vojska zapustila območje in ni bilo več svežega onesnaževanja, so koncentracije vseh kontaminantov v opazovanih curkih zaradi spiranja s padavinami hitro upadale (2). V tem obdobju je padlo prek 4700 mm padavin. Bolj prepustne razpoke so se dobro sprale, medtem ko se je del kontaminantov še vedno zadržal v slabše prepustnem delu 100 m debele vadozne cone.

The transport of solid particles (*Kogovšek* 1982), organic pollution (*Kogovšek* and *Habič* 1981) and colloids (*Shevenell* and *McCarthy* 2002) also occurs during water pulses at increased discharges along more highly permeable fissures. Spilled insoluble liquids like oils and oil derivatives on the karst surface use the same fissures and conduits as does precipitation (*Kogovšek* 1995b). In recent decades we have on several occasions monitored the consequences of traffic accident spillages, most frequently of petroleum products (*Kogovšek* 1995b, 1996a; *Kogovšek* and *Petrič* 2002a, 2002b, 2004).

2.1 Long-term observation of contaminant transport (1988–2009)

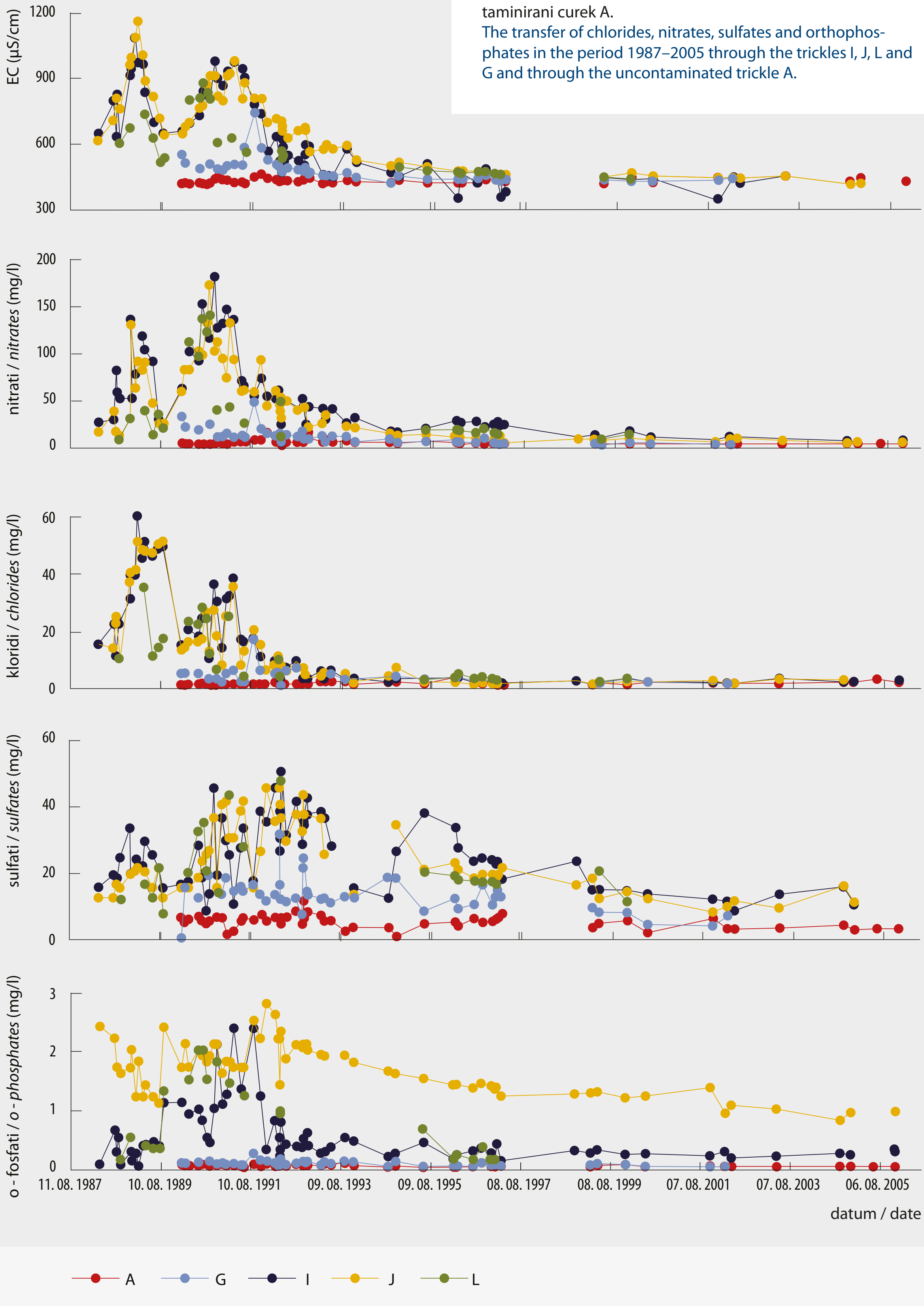
In the early 1980s, speleologists drew our attention to the pollution visible on stalactites in the Postojna cave. The source of pollution was a small military facility on the surface above this part of the cave where about 20 soldiers were stationed. After sedimentation in the sedimentation pool waste water drained into a cesspool about 4 m deep and then percolated through 100 m thick limestone in the direction of the cave passages (1). Fresh pollution stopped in the spring of 1991, when the military facility was closed. Precipitation continued to wash the remaining pollution from the cesspool and from the cave's roof. Beginning in 1988, periodic analyses of several trickles with varying discharges in the wider area in the cave provided data on the composition of the water under different hydrological conditions (*Kogovšek* 1997).

Until the spring of 1991 high nitrate (up to 180 mg NO_3^-/l), chloride (up to 60 mg Cl^-/l), sulfate (up to 50 mg SO_4^{2-}/l) and orthophosphate (up to 2.8 mg PO_4^{3-}/l) values were discovered in the selected observed trickles I, J and L in the cave. For comparative measurements unpolluted trickle A outside the immediate area was observed. Higher concentrations of contaminants were reflected in greater specific electric conductivity (EC) and greater total water hardness. After the military barracks was closed and active pollution ceased in 1991, the following three years saw a rapid decline in the concentration of all contaminants in the observed



1 Raziskovalni poligon v Postojnski jami, 100 m pod površjem (1. tloris oz. naris, 2. geodetska točka v jami, 3. opazovani curki, 4. vir onesnaženja, 5. smeri pretakanja skozi vadozno cono, 6. prečni prerez, 7. zgornje-kredni apnenec z ostanki rudistov, 8. smer in upad plasti, 9. smer in upad preloma, 10. razpoklinska cona, 11. porušena cona) (po *Kogovšek* in *Šebela* 2004).

Research polygon in Postojna Cave 100 m below surface (1. Ground plan or cross section of cave passage, 2. Geodetic point in the cave, 3. Observed trickle, 4. Source of pollution, 5. Direction of percolation water, 6. Cross section, 7. Upper Cretaceous limestone with remains of rudists, 8. Strike and dip of bedding planes, 9. Strike and dip of fault, 10. Fissured zone, 11. Broken zone) (after *Kogovšek* and *Šebela* 2004).



2 Prenos kloridov, nitratov, sulfatov in o-fosfatov v obdobju 1987–2005 skozi curke I, J, L in G ter skozi referenčni, nekontaminirani curek A.
The transfer of chlorides, nitrates, sulfates and orthophosphates in the period 1987–2005 through the trickles I, J, L and G and through the uncontaminated trickle A.

Nadaljevanje raziskav je pokazalo počasnejše upadanje koncentracij kontaminantov. Najhitreje so se spirali kloridi, saj so v desetih letih po prenehanju aktivnega onesnaževanja že dosegli izhodno stanje oz. stanje čistega referenčnega curka A (povprečna letna količina padavin v tem obdobju je bila 1557 mm). Počasneje poteka spiranje nitratov, ki so bili leta 2009 še nekoliko povečani. Spiranje sulfatov in o-fosfatov se po skoraj dvajsetih letih še nadaljuje, kar kaže na razlike v spiranju posameznih kontaminantov.

Najpočasneje se spirajo o-fosfati. Po osemnajstih letih spiranja s padavinami so koncentracije v curku I dosegale vrednosti okoli 0,2 mg PO_4^{3-}/l, v curku J s slabše prepustnim zaledjem pa le nekoliko pod 1,0 mg PO_4^{3-}/l. To pomeni, da se fosfati predvsem v slabo prepustnem delu vadozne cone krasa zadržujejo opazno dlje kot nitrati in kloridi in da je njihov prenos počasnejši. Omenjeno spoznanje narekuje nadaljnje raziskave in previdnost pri različnih vnosih fosfatnih snovi v kraško okolje. Prvi korak je bil narejen, ko so fosfatne spojine izločili iz pralnih sredstev.

Po spiranju prepustnejših razpok se je po osemnajstih letih, ko ni bilo več novega onesnaževanja, del kontaminantov zadrževal le še v slabo in najslabše prepustnem delu vadozne cone, kar je skladno z ugotovitvami polnjenja in praznjenja različno prepustnih delov vadozne cone (*Kogovšek* 2010). Dolgotrajno spremljanje prenosa tega onesnaženja je pokazalo, da se tudi manjše onesnaženje s površja spira več kot dvajset let do vzpostavitve izhodnega stanja. Meritve prenikanja odpadne komunalne vode iz umivalnic in sanitarij turističnega kampa skozi 40 m debelo vadozno cono Pivke jame pa so potrdile, da prihaja v njej lahko do učinkovitih oksidacijskih, samočistilnih procesov (*Kogovšek* 1987).

2.2 Podrobno spremljanje prenosa kontaminantov v hidrološkem letu

Pogostejše vzorčenje prenikle vode v jami je ob naraščanju pretoka po padavinah marca 1992 pokazalo, da prihaja v vodnih valovih po vsakokratnih dovolj intenzivnih padavinskih dogodkih do največjega prenosa kontaminantov (kloridov, nitratov, sulfatov

trickles (I, J, and L) due to natural leaching by precipitation (2). Over 4700 mm of precipitation fell during this period. Intense transfer of contaminants occurred when the more permeable fissures were flushed out, while a portion of the contaminants was still retained in the less permeable part of the 100 m thick vadose zone.

In the following years, a slower decline in contaminant concentration was observed. Ten years of leaching by precipitation after the active pollution on the surface had stopped resulted in the values for chlorides in all the contaminated trickles matching those of the uncontaminated reference trickle A (the average annual precipitation in this period was 1557 mm). The leaching of nitrates was similar but occurred more slowly and still showed slightly raised values in 2009. The leaching of sulfates and ortophosphates is slower, and after almost twenty years the process is still continuing, showing the differences in the leaching of individual contaminants.

The transfer of orthophosphates is the slowest process. After eighteen years of leaching by precipitation, trickles I and J still exhibit increased orthophosphates: around 0.2 mg PO_4^{3-}/l in trickle I and just below 1.0 mg PO_4^{3-}/l in trickle J. This means that phosphates are held in the less permeable part of the vadose zone significantly longer than nitrates or chlorides. This situation calls for further research and caution regarding the use of various phosphate substances in the karst environment. An initial step was taken when phosphate compounds were eliminated from laundry detergents.

After eighteen years more permeable fissures have been largely flushed out, while a fraction of the contaminants have been retained in the less permeable part of the vadose zone, in accordance with established hydrodynamics of the vadose zone (*Kogovšek* 2010). Our long-term monitoring of the transfer of pollution confirmed that washing of even minor pollution from the surface takes more than twenty years before the original conditions are restored. Measurements of trickling waste water from washrooms and lavatories in the tourist camp through the 40 m thick vadose zone in the Pivka cave/Pivka jama confirmed that effective oxidation, self-purification processes can also take place (*Kogovšek* 1987).

in fosfatov). Zato je kasneje potekalo podrobno vzorčenje izbranih curkov skozi celo hidrološko leto, od septembra 2003 do septembra 2004, s poudarkom na dogajanju v vodnih valovih po vsakokratnih padavinah. Na površju so sočasno potekale meritve padavin, v Postojnski jami pa zvezne meritve pretoka, temperature, specifične električne prevodnosti (EC) curkov in koncentracije fluorescentnega sledila v okviru sledenja, z injiciranjem na površju junija 2002 (*Kogovšek* 2010).

Pretok večjega nestalnega curka I hitro reagira na padavine (pretok mu niha do 4 l/min), ob izostanku padavin pa pogosto presuši, v poletnem sušnem obdobju tudi za 6 mesecev. Po padavinskem dogodku izteka v vodnem valu najprej shranjena voda iz slabše

3 Fizikalne meritve in avtomatski zajem vzorcev stalnega curka J v Postojnski jami.
Physical measurements and automatic sampling of the permanent trickle J in the Postojna cave.

2.2 Detailed measurement of contaminant transfer during a hydrological year

Frequent sampling of the March 1992 water pulse after a precipitation event showed that the largest transfer of contaminants (chlorides, nitrates, sulfates and phosphates) occurs in the water pulses following each relatively intense precipitation event. In the period from September 2003 to September 2004 the transfer of contaminants was therefore monitored in detail, with special emphasis on the water pulses. During this period detailed simultaneous measurements were made of precipitation on the surface and in the Postojna cave of discharge, temperature, specific electric conductivity (EC) of the trickles and concentration of the tracer in the cave after injection on the surface in June 2002 (*Kogovšek* 2010).

The trickle I reacts rapidly to sufficiently abundant precipitation (maximum discharge 4 l/min) but in the absence of rain it dries up quickly, in summer dry periods for up to 6 months. After a precipitation event, trickle I quickly drains the water stored in its catchment area. In the initial part of the water pulse this water is mixed with freshly infiltrated precipitation from the more permeable and already cleaned fissures, resulting in a dilution effect.

The less abundant, permanent trickle J (3) with maximum discharges up to 130 ml/min, whose annual outflow is more than 20 times lower than that of trickle I, exhibits a strong damping of infiltrated precipitation.

Simultaneous measurements of discharge and concentration of contaminants at the trickle I indicated that the contaminant concentrations were correlated with oscillations in the trickle's discharge. It is clear that an increasing discharge in water pulses results in a decrease in the concentration of all contaminants, most distinctly of nitrates (4), but there are nonetheless some differences in the transfer of different contaminants (*Kogovšek* 2010).

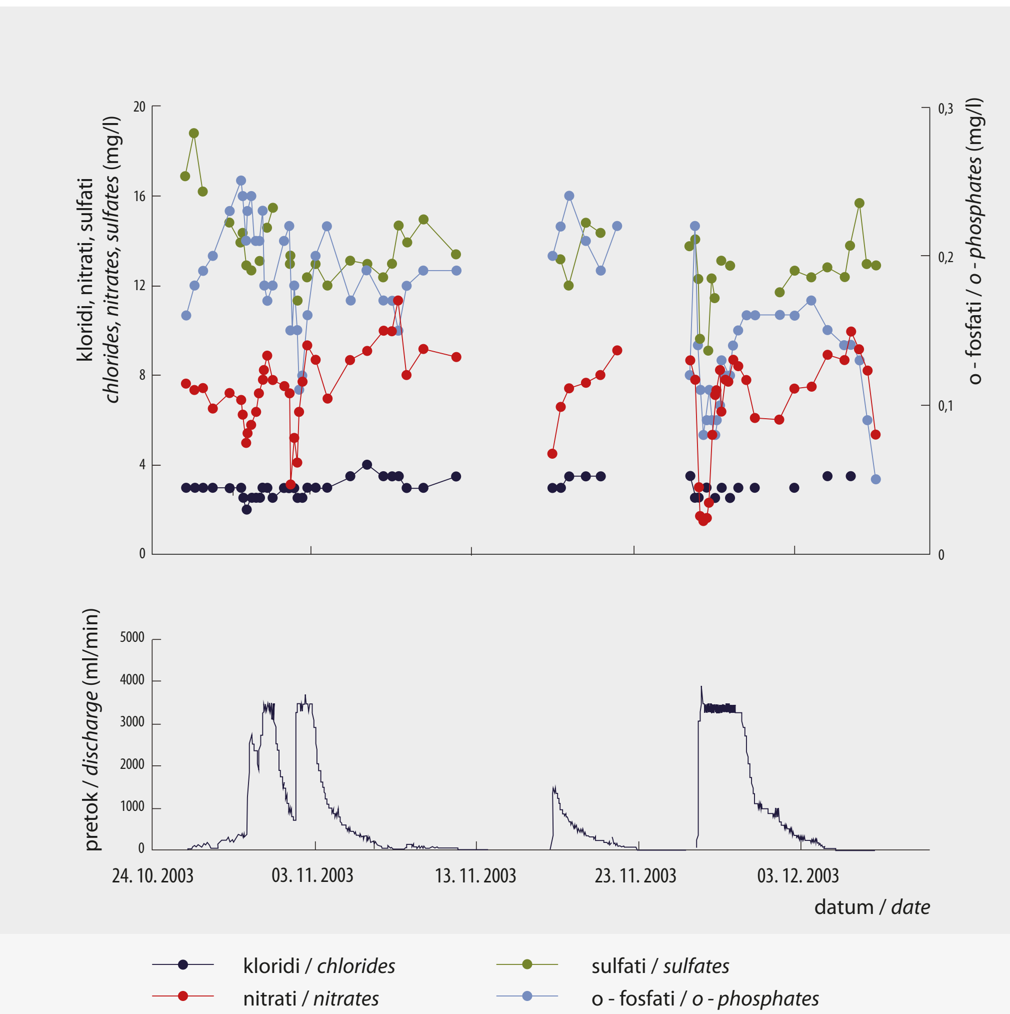
The annual pattern at trickle I did not exhibit the decreasing trend of contaminants established with trickle J. However, the concentration of nitrates, which oscillated between 2 and 11 mg NO_3^-/l in the fall of 2003, reached values below 2 mg NO_3^-/l in 2009. Durprepustnega dela zaledja, ki se ji pridruži dotok po bolj prepustnih in spranih razpokah, kar se odraža v razredčevalnem učinku. Pomemben del vode priteka torej v ta curek po dobro prepustnih razpokah in ga dopolnjuje slabše prepustni del.

Manjši, stalen curek J (3) z maksimalnim pretokom 130 ml/min, skozi katerega izteče 20-krat manjša letna količina vode kot skozi curek I, izkazuje močno dušenje infiltriranih padavin.

Sočasne meritve pretoka in kontaminantov večjega curka I so pokazale odvisnost koncentracije kontaminantov od nihanja pretoka curka. Razvidno je upadanje koncentracije vseh kontaminantov ob naraščanju pretoka v vodnih valovih, najizraziteje nitratov (4). Med posameznimi kontaminanti so opazne razlike v njihovem prenosu (*Kogovšek* 2010).

ing the hydrological year 2003/04, sulfates oscillated between 7 and 20 mg SO_4^{2-}/l. Concentrations below 7 mg SO_4^{2-}/l were measured in 2009. The values for nitrates and sulfates are after eighteen years close to those of the unpolluted reference trickle A. In the 2003/04 hydrological year, the concentration of ortophosphates oscillated between 0.05 and 0.28 mg PO_4^{3-}/l; the lowest values were recorded during the maximum discharges at the peaks of larger water pulses. Periodic analyses before 2009 do not show any substantial decrease in the concentration of phosphates.

Parallel monitoring of the smaller permanent trickle J showed a substantially different transfer of contaminants than that through trickle I. Following a long summer drought, the first water pulse began to form after abundant rainfall at the end of October



4 Nihanje koncentracij kloridov, nitratov, o-fosfatov in sulfatov v vodnem valu izdatnejšega, nestalnega curka I.
Oscillation of concentrations of chlorides, nitrates, orthophosphates and sulfates in the water pulse at the more abundant, periodical trickle I.

V celoletnem poteku curka I ni bilo opazno izrazitejše upadanje koncentracije kontaminantov, ki je bilo ugotovljeno pri curku J. Vendar pa je koncentracija nitratov, ki je jeseni 2003 nihala med 2 in 11 mg NO_3^-/l, leta 2009 dosegala vrednosti pod 2 mg NO_3^-/l. Sulfati, ki so v hidrološkem letu 2003/04 nihali v intervalu 7–20 mg SO_4^{2-}/l, so leta 2009 nihali pod vrednostjo 7 mg SO_4^{2-}/l. Vsebnosti nitratov in sulfatov v curku I so se po osemnajstih letih dokaj približale vrednostim čistega referenčnega curka A. Koncentracija o-fosfatov, ki je v hidrološkem letu 2003/04 nihala v intervalu od 0,05 do 0,28 mg PO_4^{3-}/l, v okviru občasnih analiz do leta 2009 izkazuje le minimalen upad koncentracije (pod 0,2 mg PO_4^{3-}/l).

Hkratno opazovanje manjšega stalnega curka J je pokazalo na bistveno drugačen prenos kontaminantov od njihovega prenosa skozi curek I. Po dolgi poletni suši sta v prvem vodnem valu, konec oktobra 2003 po izdatnem dežju, sočasno s pretokom naraščali tudi koncentraciji nitratov in o-fosfatov. Njun prenos je bil zelo podoben (5) in visoki koncentraciji sta vztrajali skoraj ves mesec (*Kogovšek* 2010), čeprav je pretok medtem upadel. Šele v naslednjem, najve-

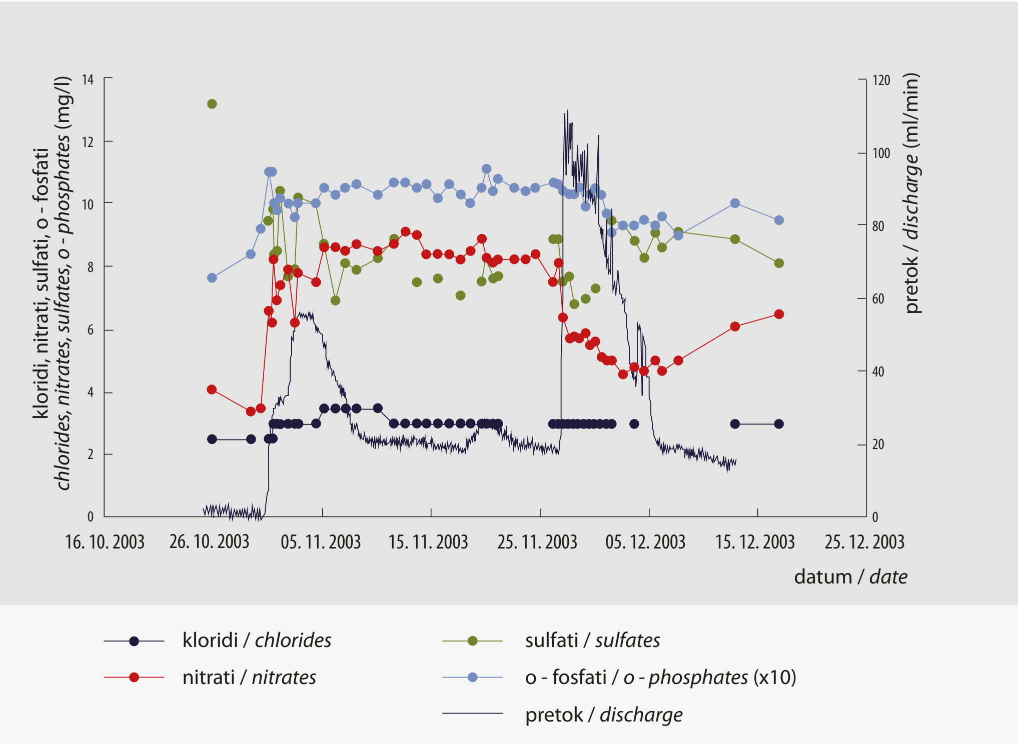
2003. Simultaneously the concentration of nitrates and ortophosphates started to increase and there transfer was very similar (5). High concentrations of nitrates and ortophosphates continued for almost a month (*Kogovšek* 2010) until the next and largest water pulse in the 2003/04 hydrological year, when concentrations of nitrates and ortophosphates decreased.

Under the given conditions, the infiltrated precipitation caused the stored water with a high concentration of contaminants to discharge first, while the very intense and abundant precipitation that followed resulted in their dilution. Later, the nitrates appeared somewhat more intensely after each increased discharge that followed precipitation events, but in lower concentrations than at the beginning of the hydrological year. Throughout the spring of 2004, the concentration of nitrates steadily and gradually dropped until it reached its initial value in trickle J from October 2003.

Similarly, ortophosphates were leached at an intense rate at the beginning of the hydrological year, but in the spring of 2004 a slightly increasing trend and higher values were again recorded during water pulses. At the same time, sulfates also reached their

5 Nihanje koncentracij kloridov, nitratov, o-fosfatov in sulfatov v vodnem valu manjšega, stalnega curka J.

Oscillation of concentrations of chlorides, nitrates, orthophosphates and sulfates in the water pulse at the smaller, permanent trickle J.



čjem vodnem valu v hidrološkem letu 2003/04 je prišlo do upadanja koncentracij obojih, tako nitratov kot o-fosfatov.

V danih razmerah so očitno dokaj izdatne infiltrirane padavine po dolgem sušnem poletnem obdobju povzročile najprej iztekanje shranjene vode z visokimi koncentracijami kontaminantov. Šele nadaljnje zelo intenzivne in izdatne padavine so povzročile razredčevanje. Nitrati so se kasneje ob vsakem povečanju pretoka po padavinah nekoliko intenzivneje spirali, vendar v opazno nižjih koncentracijah kakor na začetku hidrološkega leta po sušnem obdobju. Do pomladi 2004 je koncentracija nitratov nenehno postopno upadala do vrednosti, ki jo je curek J dosegal oktobra 2003.

Podobno so se na začetku hidrološkega leta intenzivneje spirali tudi o-fosfati, vendar pa so bile spomladi 2004 v vodnih valovih spet zabeležene večje vrednosti ob rahlem trendu naraščanja. Tudi sulfati so tedaj dosegali največje vrednosti v hidrološkem letu, njihova koncentracija je od novembra 2003 do pomladi 2004 ob večjih nihanjih celo nekoliko naraščala.

Nitrati in o-fosfati so se ponovno intenzivneje spirali v vodnem valu oktobra 2004 po poletnem sušnem obdobju, vendar ne tako izrazito kot oktobra 2003, nitrati v koncentracijah le do 6 mg NO_3^-/l in o-fosfati do 1,05 mg PO_4^{3-}/l. V drugi polovici marca 2005, po daljšem sušnem obdobju, so se po padavinah oblikovali manjši vodni valovi kakor jeseni 2003 in izmerili smo manjši prenos kontaminantov skozi curek J.

2.3 Prenos kontaminantov v vodnih valovih po padavinskih dogodkih

Več kot eno hidrološko leto dolgo zvezno spremljanje kontaminantov v curkih je pokazalo, da je njihov prenos skozi vadozno cono neposredno povezan z načinom infiltracije padavin. Do povečanega prenosa prihaja v vodnih valovih po dovolj izdatnih padavinah, do najbolj intenzivnega pa v prvih velikih vodnih valovih po daljših sušnih obdobjih. Za infiltracijo padavin in prenos kontaminantov, še posebno

highest values. From November 2003 to the spring of 2004 their concentration slightly increased with large oscillations.

The nitrates and ortophosphates again experienced more intense leaching during the water pulse in October 2004 after the summer dry period, though it was less intense than in the fall of 2003. The nitrates remained below 6 mg NO_3^-/l, and orthophosphates below 1.05 mg PO_4^{3-}/l. In the second half of March 2005, after a long dry period, water pulses formed that were less abundant than those in the fall of 2003, and a weaker leaching of contaminants was recorded at trickle J.

2.3 Contaminant transfer in water pulses after precipitation events

Monitoring of contaminants in trickles over a period of more than a hydrological year showed that their transfer through the vadose zone is directly linked to the manner of infiltration of precipitation. The most intense transfer occurred in the first water pulse after long dry periods. In addition to precipitation, previous soil and vadose zone saturation played an important role in the infiltration of precipitation and the transfer of contaminants stored in the less permeable part of the vadose zone.

The smallest transfer of contaminants occurred during the periods of minimal discharge through trickles when infiltrated precipitation largely recharged the catchment areas of trickles and when only a limited transfer of contaminants occurred, mainly within the epikarst or upper vadose zone. In arid summer and also in winter periods when earth is dried and catchment area of trickles pretty emptied storing of precipitation and accumulation of contaminants prevail in the vadose zone. To push the stored water with contaminants through the vadose zone, especially through its less permeable part, requires enough abundant precipitation along with good saturation of the soil and of the vadose zone.

tistih, ki so bili shranjeni v slabo prepustnem delu zaledij curkov, sta poleg izdatnosti in intenzivnosti padavin pomembni tudi predhodna namočenost prsti in zapolnjenost njihovega zaledja oz. vadozne cone z vodo.

Najmanjši prenos kontaminantov poteka v času minimalnih pretokov curkov, ko se infiltrirane padavine pretežno le shranjujejo v vadozni coni in zapolnjujejo zaledje curkov. Tedaj prihaja le do omejenega prenosa kontaminantov predvsem znotraj epikraške oz. zgornjega dela vadozne cone. V sušnih poletnih, pa tudi v zimskih obdobjih, ko je prst osušena in zaledje curkov dokaj izpraznjeno, prevladujeta v vadozni coni shranjevanje padavin in akumuliranje kontaminantov. Za potiskanje shranjene vode s kontaminanti in njihov prenos skozi vadozno cono v smeri kraških izvirov so potrebne dovolj izdatne in intenzivne padavine, kar je ob dobri namočenosti prsti in ustrezni zapolnjenosti vadozne cone z vodo pogoj za zvezen prenos kontaminantov.

2.3.1 Vodni val curka I oktobra 2003

V prvem vodnem valu po poletju, konec oktobra 2003, je prišlo do intenzivnega prenosa nitratov in o-fosfatov skozi curek I (4). Hitremu naraščanju pretoka curka I je sledilo njihovo značilno upadanje kot posledica razredčevanja z dotokom nove vode po prepustnejših in že spranih razpokah.

Vendar pa se je koncentracija nitratov v vodnem valu z izhodne vrednosti 7,5 mg NO_3^-/l hitro vrnila celo na nekoliko višjo vrednost (okrog 9 mg/l), ko je pretok šele začel upadati. Ob dobri namočenosti prsti je prišlo do infiltracije padavin in sočasnega iztekanja vode tudi iz najslabše prepustnega dela zaledja z visoko vsebnostjo kontaminantov.

V primerjavi z nitrati, ki so se vrnili na izhodno vrednost, ko je pretok v vodnem valu šele začel upadati, je koncentracija o-fosfatov zaostajala za ves dan oz. je naraščala sočasno z upadanjem pretoka. To obnašanje o-fosfatov je podobno pri obeh curkih (I in J) in je značilno za ta kontaminant. V zaporednih vodnih valovih, ki so sledili, je koncentracija nitratov in o-fosfatov ob maksimalnih pretokih dosegala

2.3.1 Water pulse through trickle I in October 2003

An intense transfer of nitrates and ortophosphates through trickle I was recorded in the first water pulse after the summer at the end of October 2003 (4). With the rapidly increasing discharge, the characteristic decrease of nitrates and phosphates was recorded as a consequence of dilution with the inflow of fresh water along the more permeable and previously emptied fissures.

However, the concentration of nitrates in the water pulse was quickly restored from an initial value of 7.5 mg NO_3^-/l to a slightly higher value (around 9 mg/l), as soon as the discharge began to decrease. Water with a high content of nitrates and phosphates appeared from the least permeable part of the catchment area when the soil was well saturated with water.

Compared to the nitrates, which returned to their initial value when the discharge in the water pulse started to decrease, the phosphates either lagged behind a whole day or increased simultaneously with the decreasing discharge. The response of the phosphates is similar in both trickles (I and J) and is characteristic for this contaminant. In consecutive water pulses through trickle I, the content of nitrates and phosphates at the peak of the water pulses gradually decreased.

The transfer of nitrates and phosphates in water pulses through trickle I quite clearly coincides with the pattern of EC and with the concentration of tracer injected on the surface in June 2002. These results were supported by isotopic analyses of oxygen that showed that the average retention time of water is around 2.5 months in the more permeable parts of the vadose zone (trickle I) and more than a year in the less permeable parts (trickle J) (*Kogovšek* 2010).

All the parameters confirm the finding that an initial outflow of stored water from the less permeable part of the catchment area of the trickle is joined by an inflow of new water from the more permeable and previously emptied conduits, and this is reflected in the dilution effect. This intense flow of water activates a further inflow from the less permeable part of the catchment area that nor-postopno vedno manjše vrednosti, kar kaže na vse večji del nove vode v primerjavi s shranjeno vodo.

Prenos nitratov in o-fosfatov skozi curek I v vodnih valovih dokaj dobro sovpada s potekom EC in v veliki meri tudi s spiranjem fluorescentnega sledila, ki je bilo junija 2002 injicirano na površju, ter z rezultati izotopskih analiz, ki so pokazale, da je povprečni zadrževalni čas vode približno 2,5 meseca v bolj prepustnih delih vadozne cone (curek I) in znatno daljši, leto in več, v njenem slabo prepustnem delu (curek J) (*Kogovšek* 2010).

Vsi merjeni parametri potrjujejo ugotovitev, da se začetnemu iztekanju shranjene vode iz slabo prepustnega dela zaledja curka pridruži dotok nove vode po prepustnejših razpokah, kar se odraža v razredčevalnem učinku. Intenzivno iztekanje vode po prepustnejših razpokah aktivira nadaljnje iztekanje iz slabo prepustnega dela zaledja, ki daje vodo curku, ko izostane dotok po najprepustnejših razpokah. To se je odrazilo v naraščanju EC ter v naraščanju koncentracije nitratov in fluorescentnega sledila, injiciranega junija 2002, ko je pretok šele začel upadati. Tudi sulfati nakazujejo upadanje koncentracije v vodnih valovih, vendar manj izrazito in ob večjih nihanjih.

2.3.2 Vodni val curka J oktobra 2003

Ob prvem naraščanju pretoka manjšega curka J konec oktobra 2003 sta izrazito naraščali tudi koncentraciji nitratov in o-fosfatov (5). Visoke koncentracije obojih so vztrajale skoraj ves mesec. Medtem je pretok v prvem vodnem valu upadel, nato pa vztrajal kar dva tedna na vrednostih nekoliko nad 20 ml/min. Šele ko je naslednji veliki vodni val, ki je bil največji v hidrološkem letu 2003/04, dosegel maksimalni pretok nad 110 ml/min, je začela koncentracija nitratov upadati. Podobno so se spirali tudi o-fosfati, le da je njihova koncentracija začela upadati štiri dni kasneje. Tudi pri tem curku je potek nitratov skoraj enak poteku EC in zelo podoben poteku spiranja sledila, ki je bilo injicirano junija 2002 (*Kogovšek* 2010).

Iz tega sledi, da so izdatne oktobrske padavine, ki so sledile 6-mesečnemu sušnemu obdobju z minimally supplies the trickle when the flow along the most permeable conduits stops. This is reflected by the increase of EC, the concentrations of nitrates, and concentrations of the tracer, injected in June 2002 as soon as the discharge started to decrease. Sulfates also exhibit a decrease in concentration during water pulses but less distinctly and with greater oscillations.

2.3.2 Water pulse through trickle J in October 2003

With the increasing discharge at trickle J at the end of October 2003, the concentrations of nitrates and orthophosphates increased (5), and the high concentrations persisted for almost a month. During this period the first water pulse subsided and the discharge remained at values just above 20 ml/min for more than two weeks. The concentration of nitrates began to decrease only when the next water pulse, the largest in the hydrological year 2003/04, reached its maximum discharge of over 110 ml/min. Phosphates were leached in a similar way, but their concentration began to decrease four days after the nitrates. The nitrates display almost the same pattern as EC and as the concentration of the tracer injected in June 2002 (*Kogovšek* 2010).

This logically means that with the infiltration of the October precipitation following a 6-month dry period when the trickle displayed minimal discharge, the water stored in the vadose zone was the first to discharge through trickle J. During this dry period 210 mm of rain infiltrated. The more intense precipitation saturated the soil well and enabled the recharging also of the least permeable part of the catchment area and its simultaneous discharging. These conditions led to the pushing of water along the entire hierarchy of fissures, even the least permeable ones that are only activated in extreme conditions such as those that occurred in the fall of 2003. Similar conditions did recur in the spring of 2006.

The characteristic washing of nitrates through trickle J in the first water pulse after a long dry period differs from the pattern in subsequent water pulses that follow continuously at shorter intervals, which show a noticeably more modest transfer of contaminants (5). It nimalnimi pretoki, ko se je infiltriralo in shranilo v vadozni coni kar 210 mm padavin, potisnile skozi curek J najprej to shranjeno vodo. Padavine so najprej dobro omočile prst ter s tem omogočile zapolnjevanje tudi najslabše prepustnega dela zaledja in sočasno iztekanje tam shranjene vode in kontaminantov. V takih razmerah prihaja do iztekanja vode po celotni hierarhiji različno prepustnih razpok, tudi skozi najslabše prepustne, ki se aktivirajo le ob izjemnih razmerah, kakršne so bile jeseni 2003. Pozneje so se take razmere ponovile šele spomladi 2006.

Značilno spiranje nitratov skozi curek J v prvih vodnih valovih po daljšem sušnem obdobju odstopa od vzorca dogajanja v naslednjih valovih, ki si sledijo zvezno v krajših časovnih intervalih in ko prihaja do opazno skromnejšega prenosa kontaminantov (5). Očitno se je širše zaledje curka v času prvih velikih vodnih valov dokaj dobro spralo. To kaže na pomemben vpliv načina infiltracije padavin na prenos topnih kontaminantov, tako kar zadeva njihovo razporeditev kakor tudi količino.

2.4 Prenos kontaminantov z odlagališč odpadkov

Odlagališča odpadkov na krasu pomenijo grožnjo za kraške vode. Padavine spirajo iz odlagališč topne komponente in jih odnašajo skozi vadozno cono v smeri kraških izvirov. Izcedne vode iz odlagališč so odvisne od sestave odpadkov in so običajno zelo kompleksne raztopine z visoko vsebnostjo soli, kovin in organskih snovi (*Hötzl* 1999).

Na slovenskem kraškem svetu obratujejo odlagališča odpadkov že več kot 30 let in so v zapiranju. Analiza izcednih voda na sežanskem odlagališču odpadkov (*Kogovšek* 1996b) je pokazala v sveži izcedni vodi, ki se je zbrala ob odlagališču po padavinskem dogodku, sorazmerno nizke vrednosti nitratov (3,6 mg/l), o-fosfatov (3,8 mg/l) in kloridov (445 mg/l), a visoke vrednosti organskega onesnaženja (kemijska potreba po kisiku oz. KPK je dosegala 2000 mg O_2/l, biokemijska potreba po kisiku oz. BPK_5 pa 700 mg O_2/l) in visoke vrednosti EC (6 mS/cm). V 'stari' izcedni vodi so bile zabeležene večje koncentracije kloridov (do 800 mg/l), o-fosfatov (do 5 mg/l) in nitratov (do 19 mg/l) in večja EC (9000

is obvious that the wider catchment area of the trickle has largely been drained during the period of the first water pulses. This indicates the important influence of the infiltration manner of precipitation on the transfer of soluble contaminants concerning their distribution and quantity.

2.4 Transfer of contaminants from landfills

Landfills are a serious threat to karst waters due to the washing out of waste substances by precipitation. Due to various contents of waste, the leachates from landfills are complex liquids with a high content of salts, metals and organic compounds (*Hötzl* 1999).

On the Slovene karst landfills have been working for more than 30 years and are nowadays in the closing phase. Chemical analysis of the 'fresh' leachate from Sežana landfill (*Kogovšek* 1996b) accumulated on the surface after a rain event, showed relatively low values of nitrates (3.6 mg/l), orthophosphates (3.8 mg/l) and chlorides (445 mg/l), but high values of chemical oxygen demand (COD = 2000 mg O_2/l), biochemical oxygen demand (BOD_5 = 700 mg O_2/l) and EC (6 mS/cm). In 'old' leachates higher values of chlorides (up to 800 mg/l), orthophosphates (up to 5 mg/l), nitrates (up to 19 mg/l) and EC (up to 9000 µS/cm) were measured. These high values are the result of degradation and oxidation of organic pollution. Therefore the COD (up to 900 mg O_2/l) and the BOD_5 (up to 80 mg O_2/l) were lower. Similar values are reported for landfills in Spain (*Vadillo* et al. 1999). Along more highly permeable fissures solid particles can also be transported at increased discharge (*Kogovšek* 1982) and organic pollution, heavy metals and microorganisms can be connected to them.

Several tracer tests have been performed recently (from 2005 onwards) at landfill sites on the Slovene karst with the aim to prepare an efficient plan for the monitoring of groundwater in the area of influence of the landfills (*Kogovšek* and *Petrič* 2006, 2007, 2010a). With the injection of tracers on the karst surface (6), the determining factor for their appearance in karst springs is primarily their transfer through the vadose zone, since further flow along the larger karst channels μS/cm). Te višje vrednosti so bile rezultat razgradnje in oksidacije organskega onesnaženja, saj sta bili izmerjeni vrednosti za KPK (do 900 mg O_2/l), in BPK_5 (do 80 mg O_2/l) nižji kot v sveži izcedni vodi. O podobnih vrednostih poročajo tudi iz Španije (*Vadillo* idr. 1999). V kolikor je prepustnost razpok pod odlagališči dovolj velika, voda lahko odnaša s površja tudi drobne delce netopnega onesnaženja (*Kogovšek* 1982). Na te delce pa so lahko vezani organsko onesnaženje, kovine in mikroorganizmi.

Od leta 2005 naprej je bilo za izdelavo načrta monitoringa vpliva odlagališč na vode izvedenih več sledenj s fluorescentnimi sledili na odlagališčih odpadkov s slovenskega krasa (*Kogovšek* in *Petrič* 2006, 2007, 2010a), ko smo injicirali sledilo na površju (6). Za njegov pojav v kraških izvirih je bil odločilen predvsem prenos skozi vadozno cono, saj je nadaljnje pretakanje po sklenjenih kraških kanalih znatno hitrejše. V vseh primerih sledenj je bilo sledilo sprano z veliko količino vode (5 m^3), da bi preprečili večjo adsorpcijo na prst in sedimente, kar je verjetno nekoliko pospešilo

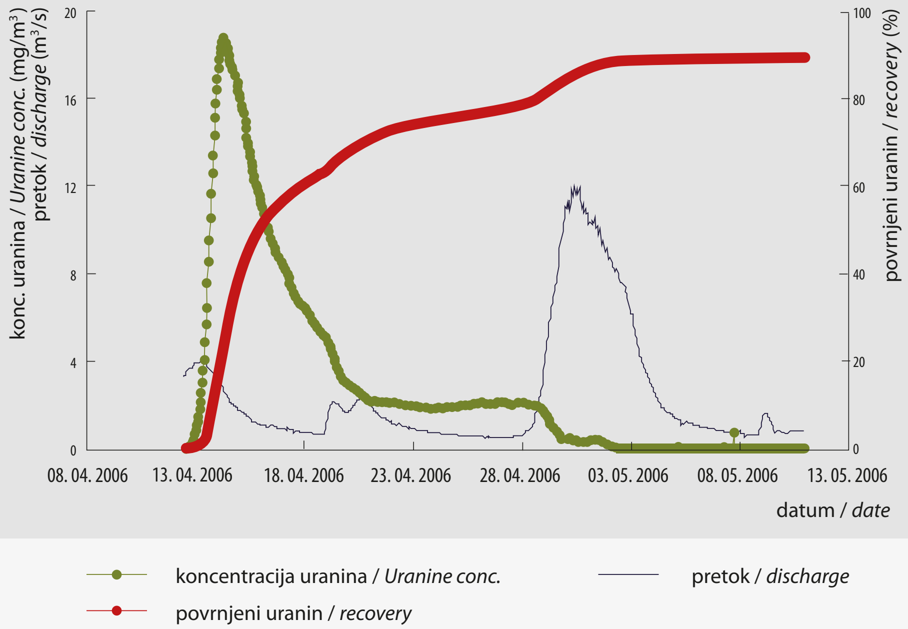
is considerably faster. In all the tests the tracer was flushed with a large amount of water (5 m^3) to prevent greater adsorption on the soil and sediment layers, somewhat accelerating the percolation through the vadose zone. However, the tracer test at the Poček military training ground in the Javorniki area (*Kogovšek* 1999) indicated that intense flushing of tracer using 11 m^3 of water did not have a substantial influence on the appearance of the tracer in the springs, and precipitation was still the decisive element for its appearance.

Transfer of the tracer in all tests from landfills was fast, specially through the Bilpa spring (7, 8) in the case of injection on the Kočevje landfill. This case is described in the chapter »Planning of groundwater monitoring in the impact areas of landfills in karst based on the results of tracer tests« in this book.

In relatively low and dropping water levels (Kočevje and Sežana tests), the dominant velocity of the flow towards springs was between 39 and 48 m/h, and in high water conditions (Ribnica test) up to 144

6 Fluorescentno sledilo smo ob kočevskem odlagališču odpadkov injicirali na površju, tako da je moralo najprej preiti vadozno cono.
The fluorescent tracer was injected on the surface at the Kočevje landfill so that it had to pass through the vadose zone at first.

7 Skozi izvir Bilpe je ob sorazmerno nizkem pretoku izteklo kar 77 % injiciranega sledila v dveh tednih od prvega pojava.
Within two weeks after the first appearance, at a relatively low discharge, 77 % of the tracer flowed through the Bilpa spring.



8 Pretok, koncentracija sledila in njegova povrnjena količina v izviru Bilpe.
Discharge, concentration of the tracer and its recovery in the Bilpa spring.

pretakanje skozi vadozno cono. Vendar pa je sledenje z vojaškega poligona Poček na območju Javornikov (*Kogovšek* 1999) pokazalo, da intenzivno spiranje sledila s kar 11 m³ vode ni bistveno vplivalo na njegovo pojavljanje v opazovanih izvirih. Za njegov prenos so bile odločilne padavine.

Prenos sledila z omenjenih odlagališč do kraških izvirov je bil hiter, še posebno skozi izvir Bilpe (7, 8) v primeru injiciranja na kočevskem odlagališču, kar je podrobno predstavljeno v poglavju »Načrtovanje monitoringa podzemne vode v vplivnem območju odlagališč odpadkov na krasu na podlagi rezultatov sledilnih poskusov« v tej knjigi.

V sorazmerno nizkih vodostajih so bile dominantne hitrosti pretakanja (kočevsko in sežansko odlagališče) med 39 in 48 m/h, ob visokem vodostaju (ribniško odlagališče) pa kar 144 m/h (*Kogovšek* in *Petrič* 2006, 2007, 2010a). Multiparametrske raziskave vadozne cone so pokazale, da viri onesnaženja s povečanimi vsebnostmi nitratov, kloridov, fosfatov in sulfatov, kot so tudi izcedne vode iz odlagališč, povzročajo povečano raztapljanje apnenca (*Kogovšek* 2011), kar vodi v postopno večanje prepustnosti razpok pod takšnimi viri in vse hitrejši prenos kontaminantov skozi vadozno cono. To razloži sorazmerno hitro pre-

m/h (*Kogovšek* and *Petrič* 2006, 2007, 2010a). Based on multiparameter studies of the vadose zone, localized sources of pollution with higher concentration of nitrates, chlorides, phosphates and sulfates such as leachate waters from landfills, foster intense dissolution of limestone (*Kogovšek* 2011). This leads to the gradual formation of increasingly permeable fissures, and water with contaminants can then penetrate faster through the vadose zone. This explains the relatively rapid percolation and appearance of the bulk of injected tracer from the landfills in the first wave of tracer in the springs (40–80 %). In contrast, the tracer test from the military training area Poček, where pollution (mainly heavy metals) is dispersed more widely, showed that only 4 % of the injected tracer flowed through the Malenščica spring in the first wave of tracer.

The long-term monitoring of pollution transfer through the 100 m thick vadose zone confirmed that the washing of even minor pollution from the surface takes more than twenty years before the original conditions are restored (*Kogovšek* 2010). Therefore we assume that the washing of contaminants from landfill sites will be much longer, which means long-term influence on spring quality in impacted areas.

takanje skozi vadozno cono pod odlagališči in velik delež injiciranega sledila, ki je izteklo skozi izvire v prvem sledilnem valu v času enega meseca (40–80 %). V sledenju z vojaškega poligona Poček, kjer prevladuje razpršeno onesnaževanje predvsem s kovinami in ki je bilo izvedeno v primerljivih razmerah, je skozi opazovani izvir Malenščica v prvem sledilnem valu izteklo le 4 % injiciranega sledila.

Dolgotrajno spremljanje prenosa onesnaženja skozi 100 m debelo vadozno cono je pokazalo, da bo tudi spiranje manjšega onesnaženja trajalo več kot dvajset let (*Kogovšek* 2010). Zato pričakujemo, da bo spiranje kontaminantov iz obsežnih odlagališč odpadkov še znatno daljše, kar pomeni tudi dolgotrajnejši vpliv na kakovost izvirov v vplivnem območju.

Sklep

Številne raziskave vadozne cone, predvsem pa večletne, zvezne in sočasne raziskave infiltracije padavin, so podale dinamiko pretakanja padavin, ki je odvisna tako od razmer na površju kot v vadozni coni, in dinamiko prenosa topnih kontaminantov (kloridov, nitratov, fosfatov, sulfatov) ter njihov vpliv na raztapljanje karbonatnih kamnin. Tako so prispevale k razumevanju vloge vadozne cone pri prenosu onesnaženja skozi kraški vodonosnik.

Prenos topnih kontaminantov skozi vadozno cono je neposredno povezan s hidrodinamiko. Ugotovljena je bila pomembna vloga predhodno shranjene vode v letnem in večletnem merilu. V poletnih sušnih obdobjih, ki so trajala od 2,5 do 6 mesecev, se je velika količina manj intenzivnih padavin (do 470 mm padavin oz. do 210 mm infiltriranih padavin) pretežno le shranjevala v vadozni coni, saj je bil iztok iz nje minimalen. V teh obdobjih, ko niso aktivne niti najbolj niti najmanj prepustne razpoke, je prenos kontaminantov skozi vadozno cono najmanjši. Tedaj imajo tudi reke ponikalnice, ki lahko prenašajo večje onesnaženje, minimalne pretoke ali pa so suhe. Zato je kakovost kraških izvirov v takšnih razmerah sorazmerno dobra. Vendar pa izdatne padavine, ki sledijo, sperejo akumulirano onesnaženje in prihaja do njegovega najbolj intenzivnega prenosa skozi vodonosnik. Takrat gre za zvezno pretakanje skozi vadozno cono po celotni hierarhiji različno prepustnih

Conclusion

Multiparameter research on the vadose zone over consecutive hydrological years showed the dynamics of the percolation and retention of infiltrated precipitation depending on conditions on the surface and in the vadose zone, and the dynamics of the transfer of contaminants (chlorides, nitrates, phosphates and sulfates) and their impact on the dissolution of carbonate rock, and has contributed to understanding the role of the vadose zone in the transfer of pollution through karst aquifers.

The transfer of soluble contaminants is directly related to the percolation of water and the processes of water storage in the vadose zone. We have established the significant role of previously stored water on an annual or multi-year scale. During the summer dry periods that last from 2.5 to 6 months, a large amount of less intense precipitation (up to 470 mm of precipitation or up to 210 mm of effective infiltrated precipitation) is stored in the vadose zone, and the discharge from it is minimal. In these periods when neither the most nor the least permeable fissures in the vadose zone are active, the transfer of contaminants is the smallest. At this time the discharges of the sinking streams that usually carry pollutants are minimal, or the streams may even be dry. The quality of karst springs is therefore relatively good in such periods. On the other hand, the abundant precipitation that follows longer dry periods flushes accumulated pollution through the aquifers, leading to the most intense transfer of contaminants. In these conditions continuous percolation occurs along the entire hierarchy of variously permeable fissures in the vadose zone. This is reflected in higher concentrations of contaminants in the initial water pulses at springs, and quality worsens, particularly if there is no major dilution effect.

Sources of pollution on the karst surface influence incresed dissolving of limestone with higher contents of nitrates, chlorides, phosphates and sulfates (*Kogovšek* 2011) which means gradual spreading of cracks and fissures in the vadose zone and faster transfer of contaminants. Long-term monitoring of the rinsing of minor pollution on the surface has confirmed that it takes more than twenty years before razpok. To se odrazi v večjih koncentracijah kontaminantov v prvih vodnih valovih izvirov po sušnih obdobjih, še zlasti, če ni prevelikih učinkov razredčenja.

Viri onesnaženja na kraškem površju z višjimi vsebnostmi nitratov, kloridov, fosfatov in sulfatov vplivajo na povečano raztapljanje apnenca (*Kogovšek* 2011), kar pomeni postopno širjenje razpok v vadozni coni in vse hitrejši prenos kontaminantov. Dolgoročno spremljanje spiranja manjšega onesnaženja na površju do vzpostavitve izhodnega stanja je pokazalo, da bo celo to trajalo več kot dvajset let. Zato v primeru odlagališč odpadkov lahko pričakujemo še daljše spiranje oz. njihov dolgotrajni vpliv na kakovost izvirov v vplivnem območju.

Spremljanje posledic ob nesrečah z izlitji naftnih derivatov na krasu je pokazalo, da ti ubirajo vodne poti skozi vadozno cono in da njihov prenos do kraških izvirov pogojujejo padavine, ki sledijo. Zaradi njihovih fizikalnih lastnosti je prenos naftnih derivatov drugačen kakor prenos topnih snovi. V vodonosniku se zadržijo dlje časa, se akumulirajo in le postopno spirajo. Po prepustnejših razpokah v vadozni coni se prenašajo tudi majhni trdni delci (*Kogovšek* 1982), na katere je lahko vezano organsko onesnaženje, pa tudi kovine in mikroorganizmi.

Zahvala

Raziskave so potekale v okviru programa Agencije za raziskovanje Republike Slovenije (ARRS) »Raziskovanje krasa« in s sofinanciranjem Slovenske nacionalne komisije za UNESCO v okviru Mednarodnega hidrološkega programa IHP (International Hydrological Program).

the original conditions are restored. Therefore we can expect, in case of landfills, even longer rinsing and their long-term impact on quality of springs in the catchment area.

On the basis of observations of accidents involving spillage of petroleum products in the karst, we know that petroleum drains along the routes that rainfall follows from the surface through the aquifer. Their first appearance at springs is influenced by conditions in the soil and the vadose zone and by the rainfall that follows. Comparisons of the transfer of petroleum products versus soluble tracers indicate that the subsequent mode of transfer of these substances through karst aquifers differs significantly because of their physical properties. Above all it involves longer retention and accumulation of petroleum products followed by gradual washing away. Along more highly permeable fissures the transport of solid particles can also occur (*Kogovšek* 1982) and organic pollution, heavy metals and microorganisms can be connected to them.

Acknowledgement

Long-term research was supported by the Slovenian Research Agency (ARRS)—research program »Raziskovanje krasa« and the Slovenian National Commission for UNESCO—»International Hydrological Program« (IHP).

3

TEMPERATURA VODE KOT NARAVNO SLEDILO ZA UGOTAVLJANJE PRETAKANJA PODZEMNIH VODA: PRIMER PODZEMNE PIVKE IN UNICE

WATER TEMPERATURE AS A NATURAL TRACER OF GROUNDWATER IN KARST: THE CASE OF THE PIVKA AND UNICA RIVERS

FRANCI GABROVŠEK, JANEZ TURK

Ugotavljanje vodnih zvez in dinamike pretakanja podzemnih voda je ena pomembnejših nalog kraške hidrologije, na kateri temelji tudi varovanje kraških vodnih virov. Povezave med dotoki in izviri največkrat ugotavljamo z uporabo različnih umetnih sledil. Sledilni poskusi dajo zanesljiv kvantitativni rezultat, ki pa je največkrat vezan le na trenutni vodostaj ob času izvajanja poskusa. Danes vemo, da so v krasu smeri vodnih tokov ob različnih vodostajih lahko precej različne (npr. *Kogovšek idr.* 1999). Tudi zato številne raziskave potekajo v smeri uporabe naravnih sledil, torej fizikalnih in kemičnih parametrov, ki posredno kažejo na vodne povezave. Nekatere od teh parametrov lahko merimo zvezno, s posebej v ta namen izdelanimi napravami, ki jih namestimo v vodni tok (t. i. data loggerji). Meritve potekajo avtomatsko. Takšne merilne naprave lahko namestimo tudi v kraške jame, ki nudijo edini dostop do aktivnih vodnih poti v krasu. Zaradi težke dostopnosti jame le redko uporabimo za mesta vzorčenja pri klasičnih sledilnih poskusih. Kljub temu pa bi prav podatki iz jam omogočali precej boljši vpogled v prostorsko porazdelitev podzemnih vodnih tokov.

Naravno sledilo je lahko tudi temperatura vode (*Saar* 2011). Razvoj razmeroma cenovno ugodnih avtomatskih merilnikov nam omogoča zajem dolgočasovnih temperaturnih nizov tudi v najtežje dostopnih jamah. V Sloveniji zadnjih pet let zvezno spremljamo temperaturo v več kraških sistemih, v tem prispevku pa prikazujeva nekatere rezultate v ponikalnicah Pivki in Unici. V prvem primeru smo merili v sistemu Postojnskih jam, v drugem primeru pa v štirih jamah med Planinskim poljem in Logatcem.

Tok ponikalnic skozi kraške jamske splete je zanimiv z več vidikov. Ponikalnice predstavljajo koncentriran dotok v kraški vodonosnik; z njimi se odvija hiter transport snovi (tudi onesnaževal) globoko v kraški masiv. Onesnažena ponikalnica zato pomeni grožnjo za celoten vodonosnik. Kraške ponikalnice odlikuje tudi velika spremenljivost fizikalnih in kemičnih lastnosti, kot so pretok, temperatura, kalnost in koncentracija v njih raztopljenih snovi.

Za ponorom se režim vodnega toka temeljito spremeni. Voda teče skozi bolj ali manj zvezen sistem jamskih rovov različnih dimenzij, ki jih lahko

One of the main goals of karst hydrology is to define the directions of groundwater flow in karst aquifers, so that protective measures of karst groundwater resources can be efficient. To this extent the use of various artificial tracers has been widespread. Dye tracing tests give reliable and also quantitative results, however these are valid for the hydrological situations at the time of the test. It has been demonstrated numerous times (e.g. *Kogovšek* et al. 1999) that direction of groundwater flow at a site depends on the particular hydrological conditions. Therefore, karst hydrologists are making efforts to use natural tracers, i.e. physical and chemical parameters of groundwater, which indirectly indicate directions of the flow. Some of these parameters can be continuously monitored by fixing the instruments with internal memory into the active flow (so called data loggers). If these are robust, autonomous and have independent (if possible internal) power source, they can be readily used in caves. Caves provide unique access to the active groundwater flow between the inputs and springs. Although data from caves would improve our knowledge on the direction and dynamic behaviour of the flow, the caves are rarely used for sampling points in classical tracer tests because of their inaccessibility.

Water temperature can also be considered as a natural tracer (*Saar* 2011). Recent development of robust and reliable instrument enabled collection of long-term temperature records also in most remote points of caves with active flow. During last five years continuous monitoring of groundwater levels and temperatures (and in some cases also electrical conductivities) has been established in several karst systems in Slovenia. This chapter shows some results and interpretation of temperature and stage monitoring in two sinking streams in Slovene classical karst: Pivka in the Postojna cave system and Unica in four caves between Planinsko polje and Logatec.

Sinking rivers are the main tributaries of many important karst systems. They present concentrated recharge to the aquifer and carry fast material (including potential contaminants) transport deep into the system. Sinking rivers show high temporal variation of physical and chemical parameters such as discharge, temperature, turbidity and concentration of dissolved substances.

prekinjajo podori. Ponekod ima odprto gladino, ponekod so rovi lahko povsem zaliti. Ob poplavnih dogodkih lahko nek rov iz odprtega kanala postane tlačni rov (popolnoma zalit z vodo). Zožitve rovov povzročajo zastajanje vode in dviganje vodnih nivojev, kar je še zlasti izrazito ob prehodu velikih poplavnih valov skozi jamo. V več slovenskih jamah beležimo dvige tudi prek 100 m, nivoji pa ob poplavnem dogodku naraščajo tudi s hitrostjo več kot 10 m na uro.

Ob prehodu v podzemlje se spremenijo tudi temperaturne značilnosti ponikalnic. Podzemlje je toplotno stabilno okolje. Na površju temperaturo rek določa izmenjava toplote med vodo in strugo ter okoliško atmosfero. Glavni vir toplote je kratkovalovno sončno sevanje, toplotne izgube pa potekajo predvsem ponoči. Temperature površinskih voda zato nihajo tako skozi vse leto kakor tudi v enem dnevu. Na temperaturo močno vplivajo še padavinski dogodki in taljenje snega, ki močno popačijo periodičnost temperaturne krivulje.

V podzemlju sončnega sevanja ni, tudi dolgovalovna sevalna izmenjava toplote je v večini primerov majhna. Temperatura vode se vzdolž toka spreminja predvsem zaradi izmenjave toplote med vodo in jamskimi stenami oziroma sedimentom v strugi. V osnovi se temperatura vode spreminja zaradi konvekcijskega prenosa toplote med vodo in steno rova in/ali sedimentom v strugi. Gostota konvekcijskega toplotnega toka je odvisna zlasti od razlike temperatur med vodo in steno ter od režima vodnega toka. Prenos toplote med steno in okoliškim masivom se vrši predvsem s prevajanjem. S sklenitvijo konvekcijskega prenosa toplote na meji med vodo in steno ter s prevajanjem v kamnini lahko pojasnimo večino temperaturne dinamike podzemnih vodotokov. Covington in sodelavci (*Covington* idr. 2011) so z analitičnim in numeričnim modelom pojasnili relativni pomen posameznih prispevkov k toplotni bilanci vode v podzemlju in z modelom tudi uspešno razložili nekatere rezultate terenskih meritev v Postojnskem jamskem sistemu.

Zaradi izmenjave toplote s kamnino se amplituda dnevnih temperaturnih sprememb vzdolž vodnega toka približno eksponentno zmanjšuje. Značilna dolžina, ki opisuje, kako hitro se to dogaja, je odvisna predvsem od pretoka, hidravličnega obsega (tj. od površine stika med vodo in kamnino), koeficienta

At the ponor, the flow regime can change abruptly. In the developed karst systems, the water flows along a system of channels of different dimensions, often obstructed by the breakdowns. Open surface or pressurized flow conditions are both possible, with frequent transition from one to the other. Flow restrictions cause water ponding and high fluctuations of the groundwater level. In several Slovene caves, the stage variations can reach 100 m or more. At flood events, the rate of water rise can exceed 10 m/h.

The temperature of any river is controlled by the heat exchange between the water and the environment. At the surface, the most important heat source is a short-wave solar radiation, which is completely absent underground. The temperature of surface rivers show typical diurnal oscillations with abrupt changes caused by rain events and snow melting.

There is no solar shortwave radiation in caves. The temperature of underground flow is governed mainly by the convective heat exchange with cave walls and sediments. The heat flux from water to rock or vice versa is proportional to the difference between the temperature of water and rock and the flow regime. However, the wall temperature also depends on the conductive heat transport within the rock massive. By coupling the convective heat transfer between the water and the cave walls to the conduction in rock, most of the temperature behaviour of the underground flow can be discussed. A good fit between modelling and field results have been demonstrated by *Covington* et al. (2011) who also give a theoretical background on different heat exchange processes in the underground rivers, among others in the Postojna cave system.

The heat exchange between water and rock diminishes the amplitude of diurnal temperature variations along the flow path. The characteristic length scale, a measure for the rate of amplitude decrease along the flow, depends on the discharge, hydraulic diameter, convection coefficients and thermal conductivity of rock. Diurnal temperature variations in some sinking rivers can reach several kilometres deep. However, the length scale for diffused flow is much shorter, usually in the order of few metres. Therefore, if diurnal temperature oscillations are recorded in cave waters, this clearly indicates the recharge from the concentrated konvekcijskega prenosa toplote, ki je odvisen tudi od značilnosti toka, in toplotne prevodnosti kamnine. Dnevna temperaturna nihanja lahko v ponikalnicah sežejo tudi več kilometrov v masiv. Torej nam dnevno nihanje temperature v jamskih tokovih dokazuje, da voda nekje koncentrirano doteka v kras. Sklepamo lahko celo na potovalni čas in hitrost vodnega toka med dvema točkama (lokacijama). Ob predpostavki, da temperaturni signal vzdolž vodne poti potuje predvsem advekcijsko (torej skupaj z vodnim tokom), lahko iz časovne razlike med dnevnim vrhom ali dnom temperaturne krivulje na dveh različnih točkah vzdolž toka sklepamo o času potovanja vode med tema dvema točkama. Torej nam temperatura služi kot naravno sledilo. V tem poglavju so prikazane meritve na podzemnem toku rek Pivke in Unice in nekateri izsledki o naravi obeh tokov na podlagi analize temperaturnih časovnih vrst.

Fizikalne lastnosti voda, tako tudi temperaturo, je možno v današnjem času razmeroma preprosto spremljati, saj imamo na voljo naprave, ki nam v rednih časovnih presledkih merijo in beležijo želene parametre. Merilno napravo lahko povežemo z računalnikom, s katerim nastavimo merilne parametre, kot so časovni presledek med dvema meritvama, začetek in konec meritev, lokacijsko specifične spremenljivke itd. Natančnost zabeleženih meritev je 0,1 °C.

3.1 Primer reke Pivke v sistemu postojnskih jam

Reka Pivka je glavni dotok v Postojnski jamski sistem. Med ponorom v Postojnski jami in odtočnim sifonom v Pivki jami teče večino 3,5 km dolge vodne poti s prosto gladino (1). Ob nizkem in srednjem vodostaju je le nekaj sto metrov toka po popolno zalitih rovih. Ob izjemno visokih vodostajih pa tok v večjem delu postane tlačni. Čeprav je pot podzemne Pivke dobro znana in dostopna, pa je o njeni poplavni dinamiki manj znanega. Drugi del poti ovirajo podori, za katerimi so jezera s počasnim tokom. Glavno oviro ob visokih vodostajih predstavlja Martelov podor (*Turk* 2010a).

Tu obravnavamo zgolj meritve na skrajnih merilnih mestih, tik za ponorom (Veliki dom) in v odtočnem sifonu v Pivki jami (1, rdeči krogi).

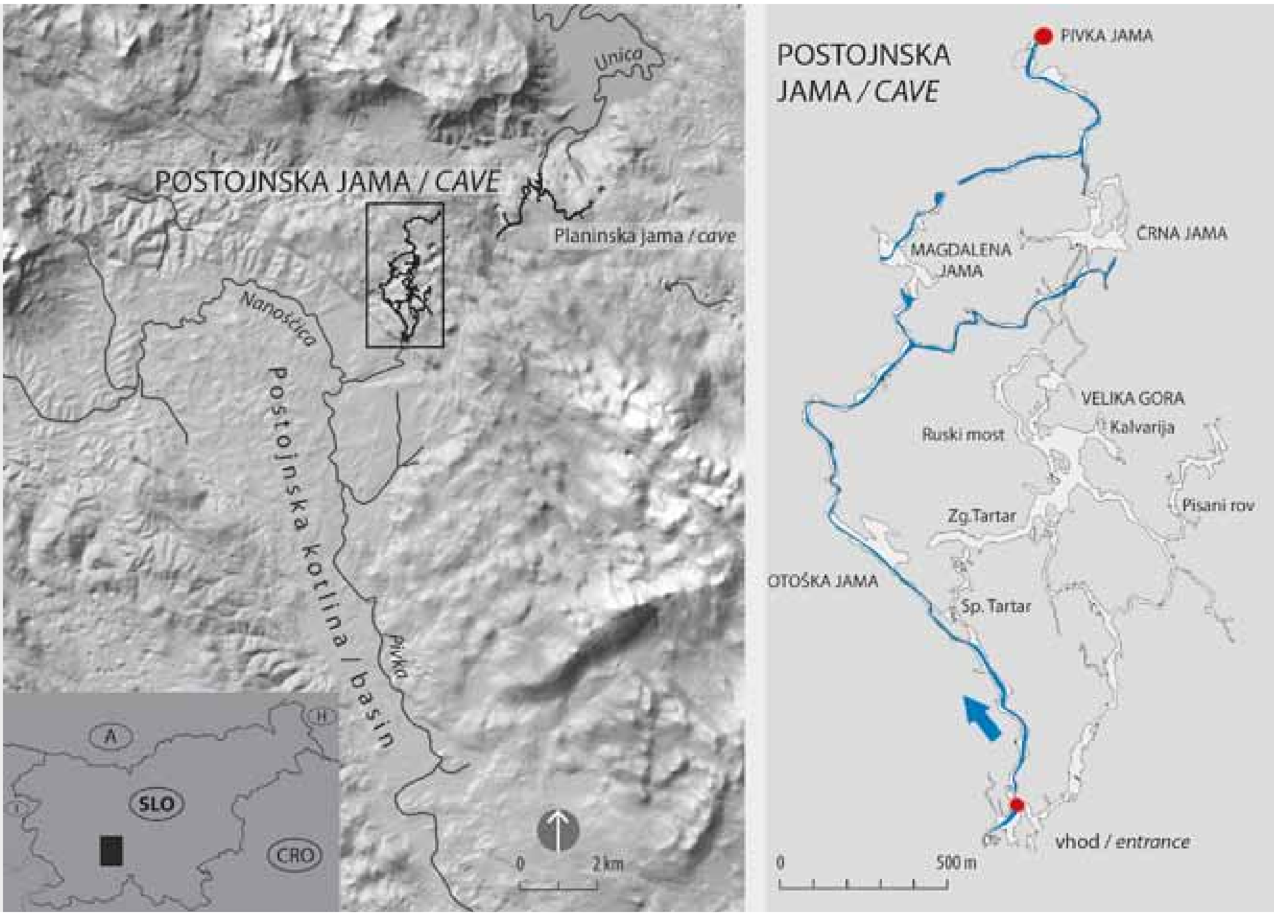
source, most probably a sinking river. If we assume the advective 'transport' of temperature signal, the time lag of between temperature curves at two points at different location along the same flow, represents the travel time of the flow between the points. So the temperature is beeing used as natural tracer. In this chapter we present the measurements of the Pivka and Unica underground water flow and some results concerning the nature of both flows based on the analysis of the temperature temporal lines.

The temperatures of groundwater was recorded with instruments which hold enough memory for several years of autonomy if measurements are taken every 30 minutes. The instruments are programmed by PC or a pocket computer through the interface via optical bridge. Accuracy of measurements is 0.1 °C.

3.1 The case of the Pivka river in the Postojna cave system

The river Pivka is the main recharge to the Postojna cave system. Between the ponor at the Postojnska jama and the terminal siphon lake in the Pivka jama there is about 3.5 km long underground flow (1). Only about few hundred metres of flow occurs along pressurized conduits at low to medium discharge and more than half in high floods. Even though most of the underground flow of the Pivka river is well explored and known, the flood dynamics has been poorly understood until recently. The second part of the flow is obstructed by numerous breakdowns with upstream lakes of slow water. A major flow restriction which causes the flooding of the entire active level up to the entrance is the Martel's breakdown (*Turk* 2010a).

Here we discuss only temperature records at the two extreme points, in Veliki dom just behind the ponor and at the terminal lake in the Pivka jama (1, red circles). The altitude difference between both points is about 35 m. The yearly temperature variations of the river Pivka is about 15–20 °C. In winter the temperature is only few degrees centigrade, in summer it reaches almost 20 °C. The amplitude of daily variations ranges between few tenths of a degree and 1 °C. A part of the record also shows daily maxima in the early



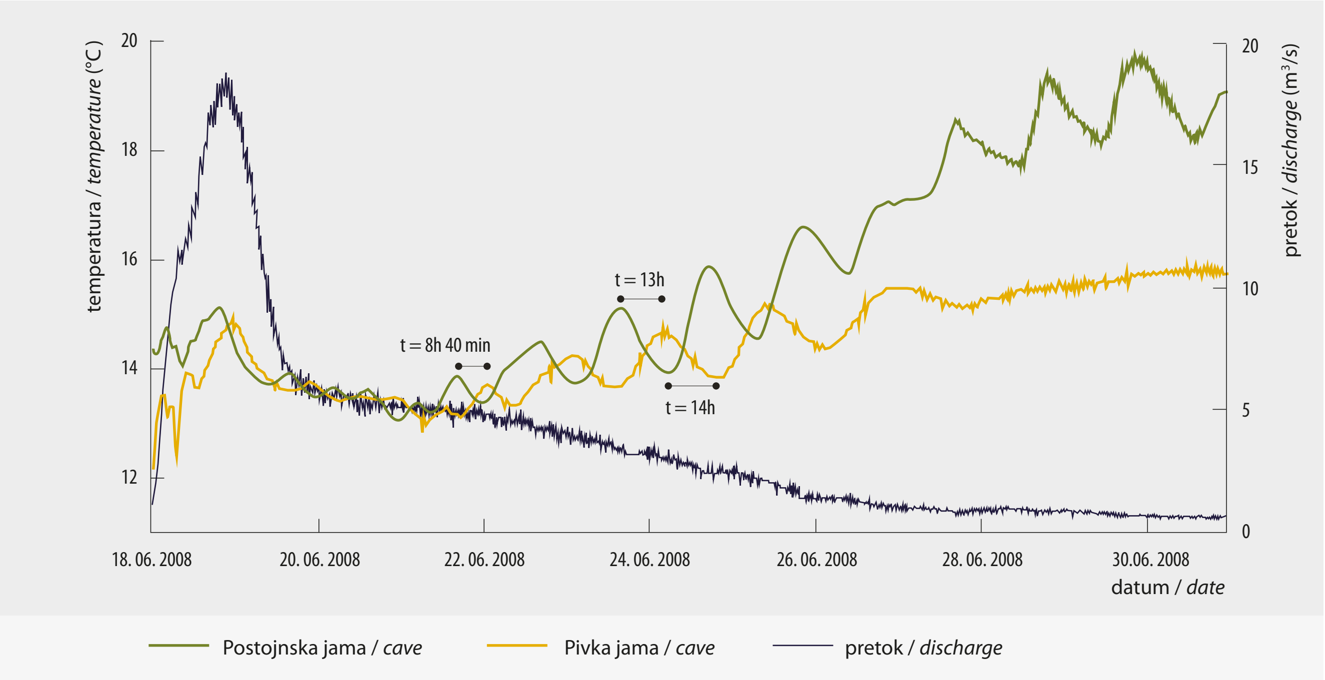
1 Levo: Digitalni model reliefa z delom Postojnske kotline, Javornikov, Hrušice in Planinskega polja s tlorisi Postojnskega jamskega sistema in Planinske jame. Desno: Tloris Postojnskega jamskega sistema z vrisanim tokom Pivke (modro) in merilnima točkama (rdeči piki). Modra puščica nakazuje generalno smer toka.
Left: Digital elevation model, including parts of Postojna basin, Javorniki, Hrušica and Planinsko polje with ground-plans of the Postojna cave system and the cave Planinska jama. Right: Ground-plan of the Postojna cave system with underground course of the Pivka river (in blue) and monitoring sites (marked by red circles). The blue arrow indicates the general flow direction.

Višinska razlika med postajama je 35 m. Na letnem nivoju temperatura Pivke pri ponoru niha med 15 in 20 °C. Pozimi je le nekaj stopinj nad ničlo, poleti navadno preseže 15 °C in se približa celo 20 °C. Značilna temperaturna nihanja se pojavljajo tudi skozi ves dan. Amplituda dnevnih nihanj znaša od nekaj desetink do okrog stopinje Celzija in je predvsem posledica dnevno-nočnega ritma sončnega obsevanja in z njim povezanih zunanjih temperatur. Kot zanimivost povejmo, da smo v nekaterih obdobjih tik za ponorom

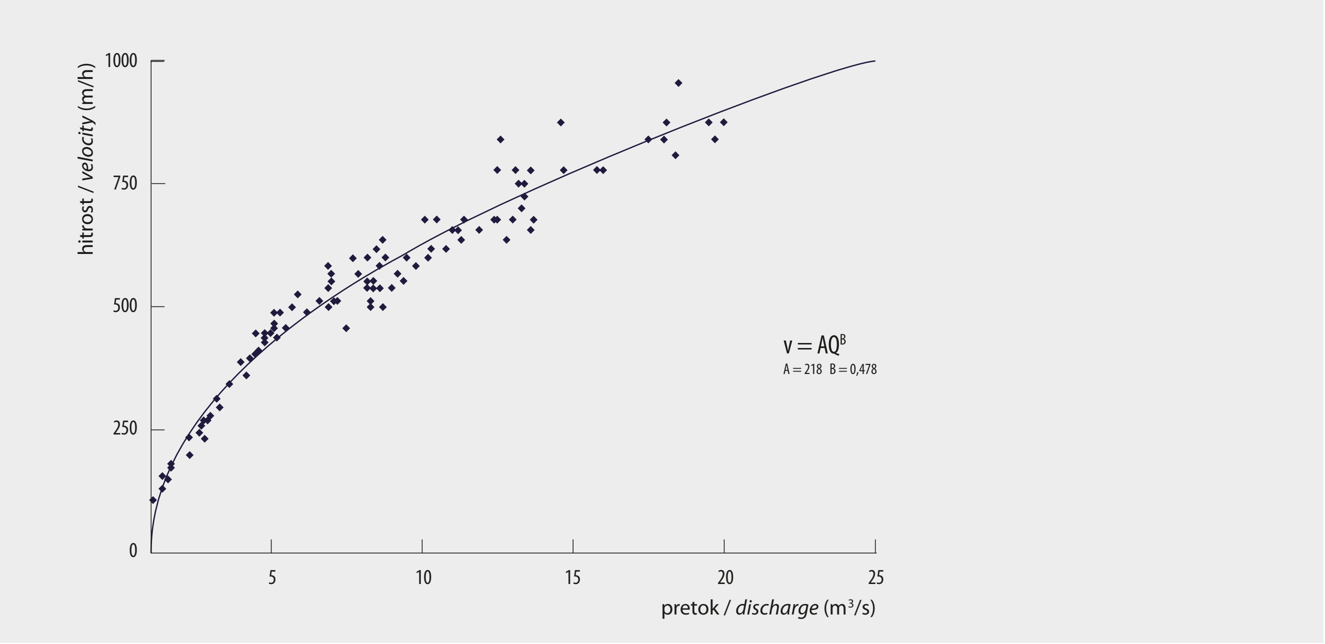
morning hours, which cannot be related to any known natural processes.

Figure 2 shows discharge and temperature of the river at the two locations in the second half of June 2008 when the discharge decreases following a rain event. Both stations show clear diurnal variations. However, when the discharge drops below 1 m^3/s, the temperature in the Pivka cave loses its diurnal character. A simple observation of corresponding daily maxima and minima leads us to several other conclusions: time lags between corresponding peaks and valleys show increase with decreasing discharge. The temperature drop along the flow increases with increasing input temperature (e.g. peaks show higher difference than valleys), which is to be expected for the summer period when the temperature of the cave walls is regularly below the temperature of the water.

The time lag analysis on a long-term record shows a clear relation between the travel time and discharge. Figure 3 shows the function of flow velocity on the discharge as



2 Potek pretoka in temperature Pivke na obeh merilnih točkah v drugi polovici junija 2008. Označeni so časovni zamiki med izbranimi ustreznimi dnevnimi ekstremi obeh merilnih točk.
Discharge and temperature records of the Pivka river at the both stations in the second half of June 2008. The time lags between selected corresponding temperature maxima and minima are shown.



3 Odvisnost hitrosti toka od pretoka, kot jo dobimo iz analize časovnih zamikov dnevnih temperaturnih ekstremov.
Dependence of the flow velocity on the discharge as obtained by the analysis of time lags between daily maxima and minima at the stations.

Pivke zaznali temperaturne vrhove sredi noči, kar je precej nenavadno in kaže na verjeten človekov vpliv.

Slika 2 prikazuje temperaturo in pretok Pivke na obeh merilnih mestih v drugi polovici junija 2008, ob stalnem upadanju pretoka v padavinskem dogodku. Temperaturni signal na obeh mestih kaže značilen dnevni ritem. Ko pretok pade pod 1 m^3/s, dnevne oscilacije v Pivki jami izginejo. Že preprosta analiza ustreznih temperaturnih vrhov in dolin nam pokaže nekatere značilnosti pretakanja in prenosa toplote skozi jamski sistem. Časovni zamik med ustreznimi vrhovi se veča s padanjem pretoka, temperaturna razlika na obeh točkah pa narašča z naraščanjem vhodne temperature (npr. razlika med vrhovi je večja kot razlika med dolinami). Slednje je posledica dejstva, da so v tem letnem času jamske stene praviloma hladnejše od vode in čim večja je razlika med temperaturo vode in stene, tem več toplote preide iz vode v okolico.

Analiza časovnih zamikov med dnevnimi vrhovi in dolinami nam da podatke o hitrosti potovanja temperaturnega signala. Slika 3 prikazuje hitrost v odvisnosti od pretoka, izračunano na osnovi 200 izbranih jasnih vrhov in dolin. Prikazana je tudi potenčna krivulja, ki se točkam najbolje prilega. Izkaže se, da ima hitrost približno korensko odvisnost od pretoka.

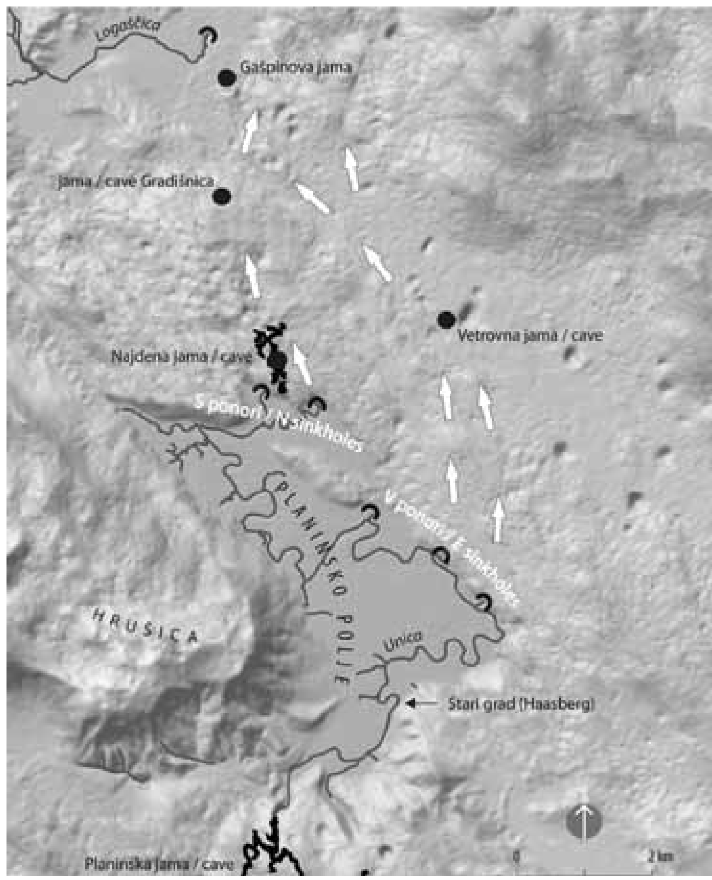
3.2 Primer Unice med Planinskim poljem in Logatcem

Reka Unica izvira na južnem obrobju Planinskega polja, glavni ponori pa so vzdolž njenega toka na vzhodnem in severnem robu polja (4). Ker Unica na Planinskem polju preteče precejšnjo razdaljo, pridobi temperaturni signal, ki je značilen za površinske reke, z dnevno amplitudo do 2 °C. Podzemno Unico med Planinskim poljem in Vrhniko lahko sledimo še v šestih jamah, v štirih izmed njih smo v letih 2006–2008 merili temperature in vodostaje. Poleg tega smo merili tudi temperaturo in pretok (na osnovi zveznih meritev vodostajev) Unice pod mostom pri Starem gradu. Minimalni pretok na merilnem mestu je nekaj sto litrov na sekundo, povprečni 25 m^3/s in maksimalni preko 100 m^3/s. Unica začne poplavljati polje, ko je presežena kapaciteta ponorov, približno pri pretoku 60 m^3/s

calculated from the time lags of 200 clear minima and maxima. The best fit curve is also shown. The velocity shows approximately a square root dependence on the discharge.

3.2 The case of the Unica river between Planinsko polje and Logatec

The Unica river represents an overflow in Planinsko polje. Its springs are located at the southern rim of the polje. Along its flow, the river sinks at several ponors at the eastern and northern rim (4). The surface flow of river Unica gains typical temperature record with diurnal amplitude of up to 2 °C. Its under-



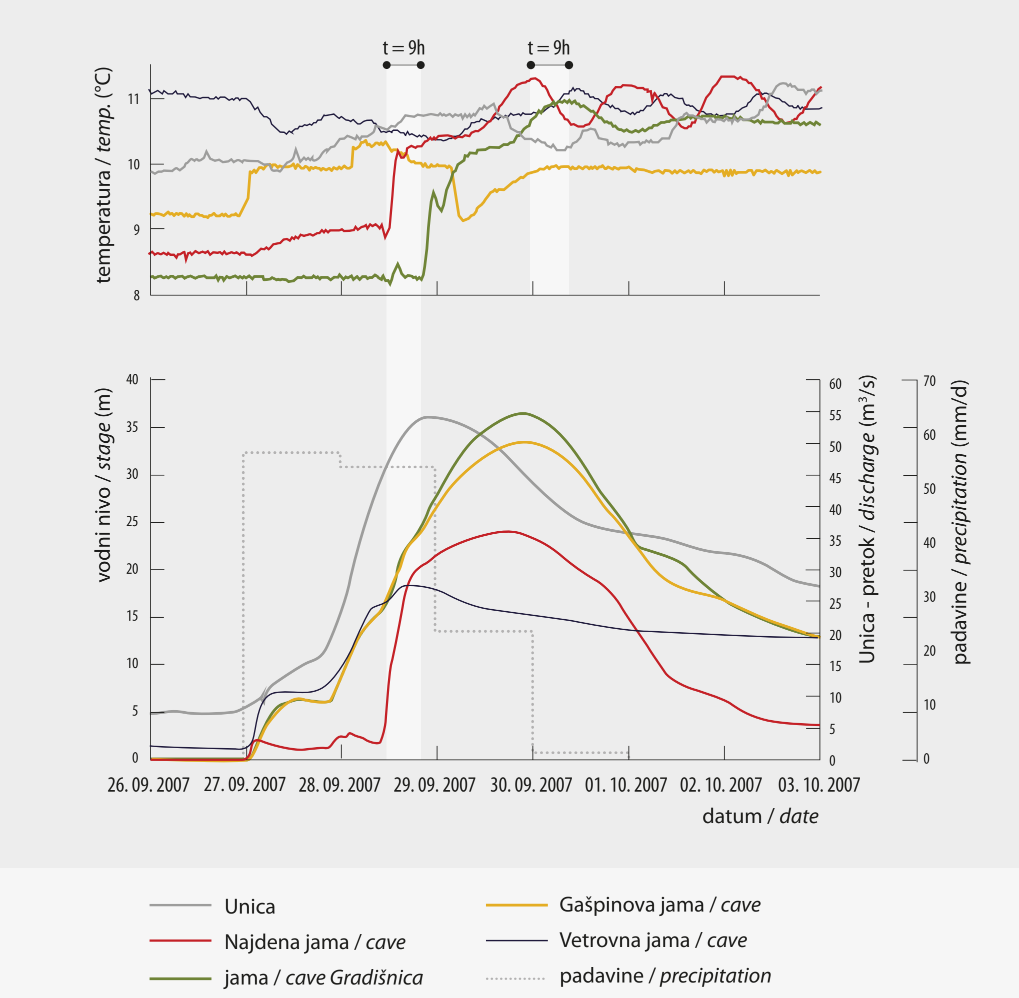
4 Območje med Planinskim poljem in Logatcem. Označeni tok Unice in ponorna območja na Planinskem polju ter jame, v katerih smo spremljali temperature in nivoje.
The area between Planinsko polje and Logatec with surface flow of the Unica river, ponor areas and the locations of measurements stations.

(*Gabrovšek* in *Turk* 2010, *Turk* 2010a, b).

Čeprav vse jame kažejo hiter odziv nivojev tudi na manjše padavinske dogodke, dnevnih temperaturnih nihanj pri pretokih, manjših od 20 m³/s, ne zaznamo v nobeni od jam. Ko Unica doseže pretoke med 20 in 25 m³/s, se pojavi jasna korelacija med temperaturo Unice in temperaturo vode v Vetrovni jami, ki se napaja skozi ponore ob vzhodnem robu polja. Pri pretokih 25–30 m³/s se dnevne temperaturne spremembe pojavijo v Najdeni jami in Gradišnici (5). Temperatura v obeh jamah se približa temperaturi Unice. Zamik signala med eno in drugo jamo je približno 9 ur. Nivoji v Gašpinovi jami, ki je od vseh najbolj oddaljena od ponorov, so skoraj identični tistim v Gradišnici, kar govori o dobri hidravlični povezanosti obeh jam. Tempera-

ground flow between Planinsko polje and the springs of Ljubljanica can be encountered in six caves, in four of them the temperature and stage were recorded in 2006–2008. Additionally, discharge and temperature of the surface flow in Planinsko polje were also recorded. Minimal discharge of the Unica river is few hundred l/s, mean discharge is about 25 m³/s, and maximal above 100 m³/s. Planinsko polje becomes flooded when the capacity of ponors is exceeded at about 60 m³/s (*Gabrovšek* and *Turk* 2010; *Turk* 2010a, b).

The water level in all caves shows quick response even to small precipitation events. However, when the discharge of the river Unica is below 20 m³/s, diurnal temperature oscillations are not seen in any of the caves. At discharge between 20 and 25 m³/s, there is



5 Potek temperature in pretoka Unice ter temperature in nivojev v jamah ob padavinskem dogodku septembra 2007. Označen je časovni zamik temperaturnega signala med Najdeno jamo in Gradišnico.
Temperature and discharge hydrograph of the Unica river and temperature and stage hydrograph of groundwater at four monitored caves in the recession period after a rain event in September 2007. The lag between temperature signals in the caves Najdena jama and Gradišnica is marked.

turni hidrogram iz Gašpinove jame pa je povsem drugačen od tistega v Gradišnici. Dnevnega nihanja ni. Ob dogodku, prikazanem na sliki 5, temperatura najprej naraste za pol stopinje, potem pa skokovito upade skoraj za celo stopinjo. Zgolj sklepamo lahko, da so med obema jamama dotoki. Dnevno nihanje temperature v Gašpinovi jami se pokaže le ob izredno visokih vodostajih, ko pretok Unice preseže 55 m^3/s (*Turk* in *Gabrovšek* 2009, *Gabrovšek* in *Turk* 2010, *Turk* 2010a, b).

Temperaturni signal Unice na sliki 5 je malce zavajoč, saj je dolžina toka od izvirov do mesta merjenja prekratka, da bi se pri tako velikem pretoku oblikoval dnevni temperaturni cikel.

Sklep

Temperature podzemnih voda so lahko pomemben kazalec navzočnosti povezav in hitrosti podzemnih tokov. Avtomatske merilnike, ki so bili razviti v zadnjem desetletju, je možno namestiti v večini jamskih sistemov z aktivnim vodnim tokom. Nove teoretične raziskave omogočajo vse boljše vrednotenje in interpretacijo dobljenih podatkov. Dolgočasovne analize podatkov o temperaturi, specifični električni prevodnosti in vodostajih bi nam vsekakor omogočale vpogled v dinamiko podzemnih vodnih tokov na celotnem območju pretokov.

a clear correlation between temperature of Unica and the temperature in the cave Vetrovna jama which is fed through the set of eastern ponors. When the discharge reaches 25–30 m^3/s, diurnal variations are also recorded in the caves Najdena jama and Gradišnica (5). The temperature in both caves is close to the temperature of the Unica river. Time lag between temperature records in Najdena jama and Gradišnica is about 9 hours. The dynamics of water level in the cave Gašpinova jama, which is most distinct from the ponor areas, is almost identical to that in Gradišnica, indicating a clear hydraulic connection between the two caves. The temperature record in Gašpinova jama is however much different. At the event presented on the figure 5 no diurnal temperature variations are visible. The temperature first rises for half a degree and then abruptly drops and slowly returns back to the pre-event value. Such behaviour indicates other tributaries of unknown origin. Diurnal temperature variations in Gašpinova jama were observed only during extreme events, when the discharge of the Unica is above 55 m^3/s (*Turk* and *Gabrovšek* 2009, *Gabrovšek* and *Turk* 2010, *Turk* 2010a, b).

The temperature signal of the Unica river on the figure 5 is a little deceptive because the flow length between the springs and the measurement point is too short that a daily temperature cycle could form at so large discharge.

Conclusion

Temperature of groundwater can be an important indicator of the flow directions and dynamics. By use of robust autonomous instruments, we could establish long-term temperature records in most of the cave systems with active groundwater flow. These could, together with the recent theoretical research which provides new means to analyse these data, enable new insights into the nature of groundwater flow in karst at all hydrological regimes.

4

OGROŽENOST KRAŠKIH VODNIH VIROV ZARADI PROMETA V REDNIH RAZMERAH

THREATS TO THE KARST WATER SOURCES FROM TRAFFIC IN NORMAL CONDITIONS

JANJA KOGOVŠEK

Zaradi prepustnosti razpokanih in topnih karbonatnih kamnin na kraškem svetu, predvsem apnenca in dolomita, je ranljivost kraškega okolja velika in vsakršno onesnaževanje na njegovem površju pomeni tudi onesnaženje kraških podzemnih voda. V celo vrsto onesnaževalcev na kraškem površju, ki ogrožajo kakovost kraške vode, spada tudi promet, ne le v primeru nesreč, ko pride do razlitja velikih količin nevarnih in škodljivih snovi, ki lahko kontaminirajo pitno vodo, temveč tudi zaradi onesnaževanja, do katerega prihaja ob rednem odvijanju prometa po cestah in železnicah.

V Mariboru so pred časom ugotavljali, da je pomemben vzrok onesnaženosti zraka tudi gost promet (*Špes* 1993). Pozneje so v neposredni bližini avtocest sledili onesnaženju tal in vegetacije s težkimi kovinami, zlasti s svincem, cinkom in nikljem (*Rotar* 1994). Večina onesnaženja zaradi prometa v rednih razmerah ostaja na cestišču. Padavine ga spirajo in z lokalnih cest odteka razpršeno vzdolž njihovega poteka, z avtocest pa se voda zbira v obcestnih kanalih in odteka bolj ali manj točkovno.

Kakšen je vpliv določenega onesnaženja s površja na kraške izvire, nam pokažejo le ustrezne raziskave. V primerih onesnaževanja kraškega površja s snovmi, topnimi v vodi, ali takrat, ko onesnaženje odteče v reke ponikalnice, lahko samo na osnovi raziskav v preteklosti, predvsem na podlagi sledilnih poskusov in raziskav prenosa teh kontaminantov skozi karbonatne kamnine (*Kogovšek* 2010), sklepamo, kateri izviri bodo onesnaženi in kakšne hitrosti prenosa lahko pričakujemo. V vadozni coni se namreč kontaminanti lahko shranjujejo tudi za daljša obdobja. Poznavanje vrste onesnaženja in njegovih razgradnih produktov nam pove, kaj in katere parametre moramo spremljati v izvirih na vplivnem območju.

V primeru izlitij nevarnih snovi v železniških in cestnih nesrečah, pa tudi kanaliziranih odtokov z avtocest gre za velika točkovna onesnaženja. Čeprav razpolagamo z določenim znanjem o vrsti in količini onesnaženja, ki odteka z avtocest v rednih razmerah, še ne vemo, kakšno onesnaženje se spira z območja železniških prog.

Kako se onesnaženje širi s površja skozi kraški vodonosnik do kraških izvirov, je odvisno od ranljivosti vodonosnika, ki je podrobno opisana v poglavju

Owing to the permeability of fissured and soluble carbonate rocks in karst areas, above all limestone and dolomite, the vulnerability of the karst environment is considerable, and every form of pollution on its surface also means pollution of karst groundwater. Traffic is among the polluters on the karst surface that threatens the quality of karst water, not only in the case of road accidents involving the spillage of large quantities of hazardous and harmful substances, but also because of the pollution caused by regular traffic flows.

Researchers in Maribor established years ago that heavy traffic was a significant cause of air pollution (*Špes* 1993). Later, pollution of the soil and vegetation with heavy metals, notably lead, zinc and nickel, was identified in the direct vicinity of motorways (*Rotar* 1994). The majority of pollution due to traffic in normal conditions remains on the roadway. It is washed away by rainfall and drains from local roads as diffuse runoff along their length, while water from motorways collects in roadside channels and drains more or less as point source runoff.

The impact of a specific type of surface pollution on karst springs can only be shown by corresponding research. In cases of pollution by water-soluble substances on the karst surface or when pollution runs off into sinking streams, it is only on the basis of past research, in particular tracer tests and research into the transfer of these contaminants through carbonate rock (*Kogovšek* 2010), that we can conclude what springs will be polluted and what speed of transfer we can expect. Contaminants can, in fact, be stored in the vadose zone for considerable periods. Knowing the type of pollution and its degradation products tells us what parameters we have to monitor in springs inside the area of influence.

In the case of spillages of hazardous substances in railway and road accidents, and also channelled drainage from motorways, pollution is point source pollution. Although we have some knowledge of runoff pollution from motorways in normal conditions, we still do not possess information about the nature of runoff pollution from railway lines.

How pollution spreads from the surface through the karst aquifer to karst springs depends on its

»Značilnosti kraških vodonosnikov, njihova ranljivost in ogroženost« v tej knjigi. Raziskave pretakanja padavin skozi kraški vodonosnik so pokazale v sušnih obdobjih sorazmerno počasno pretakanje, saj se padavine v vadozni coni lahko le shranjujejo (*Kogovšek* 2010). V deževnih obdobjih, po izdatnejših padavinah, pa prihaja do hitrega pretakanja skozi celoten vodonosnik. S pretakanjem vode pa je povezan tudi prenos snovi.

V primeru onesnaženja na določenem kraškem površju torej lahko pričakujemo zelo različno hitrost prenosa onesnaženja globlje v kras. Pri tem imajo pomembno vlogo vsakokratne razmere: predhodna namočenost prsti, stopnja zapolnjenosti vadozne cone z vodo ter intenzivnost in izdatnost padavin (*Kogovšek* 2010). Pri počasnejšem pretakanju skozi vadozno cono lahko prihaja tudi do določene stopnje razgradnje biološko razgradljivih organskih snovi (*Kogovšek* 1987).

V preteklosti smo se vse premalo zavedali, da so tudi vode, ki odtekajo s cest, lahko dokaj onesnažene in da pri tem ne gre samo za odtok padavinske vode. Le ob gradnji avtoceste Ljubljana–Razdrto, dokončane leta 1972, so na odseku pri Postojni, ki poteka v zaledju zajetega kraškega izvira Malenščica, zgradili lovilnike olj (1). Ti naj bi onemogočili neposreden odtok različnih naftnih derivatov in olj, če bi prišlo do nesreče. In šele ob gradnji novejših cest v Sloveniji so na kraškem svetu zgradili zadrževalne in čistilne objekte, z namenom preprečiti odtok prve, najbolj onesnažene vode s cestišča po padavinah v kras.

4.1 Ugotavljanje sestave vode, ki odteka s cestišča

Na Inštitutu za raziskovanje krasa ZRC SAZU so v okviru raziskav vplivov onesnaženja na prenikajočo vodo potekale tudi raziskave vode, ki odteka z avtocest. Zajem vzorcev je potekal v lovilniku olj A pri Postojni (1), kamor se steka padavinska voda z nekako 2200 m dolgega odseka avtoceste Razdrto–Ljubljana (2, 3). Cesta se tu vzpenja, kar verjetno vpliva na višjo porabo goriva in večjo obrabo vozil ter posredno tudi na močnejše onesnaževanje.

Vsakokratna sestava vode, ki odteka s cestišča, je odvisna tudi od količine padavin, ki spirajo površino

vulnerability, which is described in detail in the chapter »Characteristics of karst aquifers, their vulnerability and endangerment«. Research into the flow of precipitation through the karst aquifer revealed a relatively slow flow during longer dry periods, particularly through the vadose zone, which at such times can simply store precipitation (*Kogovšek* 2010). In rainy periods, following abundant rainfall, rapid flow through the whole of the aquifer occurs. And to the flow of water the transport of pollution is tied, too.

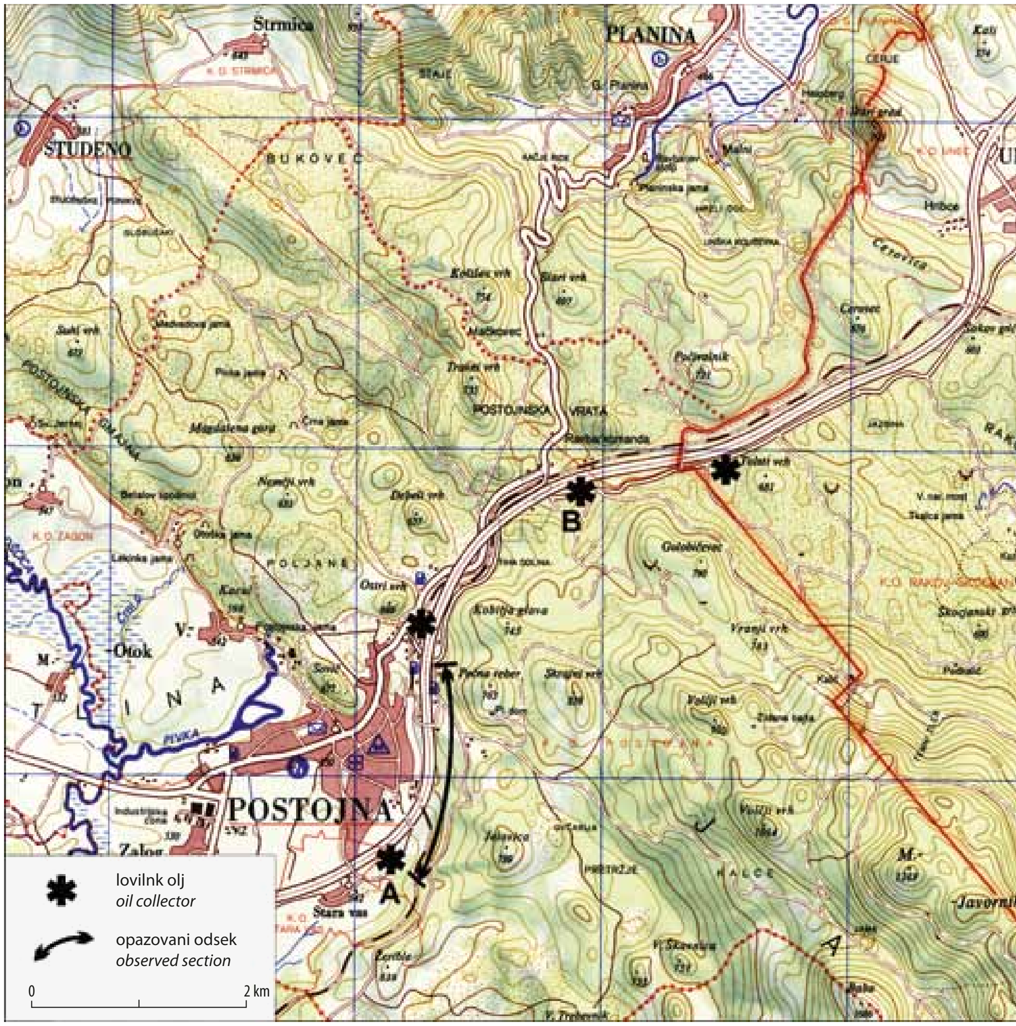
In the case of pollution on a specific karst surface, we can therefore expect the speed of transport of pollution deeper into the karst to vary considerably. An important role is played here by the conditions at the time: the wetness of the soil, the water level in the vadose zone, and the intensity and volume of rainfall (*Kogovšek* 2010). In the case of slower flow through the vadose zone, a certain amount of degradation of biodegradable organic substances also occurs (*Kogovšek* 1987).

In the past there was too little awareness that runoff from roads can be quite significantly polluted. Oil collectors were only built in the catchment area of karst springs after construction of the Ljubljana–Razdrto motorway in 1972, in the section near Postojna, which runs through the catchment area of the Malenščica karst spring (1). These are designed to prevent the direct drainage of spilt petroleum derivatives and oils in the case of accidents. It was not until the construction of newer roads in Slovenia that retention structures were also constructed for the purpose of preventing the direct discharge into the karst of the first (most polluted) runoff from roadways.

4.1 Identifying the composition of roadway runoff

In order to identify the composition of motorway runoff, research was carried out by the Karst Research Institute at the Scientific Research Centre of the Slovenian Academy of Sciences and Arts. Current samples were taken in the oil collector A near Postojna (1), into which rainwater flows from an approximately 2200 m long section of the Razdrto–Ljubljana motorway (2, 3). The road climbs at this point, which probably results in

1 Opazovani odsek avtoceste pri Postojni, kjer smo vzorčili vodo s cestišča.
Observed section of the motorway near Postojna where water was sampled.



2 Avtocesta na odseku pri Postojni poteka po kraškem svetu.
The motorway near Postojna crosses the karst area.

3 Lovilnik olj A pri Postojni, kjer se cesta vzpenja.
Oil collector A near Postojna where the road climbs.

ceste, kar pomeni manjše ali večje razredčevanje na cestišču akumuliranega onesnaženja. Zajetim vzorcem vode na dotoku v lovilnik (4) in na odtoku iz lovilnika neposredno v kras smo določali specifično električno prevodnost (EC), kalnost, kemijsko (KPK – dikromatna metoda) in biokemijsko (BPK_5) potrebo po kisiku ter vsebnosti olj in kloridov, kasneje pa tudi kadmija in svinca ter sulfatov, nitratov in o-fosfatov (6).

4.1.1 Občasne meritve in analize sestave vode, ki odteka s cestišča

Prve občasne analize in meritve leta 1992 (*Kogovšek* 1993) so pokazale na vrsto in velikost onesnaženja v odtekajoči vodi z avtoceste v najrazličnejših razmerah: ob prvem dežju po dolgotrajni suši, v času soljenja cest, med intenzivnimi nalivi in po njih.

Vzorec dotoka v lovilnik olj A (4), ki je bil zajet

increased fuel consumption and greater vehicle wear, and indirectly, more pollution.

The composition of runoff from the roadway also depends on the quantity of rainwater washing the surface of the roadway, which means greater or lesser dilution of pollution accumulated on the roadway. For samples of water taken at the oil collector inflow (4) and at the direct outflow into the karst, we determined specific electrical conductivity (EC), turbidity, chemical oxygen demand (COD – dichromate method) and biochemical oxygen demand (BOD_5), oils and chlorides content and, later, cadmium and lead content and sulfates, nitrates and orthophosphates (o-phosphates) content (6).

4.1.1 Periodic measurements and analyses of the composition of roadway runoff

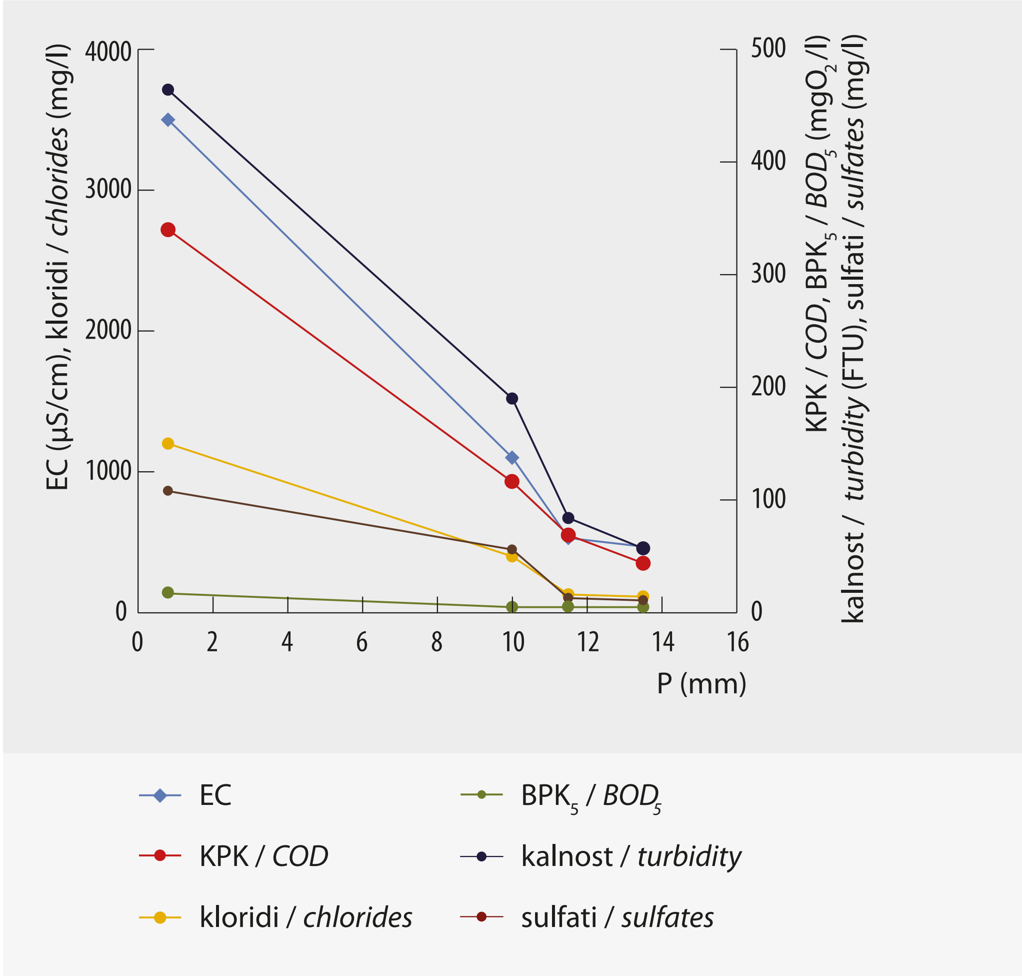
The first periodic analyses and measurements in 1992 (*Kogovšek* 1993) showed the type and scale of pollution in motorway runoff in a variety of conditions: first rain following a lengthy drought, during salting of the roads, during and after heavy precipitation events.

A sample of inflow into the oil collector A (4) taken on 17 March 1992, when salt was being applied to the

4 Dotočni jašek lovilnika olj A, kjer smo vzorčili dotočno vodo.
Inflow shaft of the oil collector A where the samples were taken.

5 Lovilnik olj B, kjer poteka avtocesta po ravnem terenu.
Oil collector B where the road runs over level terrain.

6 Merjeni parametri dotoka marca 1993 v odvisnosti od količine padavin.
Measured parameters of the inflow in March 1993 depending on the quantity of precipitation.



17. marca 1992 v času soljenja cestišča, je pokazal visoko EC (3850 µS/cm), visoko vsebnost kloridov (110 mg Cl^-/l), prisotnost olj (9 mg/l) in povišano KPK. Vzporedno zajet vzorec na lovilniku olj B v bližini odcepa regionalne ceste Postojna–Planina za Unec (5), kjer cesta poteka po ravnem terenu, je pokazal nižje vrednosti.

Naslednji vzorec v lovilniku olj A, 24. marca 1992, ni bil zajet ob začetnem spiranju cestišča, ko je voda najbolj onesnažena. Kljub temu je imel povišano kalnost ter visoki KPK in BPK_5, ob nižjih vsebnostih kloridov (34 mg Cl^-/l) in sulfatov, kar se je odrazilo v sorazmerno nizki EC. Nizka vsebnost kloridov in nizka EC govorita za to, da so predhodne padavine že dobro sprale cestišče po soljenju v zimski sezoni. Izračunano razmerje KPK/BPK_5 je bilo 17, kar kaže na velik delež težko razgradljivega onesnaženja v primerjavi z biološko razgradljivim onesnaženjem.

roadway, indicated a high EC (3850 µS/cm), a high chloride content (110 mg Cl^-/l), the presence of oils (9 mg/l) and increased COD. A sample taken simultaneously at the oil collector B near the branch of the regional road Postojna–Planina to Unec (5) where the road runs over level terrain showed lower values.

The next sample at the oil collector A, 24 March 1992, was not taken during initial runoff from the roadway, when the water is most polluted. Nevertheless, the sample showed increased turbidity and high COD and BOD_5, with a lower chloride (34 mg Cl^-/l) and sulfate content, which was reflected in a relatively low EC. The low chloride content and low EC indicate that previous rainfall had already thoroughly washed the roadway following salting during the winter season. The calculated COD/BOD_5 ratio was 17, which indicates a high proportion of non-degradable pollution in comparison with biodegradable pollution. The water

Voda, ki je tedaj odtekala iz odtočnega jaška lovilnika olj neposredno v kraško okolje, je imela znatno višjo EC in višjo koncentracijo kloridov, kar je posledica koncentriranja topnih komponent zaradi izhlapevanja, ter manjšo kalnost in KPK zaradi usedanja trdnih delcev v lovilniku.

Vzorec skromnega dotoka v času rosenja 1. junija 1992 je bil zajet po 20 dneh suhega vremena. Analize so pokazale sorazmerno majhno onesnaženost vode, razmerje KPK/BPK_5 pa je bilo le 6,4, kar kaže na manjši delež težje razgradljivega onesnaženja v primerjavi z vzorcem s konca marca. Odtočna voda iz lovilnika se ni bistveno razlikovala od sestave dotoka. Ob skromnem in neintenzivnem dežju očitno ne prihaja do učinkovitega spiranja cestišča, tako da onesnaženje ostaja tam.

Naslednji vzorec je bil zajet 12. junija 1992, potem ko je deževalo že več dni in je bil dotok v lovilnik v okviru vseh vzorčenj največji. Zato smo dobili najnižje vrednosti parametrov v času vseh meritev. Izjemi sta bila KPK, ki je dosegla 28 mg O_2/l, in razmerje KPK/BPK_5 z vrednostjo 12. Ob velikem dotoku in odtoku vode iz lovilnika se sestava odtoka skoraj ni razlikovala od sestave dotoka, kar pomeni, da ni prihajalo do usedanja trdnih delcev, verjetno pa je bil pred vzorčenjem že spran v lovilniku akumuliran sediment.

Vzorec, zajet 28. septembra 1992, ponovno po dolgi poletni suši z malo občasnih padavin, je dosegal večje vrednosti vseh parametrov v primerjavi z junijskim vzorcem. Določili smo povišane nitrate (10 mg NO_3^-/l) in sulfate (18 mg SO_4^{2-}/l) ter zvišano vsebnost svinca (0,22 mg/l) in kadmija (0,34 mg/l). V tem času je bil poleg osvinčenega v rabi tudi že neosvinčen bencin. Ob vzorčenju dotoka ni bilo odtoka vode iz lovilnika, kar si razlagamo z upadom gladine pod rob odtočnega jaška zaradi intenzivnega izhlapevanja v obdobju pred dežjem.

Naslednji vzorec 20. oktobra 1992 je bil zajet po izdatnih padavinah (170 mm), ko je bilo cestišče dobro sprano. Zato so vsi merjeni parametri dosegali nizke vrednosti, z izjemo nekoliko povišane vsebnosti kloridov in EC. Vsebnost svinca je bila le 0,062 mg/l in kadmija 0,02 mg/l. Odtočna voda se je prelivala minimalno in je imela v primerjavi z dotokom povečano vsebnost kloridov in svinca ter zvišano EC.

that then discharged from the oil collector directly into the karst environment had a significantly higher EC and a higher concentration of chlorides and lower turbidity and COD. This indicates a concentrating of soluble components as a result of evaporation and the effective sedimentation of solid particles in the oil collector.

A sample of modest inflow during drizzle on 1 June 1992 was taken following 20 days of dry weather. Analyses showed relatively low water pollution, while the COD/BOD_5 ratio was just 6.4, which indicates a smaller proportion of non-degradable pollution in comparison to the sample from the end of March. Outflow water from the oil collector did not differ significantly from the composition of the inflow. Clearly, small quantities of light rain do not lead to effective washing of the roadway, with the result that the majority of the pollution remains on the roadway.

The next sample was taken on 12 June 1992 after it had been raining for several days and inflow into the oil collector was the highest of all the samplings. As expected, we recorded the lowest values of the parameters in any of the measurements. The two exceptions were COD, which reached a value of 28 mg O_2/l, and the COD/BOD_5 ratio with a value of 12. With high inflow and outflow of water into and out of the oil collector, the composition of the outflow was practically identical to the composition of the inflow, which means that sedimentation of solid particles had not taken place, while the sediment accumulated in the oil collector had probably already been flushed away before the sampling process began.

A repeat sample taken following a long dry period with a small amount of occasional rainfall (28 September 1992) showed higher values for all parameters than the June sample. We identified increased nitrates (10 mg NO_3^-/l) and sulfates (18 mg SO_4^{2-}/l), increased lead (0.22 mg/l) and cadmium content (0.34 mg/l). In this period unleaded petrol was already being used alongside leaded petrol. At the time of the sampling of the inflow, there was no outflow of water from the oil collector, which can be explained by the fall in the water level below the edge of the drainage ditch as a result of intensive evaporation in the period before the rain.

The next sample (20 October 1992) was taken following abundant rainfall (170 mm), when the roadway

Dne 10. decembra 1992 je bilo suho vreme, vendar se je v lovilnik stekal staljen sneg. Po pričakovanju je imel vzorec visoko EC (12,7 mS/cm) in visoko vsebnost kloridov (4,2 g/l), kar je bila posledica soljenja cestišča. Podobno kot dotok je bil tudi odtok minimalen in se po sestavi skoraj ni razlikoval od dotoka.

Po enomesečnem sušnem obdobju je bil ponovno zajet vzorec na začetku skromnega dežja (12. januar 1993). Pri vseh parametrih so bile zabeležene največje vrednosti v okviru meritev. Kalnost je bila kar 290 FTU, EC 33 mS/cm in vsebnost kloridov 13,9 g/l ob visoki vsebnosti kalcija, kar verjetno odraža uporabo $CaCl_2$ za odmrzovanje cestišča. KPK je dosegla kar 2500 in BPK_5 84 mg O_2/l. Razmerje KPK/BPK_5 je bilo 30, najvišje v okviru vseh meritev, kar pomeni velik del težko razgradljivega organskega onesnaženja v primerjavi z biološko razgradljivim onesnaženjem. Vzorec je vseboval tudi 16 mg NO_3^-/l, 440 mg SO_4^{2-}/l, 0,016 mg/l kadmija in 1,1 mg /l svinca.

Iz navedenih meritev v danih razmerah vzorčenja je bilo ugotovljeno, da visoka EC dotoka z avtoceste sovpada predvsem z visoko koncentracijo kloridov zaradi soljenja cestišča pozimi, ki se začne lahko že oktobra in traja do aprila. Kalnost dotoka je večja po daljših sušnih obdobjih, ko pride do spiranja trdnih delcev, ki so se nabrali na cestišču. Večja kalnost sovpada z višjo KPK in BPK_5, kar kaže na to, da so izvor tega onesnaženja trdni delci na cestišču. Vrednosti KPK in BPK_5 so pogosto presegale vrednosti, določene za izpuste iz čistilnih naprav v vodotoke (KPK = 160 mg O_2/l in BPK_5 = 30 mg O_2/l), kjer pa prihaja še do razredčevanja.

Sestava vode, ki priteka s cestišča, se glede na padavinske razmere zelo spreminja. Intenzivnost padavin pomembno vpliva na spiranje, pa tudi na razredčevanje spranih kontaminantov, kar se odraža v njihovi različni koncentraciji. Najvišje vrednosti kontaminantov so bile izmerjene po daljših sušnih obdobjih ob začetnem spiranju cestišča z ne prevelikimi padavinami.

was thoroughly washed. As a result, all the measured parameters showed lower values, with the exception of a slightly increased chloride content and EC. Lead content was just 0.062 mg/l while cadmium content was 0.02 mg/l. Overflow of outflow water was minimal and in comparison to inflow the water had an increased chloride and lead content and increased EC.

On 10 December 1992 the weather was dry but snowmelt was flowing into the oil collector. As expected, the sample had a high EC (12.7 mS/cm) and a high chloride content (4.2 g/l), which was the consequence of salting the roadway. Like the inflow, the outflow was minimal, and its composition hardly differed from that of the inflow.

Following a one-month dry period, another sample was taken at the start of a period of slight rain (12 January 1993). The highest values at any point during the measurements were recorded for all parameters. Turbidity was 290 FTU, EC 33 mS/cm and chloride content 13.9 g/l with a high calcium content, which probably reflects the use of $CaCl_2$ to deice the roadway. COD reached 2500 and BOD_5 84 mg O_2/l. The COD/BOD_5 ratio was 30, the highest in any of the measurements, which means a large component of low degradable organic pollution in comparison to biodegradable pollution. The sample also contained 16 mg of NO_3^-/l, 440 mg of SO_4^{2-}/l, 0.016 mg/l of cadmium and 1.1 mg /l of lead.

It was established from the above measurements in the given conditions that a high EC of inflow from the motorway coincides above all with a high concentration of chlorides as a result of salting the roadway during the winter. The turbidity of the inflow is greater following long dry periods, when solid particles that have accumulated on the roadway during the dry period are washed off. Greater turbidity coincides with a higher COD and BOD_5, which indicates that the origin of this pollution are solid particles on the roadway. COD and BOD_5 values often exceeded the limit values determined for emission from waste water treatment plants into streams (COD = 160 mg O_2/l and BOD_5 = 30 mg O_2/l) where also dilution takes place.

The composition of the water that runs off the roadway changes greatly depending on rainfall conditions. The intensity of rainfall has a significant

4.1.2 Sestava dotoka in odtoka iz lovilnika olj v padavinskih dogodkih

Kako se spreminja sestava dotoka v odvisnosti od količine padavin oz. kolikšne padavine so potrebne, da se s cestišča spere večji del onesnaženja, je pokazalo zaporedno vzorčenje dotoka v lovilnik olj A ob naraščajočem ali upadajočem dotoku vode s cestišča, ki je bil posledica enkratnih, različno izdatnih in intenzivnih padavin. Sočasno spremljanje odtoka iz lovilnika olj pa je pokazalo, kakšna voda vsakokrat odteka neposredno v kras.

Za to spremljanje je bilo potrebno pogosto vzorčenje dotoka in odtoka v lovilnik, ki je potekalo ročno (*Kogovšek* 1995c). Količina dotoka je podana opisno, saj tedaj nismo imeli možnosti meritev pretoka. Vse analize in meritve so potekale z enakimi metodami kakor ob prvih opazovanjih v letih 1992 in 1993 ter na istem odseku avtoceste pri Postojni v lovilniku olj A pri Stari vasi. Meritve temperature in specifične električne prevodnosti (EC) so bile opravljene s konduktometrom LF 91 firme WTW, meritve kalnosti, vsebnosti svinca in kadmija s terenskim DR/2000 spektrofotometrom firme Hach (metode št. 750, 280 in 60), KPK in BPK_5 ter vsebnost kloridov, nitratov in sulfatov pa po standardnih metodah (*Standard Methods* …, 1992). V tabelah 1 in 2 so podane značilne vrednosti posameznih parametrov dotoka v lovilnik olj A (18 vzorcev).

Analize teh voda v letih 1993 in 1994 so pokazale (*Kogovšek* 1993, 1995c) v zimskem obdobju znatno višje vsebnosti kloridov, kar se je odrazilo v EC, ter višje vrednosti kalnosti in KPK (tabela 1) v primerjavi z meritvami v poletnem času (tabela 2), ko so bile opazno višje vrednosti svinca in kadmija, saj je bil tedaj v rabi še osvinčen bencin.

4.1.2.1 Vodni val 24. marca 1993

Po treh sorazmerno sušnih mesecih je začelo 24. marca 1993 ob 7.00 deževati, dež pa je čez dan ponehal in prešel v pršenje. Prvi vzorec je bil zajet ob 7.15, ko je padlo okrog 1 mm dežja. Izmerili smo zelo visoko kalnost (464 FTU), visoko KPK (340 mg O_2/l) in nižjo BPK_5, kar vse kaže na spiranje akumuliranega onesnaženja na cestišču v daljšem obdobju (7). Visoka

influence on the washing process, but also on the dilution of washed contaminants, which is reflected in a varying concentration of contaminants. The highest values of contaminants were measured following longer dry periods during the initial washing of the roadway with moderate rainfall.

4.1.2 Composition of inflow and outflow to/from the oil collector during rainfall events

Changes in the composition of the inflow depending on the quantity of rainfall, in other words how much rainfall is necessary for the bulk of the pollution to be washed from the roadway, were shown by the consecutive sampling of inflow into the oil collector A, as the result of one-off rainfall events of different quantities and intensities. Simultaneous monitoring of outflow from the oil collector showed what kind of water drains directly into the karst on each occasion.

This monitoring required frequent sampling of the oil collector inflow and outflow, which was done manually (*Kogovšek* 1995c). The quantity of the inflow was given descriptively, because at that time we did not have the possibility of measuring the discharge. All the analyses and measurements took place using the same methods as during the first observations in 1992 and 1993 and on the same section of the motorway near Postojna, in the oil collector A near Stara vas. Measurements of temperature and electrical conductivity (EC) were carried out using a WTW LF 91 conductivity meter. Turbidity and lead and cadmium content were measured using a Hach DR/2000 field spectrophotometer (methods No 750, 280 and 60). COD and BOD_5 and chloride, nitrate and sulfate content were measured using standard methods (*Standard Methods* …, 1992). Tables 1 and 2 show the typical values of individual parameters of inflow into the oil collector A (18 samples).

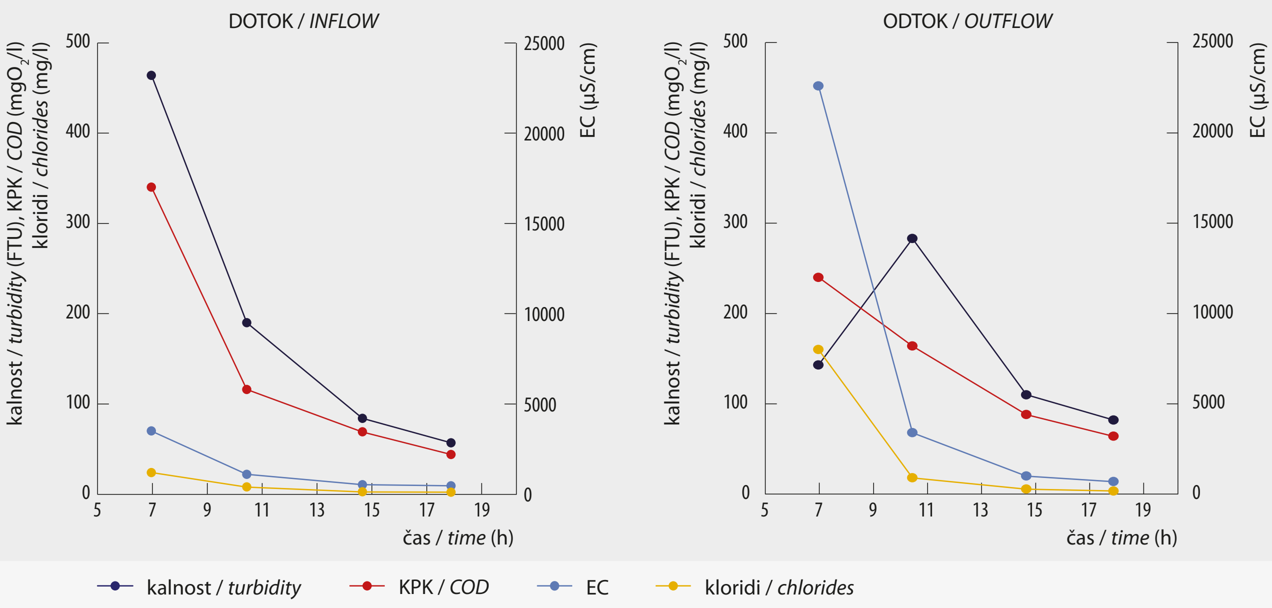
Analyses of runoff from the motorway in 1993 and 1994 have shown (*Kogovšek* 1993, 1995c) that in winter (table 1) this has a perceptibly higher concentration of chlorides, which is reflected at the same time in EC and increased turbidity and COD compared to the summer (table 2), when we identified above all

Parameter *Parameter*	T	EC	Kalnost *Turbidity*	KPK *COD*	BPK$_5$ *BOD$_5$*	Cl^-	SO_4^{2-}	Pb	Cd	NO_3^-
Enota / *Unit*	°C	µS/cm	FTU	mg O_2/l		mg/l		µg/l		mg/l
Maks. vrednost *Max. value*	9.2	7810	780	480	45	1980	158	1790	76	19
Min. vrednost *Min. value*	4.6	173	57	33	5	30	3	180	11	3
Povpr. vrednost *Average value*	6.7	1920	285	150	17	520	47	680	50	8

Tabela 1
Rezultati meritev dotoka v zimskem obdobju (T – temperatura, EC – specifična električna prevodnost, KPK – kemijska potreba po kisiku, BPK$_5$ – biokemijska potreba po kisiku, Cl^- – kloridi, SO_4^{2-} – sulfati, Pb – svinec, Cd – kadmij, NO_3^- – nitrati).
Table 1
Results of measurements of inflow in the winter period (T – temperature, EC – electrical conductivity, COD – chemical oxygen demand, BOD$_5$ – biochemical oxygen demand, Cl^- – chlorides, SO_4^{2-} – sulfates, Pb – lead, Cd – cadmium and NO_3^- – nitrates).

Parameter *Parameter*	T	EC	Kalnost *Turbidity*	KPK *COD*	BPK$_5$ *BOD$_5$*	Cl^-	SO_4^{2-}	Pb	Cd	NO_3^-
Enota / *Unit*	°C	µS/cm	FTU	mg O_2/l		mg/l		µg/l		mg/l
Maks. vrednost *Max. value*	11.7	216	93	274	70	35	39	11100	250	10
Min. vrednost *Min. value*	18.6	50	23	19	4	7	11	2280	65	2
Povpr. vrednost *Average value*	15.9	126	50	113	21	18	23	3750	167	5

Tabela 2
Rezultati meritev dotoka v poletnem obdobju (T – temperatura, EC – specifična električna prevodnost, KPK – kemijska potreba po kisiku, BPK$_5$ – biokemijska potreba po kisiku, Cl^- – kloridi, SO_4^{2-} – sulfati, Pb – svinec, Cd – kadmij, NO_3^- – nitrati).
Table 2
Results of measurements of inflow in the summer period (T – temperature, EC – electrical conductivity, COD – chemical oxygen demand, BOD$_5$ – biochemical oxygen demand, Cl^- – chlorides, SO_4^{2-} – sulfates, Pb – lead, Cd – cadmium and NO_3^- – nitrates).



7 Sestava dotoka in odtoka iz lovilnika olj v vodnem valu 24. marca 1993.
Composition of inflow to and outflow from the oil collector following a precipitation event on 24 March 1993.

vrednost EC (3500 µS/cm) je bila posledica predvsem visoke vsebnosti kloridov (1200 mg/l) zaradi predhodnega soljenja ceste, pa tudi višje vsebnosti sulfatov (108 mg/l). Sorazmerno visoka je bila tudi vsebnost svinca. Drugi vzorec, ki je bil zajet, ko je padlo 10 mm dežja, je izkazoval še vedno dokaj onesnaženo vodo z visoko kalnostjo, EC in vsebnostjo kloridov ter povišano KPK. Vendar pa so po nadaljnjem 1 mm padavin (tretji vzorec) vsi parametri izraziteje upadli. Pretok dotoka je ob zaporednem vzorčenju nekoliko upadal. Po sorazmerno dobrem spiranju cestišča s 13,5 mm dežja je pritekala v lovilnik (četrti vzorec) še nekoliko manj onesnažena voda s kalnostjo 57 FTU, vrednostjo KPK 44 mg O_2/l in vsebnostjo svinca 460 µg/l. Kloridov je bilo še 115 mg/l, EC pa je bila 470 mS/cm.

4.1.2.2 Vodna valova junija in julija 1993

Aprila in maja 1993 je padlo le 97 mm dežja. Dne 3. junija je deževalo in je skupno padlo dobrih 30 mm dežja, najintenzivneje na začetku, 15 mm. Prvo vzorčenje ob 8.30, ob največjem dotoku vode v lovilnik,

increased lead and cadmium content (leaded petrol was still in use at that time).

4.1.2.1 Water pulse of 24 March 1993

Following three relatively dry months, it began to rain at 7.00 a.m. on 24 March 1993, although over the course of the day the rain slackened and became drizzle. The first sample was taken at 7.15 a.m., when around 1 mm of rain had fallen. We measured extremely high turbidity (464 FTU), high COD (340 mg O_2/l) and lower BOD_5, all of which indicates the washing-off of pollution that had accumulated on the roadway over a longer period (7). The high EC value (3500 µS/cm) was above all the consequence of a high chloride content (1200 mg/l) as a result of earlier salting of the roadway, and also of a higher sulfate content (108 mg/l). Lead content was also relatively high. The second sample, taken after 10 mm of rain had fallen, showed lower values, although the turbidity, chlorides and EC values were still quite high and COD had increased. After a further 1 mm of rain had fallen (third sample), however, all the parameters fell more signifije pokazalo sorazmerno nizki vrednosti EC in kloridov, ker je bila sol s cestišča po zimskem soljenju že sprana. Vendar pa smo izmerili visoko BPK_5 (70 mg O_2/l), sorazmerno visoko KPK (220 mg O_2/l) ter visoki vsebnosti svinca in kadmija. Pri naslednjem vzorčenju, ob manjšem dotoku vode, so bile vrednosti vseh merjenih parametrov manjše, z izjemo svinca. Na podlagi izmerjenih vrednosti in količine padavin, ki so padle na opazovani odsek ceste med prvim intenzivnim dežjem (15 mm), ter ob oceni evaporacije na nekako 30 % smo ocenili, da je priteklo v lovilnik blizu 250 m^3 vode. Ta je sprala s cestišča več kot pol kg svinca in 10-krat manj kadmija. Organsko onesnaženje je bilo enako 35 kg O_2 (KPK), biološko razgradljiv del (BPK_5) pa 14 kg O_2. To je le ocena odteklega onesnaženja, saj bi za popolnejši izračun potrebovali bolj podrobna opazovanja, še zlasti pa meritve pretoka. Izbrani val je bil v poletnem času, ko smo na splošno beležili manjše onesnaženje kakor pozimi.

V drugi in tretji dekadi junija je padlo še 115 mm dežja. Dne 6. julija je pol ure močno, nato pa zmerneje deževalo. Skupno je padlo 37 mm padavin. Ob prvem vzorčenju je bil dotok vode v lovilnik približno enak kakor na začetku junijskega vodnega vala, vrednosti merjenih parametrov pa so bile le nekoliko višje. Izjema je bil svinec, kjer je bila zabeležena maksimalna vrednost (tabela 2) v okviru vseh dotedanjih meritev (11,1 mg/l). Pri drugem vzorčenju, ob močno povečanem dotoku, smo pri vseh parametrih zabeležili znižanje na polovične vrednosti, vsebnosti svinca pa na petino. Ob tretjem zajemu je bil dotok že tolikšen, da je zaradi omejenega odtoka iz lovilnika prišlo do zastajanja oz. naraščanja nivoja vode v njem. Ta val je pokazal, kako močan je lahko dotok vode s cestišča ob intenzivnem dežju. Intenzivnost in izdatnost padavinskih dogodkov na nekem območju narekujeta velikost zadrževalnih objektov oz. dolžino cestnega odseka, s katerega priteka meteorna voda v lovilnik.

4.1.2.3 Vodni val 29. septembra 1993

Septembra 1993 je padlo kar 330 mm dežja, od tega 47 mm dva dni pred opazovanim valom. Cestišče je bilo dobro sprano in pričakovali smo, da bo z njega pritekala v lovilnik dokaj čista voda. Vendar pa je EC dosegala 158

cantly. Following the relatively thorough washing of the roadway with 13.5 mm of rain, slightly less polluted water flowed into the oil collector (fourth sample), with a turbidity of 57 FTU, COD of 44 mg O_2/l and a lead content of 460 μg/l. The chlorides value was still 115 mg/l and EC was 470 μS/cm.

4.1.2.2 Water pulses in June and July 1993

In April and May 1993 rainfall was just 97 mm. It rained on 3 June (a total of 30 mm of rain over the course of the day), most intensively at the beginning, when 15 mm fell. The first samples, taken at 8.30 a.m. when the inflow of water to the oil collector was highest, showed relatively low EC and chlorides values because the salt had already been washed from the roadway following the winter salting. We did, however, measure a high BOD_5 (70 mg O_2/l), relatively high COD (220 mg O_2/l), and a higher lead and cadmium content. With the next sampling, when the inflow of water was smaller, the values of all the measured parameters were lower, with the exception of lead. On the basis of the measured values and quantities of precipitation that fell on the observed section of the road at the time of the first heavy rainfall (15 mm), and with an estimate of evaporation (30 %), we estimated that approximately 250 m^3 of water had flowed into the oil collector. This washed over half a kg of lead from the roadway and a 10 times smaller quantity of cadmium. Organic pollution was equivalent to 35 kg O_2 (COD), and the biodegradable portion (BOD_5) to 14 kg O_2. This is only an estimate of runoff pollution, since for a more complete calculation we would need more detailed observations and, above all, measurements of the flow. The selected pulse took place during the summer, when in general we recorded less pollution than in the winter.

In the second and third 10-day periods in June a further 115 mm of rain fell. On 6 July it rained heavily for half an hour and then more moderately. A total of 37 mm of rain fell. At the first sampling, the inflow of water into the oil collector was roughly the same as at the beginning of the June water pulse, while the values of the measured parameters were only slightly µS/cm, kalnost 64 FTU, sulfati 24 mg/l, KPK 44 mg O_2/l in BPK_5 7,3 mg O_2/l. Po dveh urah in pol je bil pretok kar nekajkrat večji, vrednosti merjenih parametrov pa do trikrat nižje. Ta vodni val je ponovno pokazal, da kljub poprejšnjemu daljšemu in dobremu spiranju s cestišča ne odteka čista meteorna voda in da je določeno onesnaženje posledica stalnega prometa.

4.1.3 Sestava vode, ki iz lovilnika olj odteka v kras

Vzporedno opazovanje sestave dotoka in odtoka iz lovilnika neposredno v kras je v razmerah umirjenega manjšega dotoka in s tem povezanega učinkovitega usedanja trdnih nečistoč v lovilniku pokazalo na boljšo kakovost odtoka (meritve KPK) v primerjavi z dotokom. Medtem pa so se topne komponente v lovilniku zaradi izhlapevanja močno koncentrirale, predvsem kloridi v zimskem obdobju. Tako je imel odtok iz lovilnika olj neposredno v kraško okolje v primerjavi s sestavo dotoka do 7-krat povečane vrednosti EC in vsebnosti kloridov ter do 2-krat povečane koncentracije sulfatov.

Vendar pa se je v lovilniku usedlo onesnaženje že med prvim večjim intenzivnim nalivom ob velikem dotoku vode dobro premešalo in kot suspenzija odteklo v kras. Tedaj so bile v odtoku v primerjavi z dotokom povečane vrednosti skoraj vseh parametrov, predvsem pa kalnost, KPK, vsebnosti kloridov, sulfatov in svinca. Tako se je zgodilo po dežju 24. marca 1993, kar je razvidno iz slike 7. Vsi parametri so dosegali višje vrednosti na odtoku iz lovilnika olj v primerjavi z dotokom, le ob prvem vzorčenju sta bili kalnost in KPK višji na dotoku, ker še ni prišlo do premešanja usedline v lovilniku in njenega odtoka.

Lovilnik olj je imel torej tudi vlogo usedalnika, kjer so se ob nizkih dotokih usedali trdni delci, za katere smo ugotovili, da so nosilci organskega onesnaženja in kovin. Odstranjevanje sedimenta pred večjimi deževnimi dogodki prepreči njegov odtok v kras, kar je še zlasti pomembno v zaledju zajetih kraških izvirov.

higher. The exception was lead, where the highest value (table 2) in any of the measurements was recorded (11.1 mg/l). In the second sampling, with a significant increase in flow, we recorded values that were half as high as in the first sampling for all parameters, with the exception of lead, where the value was a fifth of the starting value. At the time of the third sampling, the inflow was already so high that, as a result of the limited outflow from the oil collector, stagnation or an increase in the water level in the oil collector was taking place. This pulse showed how powerful the inflow of water from the roadway can be when rainfall is heavy. The intensity and volume of rainfall events in a given area dictate the size of the retention ponds or the length of the road section from which precipitation flows into the collector.

4.1.2.3 Water pulse of 29 September 1993

September 1993 saw rainfall of 330 mm, of which 47 mm fell two days before the observed pulse. The roadway was thoroughly washed and we anticipated a relatively clean inflow of water into the collector. Instead, EC reached 158 µS/cm, turbidity 64 FTU, sulfate content 24 mg/l, COD 44 mg O_2/l and BOD_5 7.3 mg O_2/l. After two and a half hours the inflow was several times greater, and the values of the measured parameters were up to three times lower. This water pulse once again showed that despite earlier extended and thorough washing, roadway runoff is not clean, and that a certain amount of pollution is the consequence of constant traffic.

4.1.3. Composition of water draining from the oil collector into the karst

The parallel observation of the composition of inflow and outflow from the oil collector directly into the karst revealed, in conditions of lower inflow and the related efficient sedimentation of solid particles in the oil collector, a better quality of outflow (COD measurements) in comparison to inflow. Meanwhile soluble components, particularly chlorides in the winter pe-

4.2 Učinkovitost čistilnih in zadrževalnih objektov ob novozgrajenih avtocestah

Na podlagi v letih 1997 in 1998 opravljenih meritev dotoka v usedalnik na odseku avtoceste Čebulovica–Sežana pri divaškem pokopališču je bilo potrjeno, da intenzivnost in količina padavin vplivata na koncentracije kontaminantov v vodi (*Pintar* idr. 1998). Kot najpomembnejši so se ponovno pokazali svinec, celokupni organski ogljik (TOC) in suspendirane snovi, na katere je vezana večina kovin. Vendar pa so izmerjene vrednosti le občasno presegale tedaj veljavno dovoljeno mejo (MDK) za odvajanje odpadnih voda iz virov onesnaženja po *Uredbi o emisiji snovi pri odvajanju odpadnih vod iz virov onesnaženja* (*UrES*, 1996).

Kasneje so potekale pogoste meritve (na 20 minut) sestave dotoka in odtoka na istem usedalniku v deževnem dogodku 4. in 5. oktobra 2001 (*Kompare* idr. 2002). Ugotovljeno je bilo, da niti dotok niti odtok z objekta nista presegala mejnih dovoljenih koncentracij (MDK). Vendar pa za učinkovito zaščito okolja ne zadošča le normativ MDK, ampak je pomembna količina snovi, ki odteka v kras. V kraški vadozni coni lahko prihaja do daljšega zadrževanja vode in z njo kontaminantov (*Kogovšek* 2010), kar pa pomeni akumulacijo in le občasno spiranje (po dovolj izdatnih padavinah) naprej skozi kraške vodonosnike do kraških izvirov.

4.3 Ugotavljanje ogroženosti zajetega kraškega vira

V primerih, kot je zajeti izvir Malenščice, pri katerem avtocesta poteka le dobra 2 km stran v njegovem zaledju, je treba podrobneje preučiti, kam odteka onesnažena voda z avtoceste. Da bi ugotovili vodne povezave, smo izvedli sledilni poskus, ko smo v odtok lovilnika olj B (8) injicirali fluorescentno sledilo (*Gabrovšek* idr. 2010). Po desetih dneh brez dežja smo ga najprej zasledili v Unici (slika 2 v poglavju 5). Ob povečanju pretokov po intenzivnem in izdatnem dežju je prišlo do izrazitejšega pojava sledila v izviru Unice (9) in čez dva dni tudi v izviru Malenščice (10). Podrobneje je to sledenje predstavljeno v poglavju

riod, are highly concentrated as a result of evaporation. Outflow from the oil collector directly into the karst environment thus had EC and chloride content values that were up to seven times higher than inflow, and up to two times higher concentrations of sulfates.

At the first major downpour, however, with a high inflow of water, the pollution that had settled in the oil collector was thoroughly mixed up and discharged into the karst as a suspension. At that point the values of almost all the parameters, in particular turbidity, COD, chlorides, sulfates and lead, were higher in the outflow than in the inflow. This occurred following rainfall on 24 March 1993, as can be seen from figure 7. Only in the first sampling turbidity and COD were lower, since at that time the mixing and outflow of the sediment in the oil collector had not yet taken place.

The oil collector also played the role of a sedimentation tank, where at times of low inflow there was sedimentation of solid particles which we identified as carriers of organic pollution and metals. Removal of sediment before major rainfall events prevents its discharge into the karst, which is particularly important in the catchment area of karst springs used to supply water.

4.2 Efficiency of retention structures along newly constructed motorways

It was established, on the basis of measurements of inflow into the retention pond on the Čebulovica–Sežana motorway section taken in 1997 and 1998, that the intensity and quantity of rainfall affect concentrations of contaminants in water (*Pintar* et al. 1998). Once again the most important pollutants proved to be lead, total organic carbon (TOC) and suspended substances to which the majority of metals are bound. However, the measured values only occasionally exceeded the maximum allowable concentration (MAC) values valid at that time for the discharge of waste water from sources of pollution (*Decree on the emision of substances and heat in the discharge of waste water from pollution sources – UrES,* 1996).

Later, frequent measurements were taken (every 20 minutes) of the composition of inflow and outflow

8 Injiciranje fluorescentnega sledila v odtočni jašek lovilnika olj B.
Injecting fluorescent tracer into the outflow shaft of the oil collector B.

9 Sledilni poskus z injiciranjem v lovilnik olj B je pokazal povezavo s kraškim izvirom Unice.
Tracer test using injection into the oil collector B proved connection with the Unica karst spring.

»Izlitja nevarnih snovi ogrožajo kraške vode« v tej knjigi. Ocenjujemo, da odteka voda z avtoceste predvsem v Unico, a z določenim časovnim zamikom in manj izrazito tudi v Malenščico.

Kovine, ki smo jih določali v odtoku s cestišča avtoceste, so navzoče tudi v sedimentu izvira, vendar pa je možen vnos teh kovin tudi iz drugih virov onesnaževanja. V *Uredbi o emisiji snovi pri odvajanju padavinske vode z javnih cest* (*UrES*, 2005a) je navedeno, da je treba z javnih cest, ki prečkajo kraške vodonosnike in na katerih je povprečje vozil večje od 6000 na dan, zajeti padavinske odpadne vode v zadrževalniku ločeno od zalednih voda. V primeru, ko cesta prečka vodovarstveno območje, je treba zagotoviti zajetje in čiščenje, če tako določa predpis s po-

10 Sledilni poskus v lovilniku olj B je pokazal tudi povezavo s kraškim izvirom Malenščicice, zajetim za vodooskrbo.

The tracer test from the oil collector B proved also connection with the Malenščica karst spring captured for the water supply.

in the same retention pond during the rainfall event of 4 and 5 October 2001 (*Kompare* et al. 2002). It was established that neither inflow to the retention pond nor outflow from it exceeded MAC values. MAC norms are not, however, sufficient for the effective protection of the environment. It is the quantity of substances draining into the karst that is important. Water, and with it contaminants, can be retained for a long time in the karst vadose zone (*Kogovšek* 2010), which means accumulation and only occasional onward flushing (following sufficiently abundant rainfall) through karst aquifers to karst springs.

4.3 Identifying threats to a water source

In cases such as the spring of the Malenščica, where the motorway runs through its immediate catchment area, just over 2 km from the spring, it is necessary to study in detail where polluted water from the motorway drains to. In order to establish hydrological connections, we carried out a tracer test, injecting fluorescent tracer into the outflow of the oil collector B (8) (*Gabrovšek* et al. 2010). After ten days without rain, the first traces of tracer appeared in the Unica river (figure 2 in chapter 5). With the increase in rates of flow following heavy and abundant rainfall, there was a clearer appearance of tracer in the spring of the river Unica (9) and, two days later, in the spring of the river Malenščica (10). This tracer test is presented in more detail in the chapter from this book entitled »Spillages of hazardous substances endanger karst waters«. We estimate that water drains from the motorway into the Unica river and, with a certain delay and less distinctly, into the Malenščica river.

The metals which we identified in motorway runoff are also present in the sediment of the spring, although it is possible that these metals come from other sources of pollution. *The Decree on the emission of substances in rainwater runoff from public roads* (*UrES*, 2005a) states that rainwater runoff from public roads that cross karst aquifers and have an average daily traffic of more than 6000 vehicles per day must be collected in a retention structure separately from catchment area waters. In the case of the road crossing a water protecdročja urejanja voda, ki ureja vodovarstveni režim za to območje. Posredno odvajanje v podzemne vode naj bi potekalo skozi vsaj meter debelo plast sedimentov. Ker pa so razmere na kraškem svetu zelo heterogene in predpisi precej ohlapni, je njihova učinkovitost zato vprašljiva.

Sklep

Iz naštetih podrobnejših raziskav meteorne vode, ki odteka z avtocestnega odseka Ljubljana–Razdrto pri Postojni, izhaja, da ima ta v zimskem obdobju opazno povišane koncentracije kloridov in sulfatov, kar se vzporedno odraža tudi v EC ter povišani kalnosti in KPK, v primerjavi s poletnim časom, ko smo ugotavljali predvsem povišani vsebnosti svinca in kadmija. Ob zadostni količini padavin v posameznem nalivu se cestišče postopno spira, kar se kaže v vse boljši kakovosti zaporednih vzorcev. To pomeni, da največja količina onesnaženja odteka ob začetnem spiranju (okrog 10 mm padavin), pri čemer je pomembna tudi intenzivnost padavin. Vendar pa vrednosti parametrov tudi po močnem spiranju cestišča po izdatnih in intenzivnih padavinah ne padejo pod neko določeno mejo, česar tudi ni moč pričakovati, saj stalni promet pomeni nenehno onesnaževanje. Na podlagi izmerjenih koncentracij kontaminantov in ocenjene količine vode so nekateri kontaminanti presegali tedaj določene mejne vrednosti. Tudi po novi uredbi o emisiji snovi pri odvajanju padavinske vode z javnih cest (*UrES*, 2005a) bi kadmij kot zelo nevarna snov občasno presegal mejno vrednost, svinec pa ni več sestavni del uredbe, saj je zdaj v rabi neosvinčen bencin. Odtok iz lovilnika neposredno v kras je bil ob majhnih dotokih v lovilnik običajno boljše kakovosti kakor dotok, ob velikih dotokih pa znatno slabše kakovosti, saj se je spirala tudi v lovilniku akumulirana usedlina, na katero so vezane večina organskega onesnaženja in kovine. To pa narekuje predvsem redno vzdrževanje tovrstnih objektov.

Prve analize meteornih voda z avtoceste Ljubljana–Razdrto in poznejše sistematične meritve v času padavinskih dogodkov (*Kogovšek* 1993, 1995c) so pokazale, da je voda s cestišča občasno zelo onesnažena. To spoznanje je vplivalo na postavitev zadrževalnikov

tion area, capture and treatment must be ensured if so provided by the waters regulation governing the water protection regime for this area. In the case of indirect discharge into groundwater, this should take place through a layer of sediments at least one metre thick. Conditions in the karst area are extremely heterogeneous and the regulations extremely lax, and therefore their effectiveness is questionable.

Conclusion

It follows from the above detailed research into rainwater runoff from the Ljubljana–Razdrto motorway section near Postojna that runoff has noticeably higher concentrations of chlorides and sulfates in winter, something that is reflected at the same time in EC and increased turbidity and COD in comparison to the summer, when above all increased lead and cadmium content was identified. With a sufficient quantity of precipitation in a single precipitation event, the roadway is gradually washed. This is reflected in the increasing quality of successive samples. This means that the largest quantity of pollution runs off during the initial washing (around 10 mm of rainfall), where the intensity of rainfall is also significant. However, even after a thorough washing of the roadway following abundant and heavy rainfall, the values of the parameters do not fall below a certain level. This is not to be expected, given that constant traffic means continuous pollution. On the basis of the measured concentrations of contaminants and the estimated quantities of water, some contaminants exceeded the maximum allowable concentration defined in the above mentioned Decree from 1996. Even under the new *Decree on the emission of substances in rainwater runoff from public roads* (*UrES,* 2005a), cadmium, as a highly dangerous substance, would occasionally exceed the limit value, while lead is no longer a constituent part of the Decree, because unleaded petrol is now used. Outflow from the oil collector directly into the karst was occasionally—when inflow into the oil collector was low—of better quality than inflow, while when inflows were high it was of considerably worse quality, because the sediment accumulated in the collector, to which the majority in čistilnih objektov ob nadaljnji gradnji avtocest v Sloveniji. Sistematične analize so bile narejene tudi na novih objektih (*Pintar* idr. 1998; *Kompare* idr. 2002). Iz vseh opravljenih meritev je razvidno, da je obremenjenost posameznih odsekov avtocest lahko različna (število in vrsta vozil, vožnja po klancu navzgor oz. navzdol) ter da pravo sliko lahko podajo samo pogoste in sistematične meritve na različno obremenjenih odsekih.

Glede na današnje poznavanje pretakanja in prenosa kontaminantov skozi kraško vadozno cono (*Kogovšek* 2010), ki se v njej lahko akumulirajo tudi za daljši čas, njihove koncentracije niso zadostno merilo onesnaženja, ki s cestišča avtocest odteka v okolje. Na kraškem svetu bi bilo treba upoštevati tudi količino vnosa posameznih kontaminantov v določenem časovnem obdobju, še posebej, če so odtoki takih voda v neposrednem zaledju zajetih kraških izvirov za pitno vodo, kot na primer izvira Malenščice.

Vsa omenjena spoznanja narekujejo, da se za izpuste voda z avtocest, ki potekajo v zaledju zajetih kraških izvirov, s fluorescentnimi sledili ugotovi njihov dejanski vpliv na izvire. V kolikor se vodna povezava potrdi in ugotovijo velike hitrosti pretakanja, je treba urediti učinkovito čiščenje teh voda pred izpustom v kraško okolje. Vendar pa bi bilo v primerih točkovnih izpustov onesnaženih voda z avtocest neposredno v kras smiselno predpisati sprejemljive mejne dopustne vrednosti glede na značilnosti območja (kam in kako te vode odtekajo), saj sta tako kontrola in ukrepanje lažje izvedljiva. Osnova mora biti poznavanje značilnosti pretakanja in prenosa posameznih kontaminantov skozi vadozno cono in naprej skozi vodonosnik do kraških izvirov, ki pa ga je treba nenehno dopolnjevati z novimi spoznanji.

of organic pollution and metals are bound, is also washed out. For this reason, such collectors need to be maintained regularly.

It is evident from the first analyses of rainfall runoff from the Ljubljana–Razdrto motorway (*Kogovšek* 1993, 1995c) and later analyses at treatment ponds along newly constructed motorways in Slovenia (*Pintar* et al. 1998; *Kompare* et al. 2002) that the loading of individual motorway sections (number and type of vehicles, upwards or downwards gradient) can vary, and that only frequent and systematic measurements on sections with varying loading can give a true picture.

In view of today's knowledge of the flow and transport of contaminants through the vadose zone of the karst (*Kogovšek* 2010), where they can accumulate for longer periods, concentrations of contaminants are not a sufficient criterion for the pollution that runs off motorways into the environment. In the karst region it would also be necessary to take into account the quantity of individual contaminants in a specific period, particularly if outflows of such waters are in the direct catchment area of karst springs that are used to supply drinking water, as is the case of the Malenščica spring.

All the above findings dictate that for runoff from motorways in the catchment areas of karst springs, the actual impact on springs should be ascertained via tracing. If a hydrological connection is confirmed and high rates of flow are ascertained, the effective treatment of these waters before discharge into the karst environment needs to be organized. It would be a good idea to prescribe acceptable limit values with regard to the characteristics of the area, since this would make it easier to carry out checks and take action. The basis has to be a knowledge of the characteristics of flow and the transport of contaminants through the aquifer to karst springs, which needs to be constantly supplemented by new findings with regard to both flow characteristics and the transport of individual contaminants.

5

IZLITJA NEVARNIH SNOVI OGROŽAJO KRAŠKE VODE

SPILLAGES OF HAZARDOUS SUBSTANCES ENDANGER KARST WATERS

JANJA KOGOVŠEK, METKA PETRIČ

Na kraškem svetu se zaradi velike prepustnosti in topnosti karbonatnih kamnin vsakršno onesnaževanje na površju odrazi v kakovosti kraških podzemnih voda. Med celo vrsto onesnaževalcev so promet, skladišča naftnih derivatov, industrija in druge dejavnosti, kjer lahko pride do nesreč ter do razlitja nevarnih in škodljivih snovi. V zadnjih desetletjih smo večkrat spremljali posledice prometnih nesreč, najpogosteje je šlo za razlitja naftnih derivatov (*Kogovšek* 1996a; *Kogovšek* in *Petrič* 2002a). V nekaterih primerih so bila vzrok za onesnaženje kraških voda tudi iztekanja iz skladišč naftnih derivatov.

Ob tovrstnih nesrečah nas še zlasti zanima, ali bodo onesnaženi viri, ki so zajeti za oskrbo prebivalstva s pitno vodo. Za to oceno je potrebno dobro predhodno poznavanje smeri in značilnosti podzemnega pretakanja vode z obravnavanega območja.

Spremljanje razmer po izlitju in analize posledic so pripomogli k postopno vse boljšemu razumevanju pretakanja v vodi netopnih snovi. Sledilni poskusi s tako nevarnimi snovmi niso ekološko sprejemljivi, do zdaj pa tudi še ni bila opravljena načrtna primerjalna raziskava pretakanja v vodi topne in v vodi netopne snovi. Razlike v načinu pretakanja bi lahko ugotovili z izvedbo sledilnega poskusa s topnim sledilom neposredno ob nesreči z izlitjem naftnih derivatov, kar bi pomembno prispevalo k boljšemu razumevanju širjenja naftnih derivatov in drugih tekočin, ki se z vodo ne mešajo, skozi kraške vodonosnike.

5.1 Nesreče v zaledju zajetega izvira Malenščica

Izvir Malenščica je zajet za vodooskrbo območja Postojne in Pivke. V njegovem zaledju se je pred več kot 40 leti v vrtačo na Ravbarkomandi pri Postojni (1) prevrnila cisterna s 25.000 litri jedilnega olja. Po nekaj urah je bila na dnu vrtače le velika lisa rumenega snega. Ugotovljena je bila 8 m debela plast z oljem prepojene ilovice (*Habič* 1988). Ta in podobne nesreče so že tedaj pokazale, da razlite tekočine, tudi če niso topne v vodi, odtečejo s kraškega površja hitro, še preden je možna učinkovita intervencija.

Maja 1984 je prišlo do večjega primanjkljaja nafte

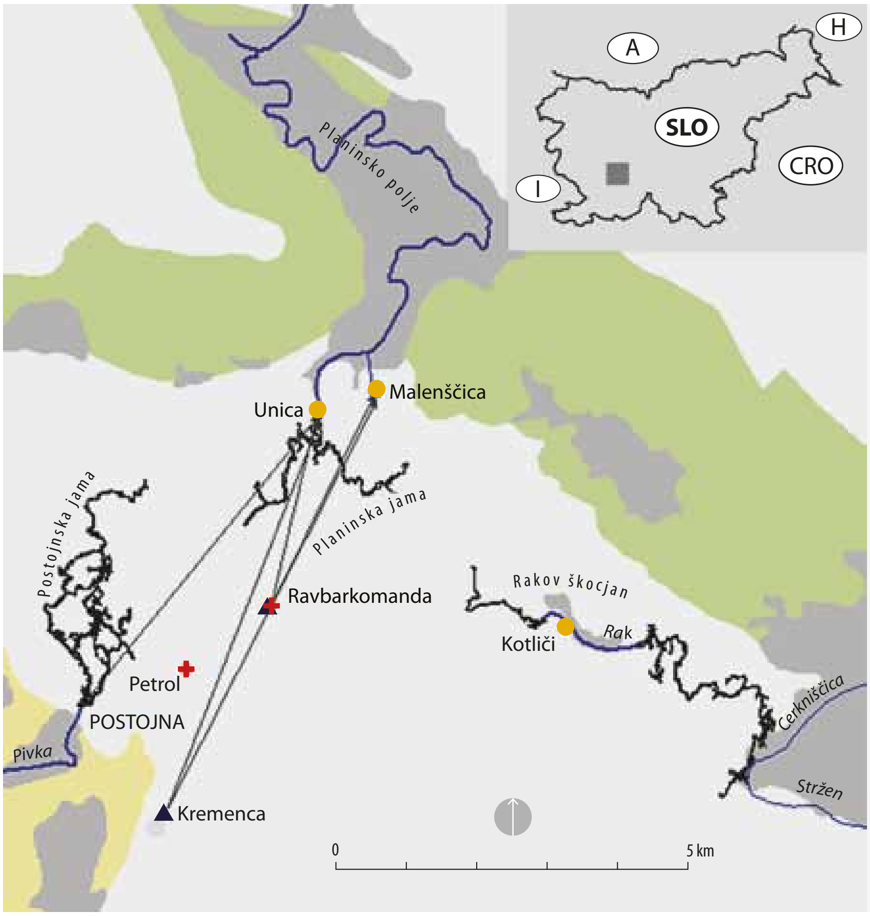
Any kind of pollution on karst surface has an effect on groundwater quality due to high permeability and solubility of carbonate rock. Traffic, oil reservoirs, industry and other activities are some of the pollution sources which can result in accidents involving the spillage of hazardous and harmful substances. In recent decades we have on several occasions monitored the consequences of traffic accident spillages, most frequently of petroleum products (*Kogovšek* 1996a; *Kogovšek* and *Petrič* 2002a). Accidents in petroleum products storages have likewise been the cause of pollution of karst waters.

In cases of these accidents we are particularly interested in whether springs that are used for drinking water supply are going to be polluted. It is only on the basis of past research of the directions and characteristics of groundwater flow from this area that we can make this assessment.

Analyses of accidents involving spillages and monitoring of the consequences have contributed to a gradually improving understanding of the flow of substances insoluble in water, since tracer tests using such hazardous substances are not environmentally acceptable. No comparison study of the flow of substances soluble and insoluble in water has been carried out recently. By means of the proposed tracer test using soluble tracer directly after an accident involving the spillage of petroleum products, we could establish differences in the mode of the flow which would represent a significant contribution to the better understanding of the spread of petroleum products through karst aquifers.

5.1 Accidents in the catchment area of the Malenščica water source

The Malenščica karst spring is used for the water supply of the municipalities of Postojna and Pivka. Over 40 years ago a tanker carrying 25,000 litres of table oil overturned into a sinkhole at Ravbarkomanda near Postojna (1). After several hours only a large spot of yellow snow remained at its bottom. The thickness of the soil soaked with oil was 8 m (*Habič* 1988). This and similar



1 S širšega območja Postojne podzemne vode odtekajo proti izvirom na Planinskem polju.
The groundwater flow from the Postojna area is directed towards the springs at Planinsko polje.

v Petrolovem skladišču pri Postojni (1). Domnevno je odtekla v kraško podzemlje. Zaradi že znane vodne povezave bližnjega požiralnika pod Kremenco z izviroma Unice in Malenščice na Planinskem polju (*Gams* 1965) je bil verjeten pojav nafte v obeh izvirih. Občinski štab za civilno zaščito je organiziral daljše opazovanje teh voda. Na veliko srečo se nafta ni pojavila na opazovanih točkah, kar je sprožilo domnevo, da ni odtekla v kras. Tedaj je bilo to eno prvih resnih opozoril, kakšno grožnjo lahko pomenijo skladišča naftnih derivatov na kraškem svetu.

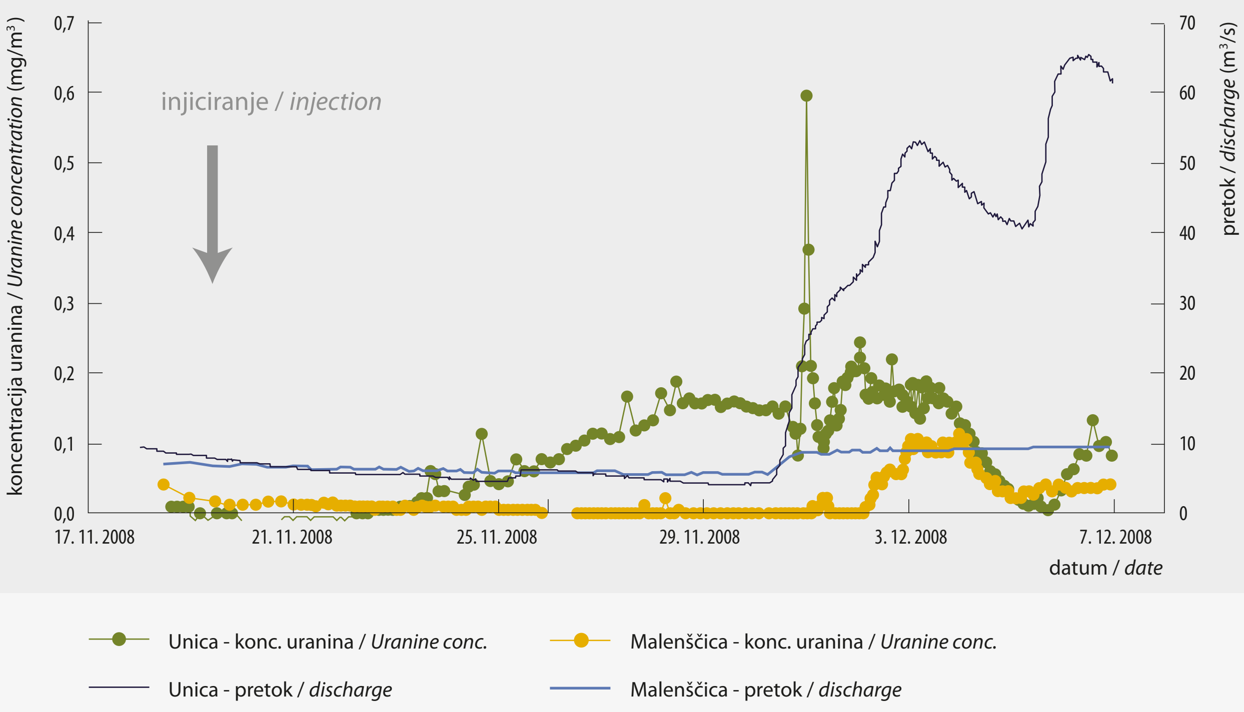
V neposrednem zaledju Malenščice potekajo avtocesta, železnica in lokalne ceste. Prometne nesreče z izlitji nevarnih snovi bi zelo verjetno ogrozile kakovost izvira. Novembra 2008 smo izvedli sledenje, ko smo na Ravbarkomandi v lovilnik olj ob avtocesti, 3 km od izvira Malenščice (1), injicirali fluorescentno sledilo. Želeli smo ugotoviti, kateri izviri in kako hitro bi bili ogroženi v primeru nesreče z izlitjem

accidents showed that spilled liquids, even though they are not soluble in water, run quickly off the surface before an efficient intervention is possible.

In May 1984 a major oil leak occurred at Petrol's depot near Postojna (1), and it was assumed that the oil had drained into the karst underground. Previously proved groundwater connection between the Kremenca cave and the Unica and Malenščica springs at Planinsko polje (*Gams* 1965) indicated the great likelihood of pollution of the two springs. A long-term observation of the springs was organized by the local Civil protection unit. Fortunately, the oil did not appear at the observation points and it was assumed that it did not leak into the ground at all. This was one of the first serious warnings of the potential threat represented by storage facilities for petroleum products in karst areas.

The immediate vicinity of the Malenščica spring includes a motorway, a railway and a number of local nevarne snovi (*Gabrovšek* idr. 2010). Pretok izvirov Malenščice (7 m³/s) in Unice (9 m³/s), kjer je bil najverjetnejši pojav sledila, je takrat upadal. Manjše padavine, ki so sledile šele teden dni po injiciranju in nekoliko povečale pretoke, so povzročile zvezno naraščanje koncentracije sledila v Unici (2). Zelo izdaten in intenziven dež čez nadaljnjih 5 dni pa je močno povečal pretoke in povzročil poplave. Hitremu naraščanju pretoka Unice je z 12-urnim zamikom sledilo tudi naraščanje koncentracije sledila. Sočasno z Unico se je povečeval pretok Malenščice, vendar pa je koncentracija sledila v Malenščici naraščala z dvodnevnim zamikom za pretokom. Iz tega sklepamo, da bi v primeru nesreče z razlitjem nevarne snovi na Ravbarkomandi to najprej in izraziteje zaznali v Unici, v primeru padavin ob naraščanju pretokov že približno v 12 urah, s časovnim zamikom približno dveh dni pa tudi v Malenščici.

roads. Traffic accidents involving spillages of hazardous substances would very probably threaten the quality of the spring. In November 2008 we carried out a tracer test with the injection of fluorescent tracer into the oil collector by the motorway at Ravbarkomanda, 3 km away from the Malenščica spring (1). The idea was to assess what springs and when they would be endangered in a case of accident involving the spillage of harmful substances (*Gabrovšek* et al. 2010). The discharge of the Malenščica (7 m³/s) and Unica springs (9 m³/s), where the appearance of the tracer would be the most probable, were in recession. Less intensive precipitation one week after the injection resulted in a slight increase of the discharges and a slow, continuous increase of the Uranine concentrations in the Unica spring (2). After additional 5 days, very intensive rain resulted in floods. The Unica spring reacted rapidly with higher discharges, and after 12 hours the tracer concentrations started



2 Sledenje z injiciranjem v lovilniku olj na Ravbarkomandi je pokazalo, da onesnažene vode z avtoceste ogrožajo kakovost kraških izvirov Unice in Malenščice. V primeru razlitja v prometni nesreči bi onesnaženje najprej zaznali v Unici, s približno dvodnevnim zamikom pa tudi v Malenščici.
The tracer test in the oil collector near Ravbarkomanda confirmed that the quality of the Unica and Malenščica karst springs is threatened by polluted water from the motorway. In a case of an accident involving spillage the contaminants would be observed first in the Unica spring and then, after a delay of approximately two days, also in the Malenščica spring.

5.2 Razlitje plinskega olja v skladišču naftnih derivatov je ogrozilo kakovost zajetega izvira Globočec

Iztekanje iz skladišča naftnih derivatov pri Ortneku (3) je pokazalo na potencialno nevarnost tovrstnih objektov za kraško vodo. Oktobra 1998 je pri prečrpavanju plinskega olja v tamkajšnjem skladišču prišlo do napake in neznana količina olja je odtekla po odtočnih drenažah v potok Tržiščico (*Genorio* 1999). Skladišče leži na nekraškem svetu, vendar pa Tržiščica po približno 4 km površinskega toka na stiku z apnencem ponika v kras (4). Na podlagi starejših sledenj so sklepali, da bo onesnaženje prizadelo izvire na Dobrepolju in v dolini Krke.

Pod vodstvom upravljavca je potekalo spremljanje pojava plinskega olja v zajetem izviru Globočec (3, 5). Monitoring s fluorescenčnim spektrofotometrom Shimadzu RF 1501 v prvem tednu po nesreči je pokazal, da Globočec tedaj še ni bil onesnažen. To so potrdile tudi vzporedne kromatografske analize mineralnih olj v laboratoriju (*Genorio* 1999).

Prvič so v Globočcu določili pojav plinskega olja v koncentraciji 0,013 mg/l dobrih 8 dni po nesreči in približno tri dni po močnejšem dežju. Na osnovi teh podatkov bi bila izračunana navidezna hitrost pretakanja 108 m/h. Vendar pa je že čez 8 ur koncentracija padla pod 0,005 mg/l (najvišja dopustna meja za pitno vodo je 0,01 mg/l). Redno 5-krat dnevno jemanje vzorcev je nato potekalo še teden dni. Z analizami niso zaznali plinskega olja, ampak le njegove derivate in značilen vonj, v naslednjih dneh pa tudi tega ne.

Po izdatnih padavinah tri tedne po nesreči so zaradi iztiskanja plinskega olja po infiltraciji novih padavin dva dni ugotavljali omenjeni vonj. Vendar s poznejšimi analizami do konca novembra nista bila ugotovljena niti navzočnost plinskega olja in derivatov niti vonj. Decembra 1998 pa vse do marca 1999 so bile padavine sorazmerno skromne in večinoma v obliki snega.

Spomladi 15. aprila 1999 so na izviru namestili avtomatski merilnik ogljikovodikov, ki je zvezno beležil koncentracijo plinskega olja. Po močnih padavinah v zaledju Tržiščice 21. maja 1999 so 5 ur beležili prekoračitev dovoljene vsebnosti plinskega olja v vodi (več kot 0,01 mg/l). Kasneje povečanj niso več zasledili. Ob

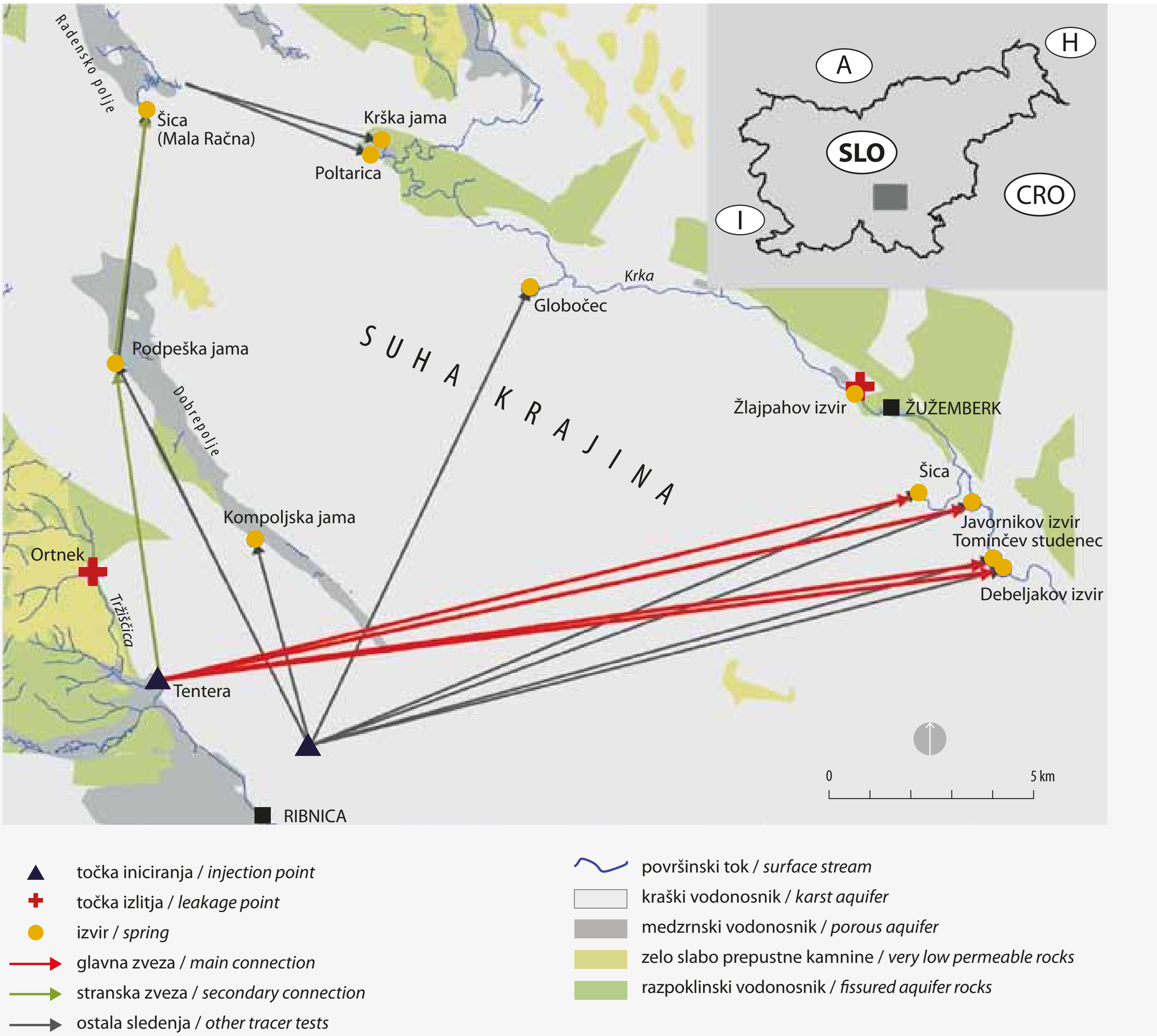
to increase quickly. At the same time the increase of discharge of the Malenščica spring was observed, while the concentration of tracer there increased after a delay of two days. From this we can conclude that in the case of pollution at Ravbarkomanda, this would be observed first and most markedly in the Unica spring (following the precipitation events and increase of discharge already in 12 hours) and then, after a delay of approximately two days, in the Malenščica spring.

5.2 A spillage of gas oil in the petrochemical depot endangered the Globočec spring

A leakage from the petrochemical depot near Ortnek (3) indicated a potential threat of such storage facilities to karst waters. In October 1998, during the pumping of gas oil in the depot, an unknown quantity of oil passed through the drainage system into the Tržiščica stream (*Genorio* 1999). The depot is located in non-karst area, but after 4 km of surface flow the Tržiščica stream sinks underground at the contact with the limestone (4). Based on the results of previous tracer tests the possible pollution of the springs in Dobrepolje and in the Krka valley was expected.

Close monitoring of the presence of gas oil was organized in the Globočec spring, which is used for the water supply (3, 5). In the first week of monitoring with a fluorescent spectrophotometer Shimadzu RF 1501 no pollution was detected. This was additionally confirmed by a parallel chromatographic analysis of mineral oils in the laboratory (*Genorio* 1999).

The gas oil was first detected 8 days after the accident and three days after an intensive precipitation event in concentration 0.013 mg/l. This would give the apparent flow velocity of 108 m/h. However, already after 8 hours the concentration decreased below 0.005 mg/l (the highest allowed value for drinking water is 0.01 mg/l). In the following week, the water samples were regularly taken 5 times per day. The gas oil was not detected, while the presence of its derivatives and a distinctive odour was noticed only in the first days.



3 S sledilnimi poskusi ugotovljene smeri podzemnega raztekanja iz ponora Tržiščice.
Directions of groundwater flow of the Tržiščica sinking stream proved by tracer tests.

našem obisku ponora Tržiščice konec avgusta 1999, eno leto po nesreči, je bil še vedno prisoten močan vonj po plinskem olju, ki se je absorbiralo na sediment ob robu struge. Spremljanje navzočnosti plinskega olja in vonja v Globočcu je pokazalo, da je bil prenos postopen daljše obdobje in da je voda neuporabna že samo ob prisotnosti vonja po plinskem olju.

Three weeks after the accident, a distinctive odour has been noticed for two days as a result of infiltration following intensive precipitation events, which pushed previously stored gas oil through the system. Then until the end of November the presence of gas oil or its derivatives or a distinct odour were not detected. From December 1998 until

Navzočnost plinskega olja so ugotovili tudi v Kompoljski jami (3). Po pripovedovanju domačinov so plinsko olje vidno zaznali v Tominčevem studencu v dolini Krke, vendar pa tega izvira tedaj v sklopu monitoringa niso opazovali.

5.3 Raziskave ugotavljanja možnega vpliva skladišča naftnih derivatov na kraške vode

Sledilni poskusi so učinkovita metoda za ugotavljanje podzemnih vodnih povezav v krasu in tako tudi za določanje smeri prenosa onesnaženja s površja skozi kraške vodonosnike. Zaradi kasnejše načrtovane razširitve skladišča v Ortneku je bila izvedena raziskava možnega vpliva na kraške vode s sledilnim poskusom.

Poskus z injiciranjem sledila na ponoru Tržiščice (3, 4), v katero bi v primeru razlitja iztekli naftni derivati iz skladišča, je pokazal, da v hidroloških razmerah upadanja pretokov od srednjih do nizkih vodostajev vode odtekajo predvsem v Tominčev studenec ter Javornikov in Debeljakov izvir v dolini Krke (3). Ker ni

March 1999 the precipitation events were rare and mainly in the form of snow.

For continuous measurements of gas oil concentrations an automatic detector of hydrocarbons was installed on 15 April 1999. The maximum allowed concentration of gas oil in water (0.01 mg/l) had been exceeded for 5 hours on 21 May 1999 following heavy rain in the catchment area of the Tržiščica stream. Later no such increases were noticed. However, during our field trip to the Tržiščica ponor at the end of August 1999, one year after the accident, a distinctive odour of the gas oil absorbed on the river sediments was still present. A long-lasting and gradual transfer was confirmed by monitoring of the presence of gas oil and its odour in the Globočec spring. Already a detection of odour makes the water unsuitable.

The presence of gas oil in the cave Kompoljska jama was confirmed, too (3). According to the information given by the locals, the gas oil was visible in the spring Tominčev studenec in the Krka valley. However, no monitoring was organized at this location then.

4 Iz skladišča naftnih derivatov pri Ortneku, ki leži na nekraškem svetu, je plinsko olje odteklo po Tržiščici do ponora.
From the petrochemical depot near Ortnek which is located on a non-karst terrain the gas oil flowed along the Tržiščica stream into the ponor.

5 Izvir Globočec, zajet za oskrbo prebivalstva Suhe krajine s pitno vodo.
The Globočec spring used for the water supply of the Suha krajina region.

bilo natančnih meritev pretokov izvirov, smo lahko le ocenili, da sta skozi te izvire do konca maja 2000 iztekli nekako 2/3 injiciranega sledila. V znatno manjši meri in z velikim časovnim zamikom se je sledilo pojavilo tudi v Podpeški jami in v Šici pri Mali Račni na Radenskem polju (*Kogovšek* in *Petrič* 2002b). Nismo pa ugotovili povezave z izvirom Globočec, ki je zajet za oskrbo prebivalstva Suhe krajine s pitno vodo, čeprav je bilo vzorčenje tam najbolj pogosto.

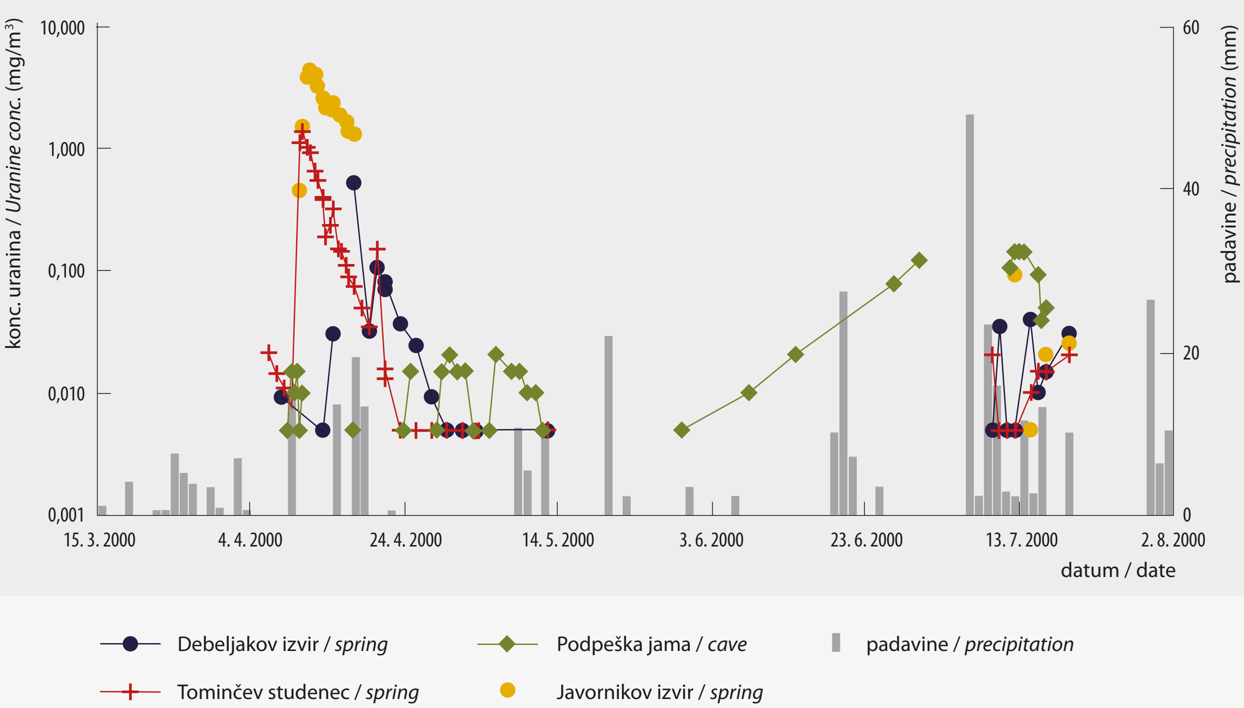
Voda se je v stalni Tominčev studenec pretakala z navidezno hitrostjo 144 m/h, v občasni Javornikov izvir s 137 m/h, v Debeljakov izvir pa s 86 m/h, računano glede na pojav maksimalne koncentracije (dominantne hitrosti). Te dokaj velike hitrosti pretakanja vode nakazujejo v primeru onesnaženja Tržiščice tudi hiter prenos onesnažil do naštetih izvirov. V Javornikovem izviru smo zabeležili kar trikrat višje koncentracije sledila kakor v Tominčevem studencu, kar kaže na bolj koncentriran odtok oz. manjše razredčevanje vzdolž podzemnega toka (6).

Zaključimo lahko, da je podzemno raztekanje vode

5.3 The study of a possible impact of the petrochemical depot on karst waters

Tracer tests are a very useful tool for defining the characteristics of the groundwater flow and the transport of pollution from the surface through karst aquifers. Because of the planned enlargement of the petrochemical depot near Ortnek an assessment of the possible impacts on the karst water by a tracer test was carried out.

The tracer was injected into the Tržiščica sinking stream (3, 4), into which the petroleum products from the depot would flow in a case of accident. The main flow towards the springs in the Krka valley (Tominčev studenec, Javornikov izvir, Debeljakov izvir) was proved at medium to low recession conditions (3). In the absence of reliable discharge data the recovery through the three springs until the end of May 2000 was only roughly assessed to 2/3 of the injected tracer. In much lower amount and with a significant time



6 Rezultati sledenja za ugotovitev možnega vpliva skladišča naftnih derivatov pri Ortneku na kraške vode.
The results of tracer tests aimed at the assessment of a possible influence of the petrochemical depot near Ortnek on karst waters.

iz Tržiščice zelo odvisno od hidroloških razmer. O pretakanju voda ob zelo visokem vodostaju imamo nekaj informacij iz zgoraj opisanih posledic razlitja plinskega olja oktobra 1998. Le občasno, kratkotrajno pojavljanje plinskega olja po vsakokratnih padavinah nakazuje, da se lahko snovi, ki se v vodi ne topijo oz. se z njo ne mešajo, v kraškem podzemlju za dlje časa akumulirajo in se po vsakih izdatnejših padavinah dolgo, postopno spirajo.

Sklepamo lahko, da ob visokih vodostajih obstaja tudi zveza med Tržiščico in Globočcem. Čeprav je povezava slaba in so bile izmerjene koncentracije nizke ter so se pojavljale le občasno, pa ugotavljamo, da je v primeru onesnaženja z nevarnimi snovmi (kot so tudi naftni derivati) to dovolj za onesnaženje zajetega izvira, saj so ga morali za daljši čas izključiti iz omrežja. Zaledje Tržiščice je torej tudi zaledje Globočca in vsako onesnaženje na tem območju pomeni tudi nevarnost za slednjega. Pokazalo se je še, da netopne, nepolarne tekočine ubirajo podzemne vodne poti, da pa je dinamika njihovega prenosa drugačna in močno odvisna od spreminjanja hidroloških razmer, ki omogočajo v kraškem vodonosniku akumuliranje in kasnejše različno intenzivno potiskanje teh snovi v smeri izvirov.

5.4 Iztekanje kurilnega olja na dolomitnem svetu

Ko je iz Tovarne kemičnih kondenzatorjev v Žužemberku, ki leži na dolomitnem svetu neposredno ob reki Krki (3), leta 1991 izteklo približno 30 m^3 kurilnega olja, smo spremljali značilnosti njegovega prenosa skozi dolomit.

Ugotovljeno je bilo, da se je velik del olja dlje časa zadržal v podzemlju kot izoliran oljni madež. Dosegli so ga z vrtino in ga določeno količino izčrpali, pozneje pa spremljali višino olja v vrtini. Od začetnih več kot 30 m višine ga je po 6 letih ostalo še 0,26 m. To kaže na zelo počasno odtekanje z območja oljnega madeža, kar je bil tudi razlog, da med nesrečo ni prišlo do hitrega in velikega onesnaženja Krke. Počasno in dolgotrajno iztekanje pa pomeni pomembno akumulacijo tega onesnažila v kraškem podzemlju.

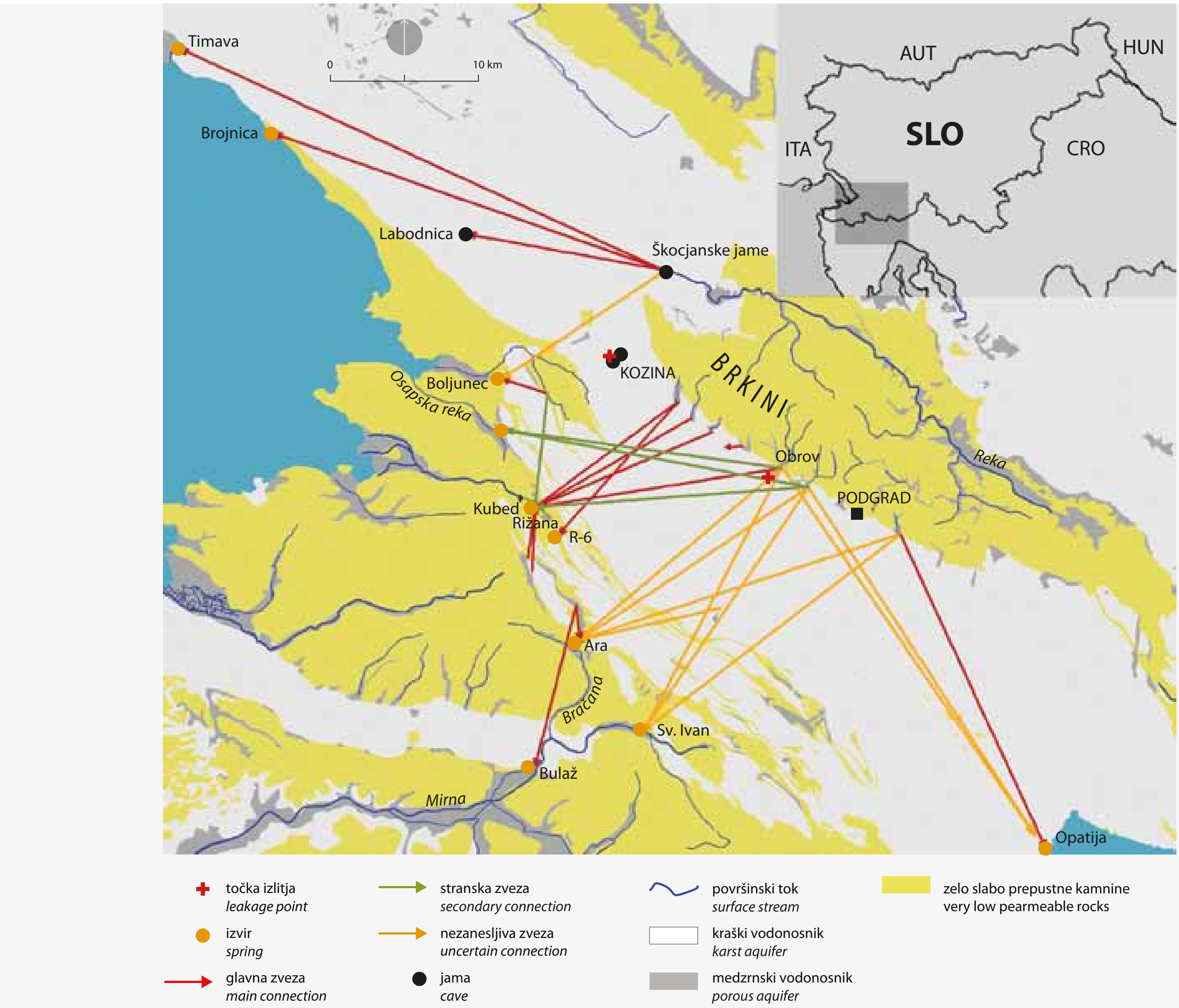
Da bi pridobili novo znanje o pretakanju snovi, ki se z vodo ne mešajo, je bilo opazovanje širjenja

lag the tracer appeared in the cave Podpeška jama and in the Šica spring near the village Mala Račna on Radensko polje (*Kogovšek* and *Petrič* 2002b). Although the sampling was the most frequent in the Globočec spring, which is used for the water supply of the Suha krajina region, no tracer was detected there.

The dominant velocity of flow (regarding the time of detected maximal tracer concentration) towards the spring Tominčev studenec was 144 m/h, towards the intermittent spring Javornikov izvir 137 m/h and towards Debeljakov izvir 86 m/h. Considering these relatively high velocities, we can predict that in a case of pollution of the Tržiščica stream the contaminants would soon appear in the springs. The tracer concentrations in Javornikov izvir were three times higher than in Tominčev studenec which indicates more concentrated flow and less dilution along the groundwater flow (6).

The results indicate that hydrological conditions significantly influence the groundwater flow of the Tržiščica stream. Observed consequences of the spillage of gas oil in October 1998 are a source of information about the characteristics of flow at very high waters. Only occasional, short-lived occurrences of gas oil induced by precipitation events indicate that substances, which are not soluble in water and can be delayed in the underground, are flushed out after the following precipitation events in a long-continued process.

We can therefore infer that the underground connection between the Tržiščica sinking stream and the Globočec spring exists at high waters. Although the connection is weak, in the case of pollution with harmful substances (e.g. petroleum products) the water source can be polluted and for a longer period excluded from the water supply system. Any pollution in the catchment of the Tržiščica stream, which is within the recharge area of the Globočec spring, may endanger the quality of this drinking water source. Substances, which are not soluble in water, follow underground watercourses, however the dynamics of their transfer differ significantly from the dynamics of water flow and depend largely on the changes of hydrological conditions, which enable longer accumulation in the karst aquifer and later variously intensive outflow of these substances towards karst springs.



7 Kraja razlitja naftnih derivatov pri Kozini in Obrovu ter smeri pretakanja podzemne vode, ugotovljene s sledilnimi poskusi (*Krivic* idr. 1987, 1989).
Locations of spillages of petroleum products near Kozina and Obrov, and by tracer tests proved directions of the groundwater flow (*Krivic* et al. 1987, 1989).

kurilnega olja dopolnjeno s sledilnim poskusom s fluorescentnima slediloma, ki sta topni v vodi (*Habič* 1991). Na površju, kjer je iztekalo kurilno olje, je bil injiciran uranin, v vrtino pa rodamin. Od številnih manjših izvirov ob Krki sta se sledili tako kot kurilno olje najizraziteje pojavili v največjem, Žlajpahovem izviru (3). Uranin se je najprej pojavil v vrtini, kasneje pa v izviru v več valovih po zaporednih vlitjih vode na mestu injiciranja. Spremljanje koncentracij obeh sledil

5.4 A spillage of heating oil on dolomitic terrain

The spillage of approximately 30 m³ of heating oil happened in 1991 in the factory of chemical condensers, which is located on dolomitic terrain near Žužemberk above the Krka river (3). The characteristics of the oil transport through dolomite were surveyed.

v vrtini je pokazalo na počasno izmenjavanje kraške vode v dolomitu na območju vrtine

5.5 Izlitje kurilnega olja v prometni nesreči pri Kozini

Oktobra 1993 se je v prometni nesreči na kraškem svetu pri Kozini (7) v bližnjo okolico izlilo 18 ton nafte in kurilnega olja. Nafta je s površja z malo preperine pod travnato rušo hitro odtekla, po ocenah očividcev je bila požiralnost okoli 15 l/s. Na podlagi že pred časom opravljenih sledilnih poskusov na tem območju, ki so dokazali odtekanje podzemnih voda izpod Brkinov v izvire Osapske reke, Rižane, Bračane, Mirne in v obmorske kraške izvire v Kvarnerskem zalivu pri Opatiji (*Krivic* idr. 1987, 1989), smo sklepali na možen pojav nafte na vseh teh točkah. Možen je bil tudi pojav nafte v izvirih Timave, saj vode z območja severozahodno od Kozine odtekajo v to smer. Vzorčenje na terenu in ogled jam smo opravili sodelavci Inštituta za raziskovanje krasa ZRC SAZU (*Knez* idr. 1994) po naročilu Ministrstva za okolje in prostor.

Spremljanje koncentracije mineralnih olj v izvirih Rižane, ki je glavni vir za vodooskrbo obalnih občin (9), je potekalo redno od 9. oktobra do 17. novembra, kasneje do večjega zmanjšanja vodostaja pa le še občasno. Mineralna olja se v Rižani niso pojavila. Ta nesreča se je tako za izvir Rižane srečno končala, je pa nakazala možnost, da bi v primeru onesnaženja lahko prišlo do zelo hudih posledic.

Vzorci vode so bili vzeti še na šestih drugih mestih, a le v Osapski reki je bila 18 dni po nesreči, ob zelo visokem vodostaju, zabeležena navzočnost olj (0,016 mg/l). Povečanja so bila ugotovljena v Veliki Kozinski jami in v Cikovi jami, vendar smo jih pripisali direktnemu prenikanju s površja.

Naftni derivati se z vodo ne mešajo oz. se v njej ne topijo in so lažji. Zato se njihov prenos skozi kras verjetno precej razlikuje od prenosa topnih snovi, čeprav smo ob spremljanju razlitij naftnih derivatov ugotavljali, da se pretakajo po vodnih poteh in iztekajo skozi izvire, v zaledju katerih je prišlo do nesreče.

A large portion of oil was retained for longer time in the underground as an isolated contaminant plume. A borehole was drilled through it and a certain amount was pumped out. Later the level of oil in the borehole was measured. From the initial height of 30 m it has dropped to 0.26 m in the period of 6 years. Such slow flow from the area of oil plume was the reason why no immediate and serious pollution of the Krka river occurred in the time of the accident. However, very slow and long-lasting outflow means an important accumulation of the contaminant in the karst underground.

With the aim to get some new knowledge about the transfer of substances, which are not soluble in water, the tracer test with two water-soluble fluorescent dyes were carried out parallel to the monitoring of the oil spreading (*Habič* 1991). Uranine was injected on the surface at the location of spillage, and Rhodamine in the borehole. The tracers as well as the heating oil occurred mainly in the spring Žlajpahov izvir, which is the biggest among numerous smaller springs along the Krka river (3). Uranine was first detected in the borehole, and then later in the spring in several successive peaks following the flushing with water at the injection point. Measurements of tracer concentrations in the borehole showed that the exchange of karst water in dolomite is slow.

5.5 A spillage of heating oil in a traffic accident near Kozina

In October 1993 a spillage of 18 tons of petroleum and heating oil occurred in a karst area near Kozina (7). The petroleum ran quickly off the surface through a thin layer of soil. Eyewitnesses estimated that the swallow capacity was 15 l/s. On the basis of the earlier tracer tests carried out in this area, which showed the flow of groundwater from under the Brkini hills into the karst springs Osapska reka, Rižana, Bračana and Mirna and the coastal karst springs in the Kvarner Gulf near Opatija (*Krivic* et al. 1987, 1989), it was concluded that petroleum could appear at all these points. The appearance of petroleum was also possible in the Timava spring since the waters north-west of Kozina flow in this direction. By the order of the Ministry of the Environment and Spatial Planning the field sampling and the surveying of caves

5.6 Onesnaženje kraških izvirov zaradi izlitja plinskega olja v prometni nesreči pri Obrovu

Dne 12. oktobra 1994 je prišlo do prometne nesreče na cesti Podgrad–Kozina pri Obrovu v zaledju Rižane (7), ko je iz cisterne izteklo blizu 16 m^3 plinskega olja D2. Kot je bilo ugotovljeno že ob omenjeni nesreči pri Kozini, je izliti tovor tudi tokrat zelo hitro odtekel s površja (po oceni v 15 do 20 minutah). Po tem sklepamo, da ob podobnih nesrečah na kraškem svetu izlite snovi ni možno pravočasno prečrpati in preprečiti njenega odtoka v kras. V primeru izlitja pri Obrovu se je posrečilo izolirati samo zemljo, prepojeno z oljem (8). Do izlitja je prišlo na območju drugega varstvenega pasu zajetega vodnega vira Rižana, približno kilometer jugozahodno od ponikalnice v slepi dolini Jezerina, za katero je bila s sledilnimi poskusi leta 1986 ugotovljena zanesljiva povezava z izviroma Rižane in Osapske reke (*Krivic* idr. 1989).

V Rižani se je pri poskusu leta 1986 sledilo pojavilo po padavinah, in sicer 18 dni po injiciranju. V enem mesecu po prvem pojavu je skozi Rižano izteklo 10,6 % sledila, hitrost pretakanja pa je znašala 35 m/h. V Osapski reki se je sledilo pojavilo 21 dni po injiciranju v vodnem valu po padavinah, maksimalna koncentracija pa je bila štirikrat manjša kot v Rižani. Hitrost pretakanja v smeri Osapske reke je bila enaka kakor v smeri Rižane. V nizkih koncentracijah se je sledilo pojavilo tudi v izviru Ara pri naselju Mlini in v izviru Sv. Ivan v Buzetu na Hrvaškem, in sicer 11 dni po injiciranju, še pred nastopom vodnega vala po padavinah. Izračunana hitrost pretakanja bi bila 67 m/h do izvira Ara in 72 m/h do izvira Sv. Ivan. Zaradi nizkih koncentracij ni bilo moč ne ovreči ne potrditi vodne zveze s povodjem Mirne (*Krivic* idr. 1987).

Na podlagi tega znanja je bila ob nesreči pri Obrovu sprejeta ocena, da bodo na širjenje onesnaženja vplivale predvsem padavine oz. povečani pretoki voda in da je treba podrobneje spremljati Rižano (9), pa tudi izvir Osapske reke in izvir Ara. Najpogosteje je bila vzorčena Rižana; podatki o količini padavin so bili pridobljeni na bližnji padavinski postaji Podgrad, srednji dnevni pretoki Rižane pa na

was carried out by the co-workers of the Karst Research Institute at ZRC SAZU (*Knez* et al. 1994).

The concentrations of mineral oils in the Rižana spring, which is used for the water supply of the whole coastal region (9), were measured regularly from 9 October to 17 November, and later only occasionally in the period of recession. However, the mineral oils were not detected. This accident ended happily as far as the Rižana spring is concerned. It showed, however, that the pollution of this water source could have extremely serious consequences.

The water samples were taken at six other locations. Only in the Osapska reka spring the oils were detected (0.016 mg/l) 18 days after the accident, at very high waters. Increased concentrations in the caves Velika Kozinska jama and Cikova jama were attributed to a direct seepage from the surface.

Petroleum products are not soluble in water and are lighter. Therefore the mode of their transfer through karst probably differs significantly from the transfer of water-soluble substances. The monitoring of spreading of petroleum products after spillages showed, however, that they flow along the water courses and outflow through the springs which drain the areas of accidents.

5.6 Pollution of karst springs due to a spillage of gas oil in the traffic accident near Obrov

On 12 October 1994 an accident occurred on the Podgrad–Kozina road near Obrov in the catchment of the Rižana spring (7) when almost 16 m^3 of D2 gas oil spilled from a tanker. Similar as it was observed during the before mentioned accident near Kozina, the oil ran rapidly off the surface (in an estimated 15 to 20 minutes). We observe that with such accidents in karst areas it is not possible to pump up the spilled substance in time to prevent its drainage into the karst. Only the soil soaked with oil was isolated after the spillage near Obrov (8). The spillage occurred in the area of the second protection zone of the Rižana catchment, approximately one kilometre south-west of the sinking stream in the blind valley of Jezerina,

8 Po izlitju plinskega olja pri Obrovu se je posrečila le izolacija z oljem prepojene prsti.
Only the soil soaked with oil was isolated after the spillage of gas oil near Obrov.

9 Izvir Rižane je zajet za oskrbo prebivalstva obalne regije s pitno vodo.
The Rižana spring is used for the water supply of the coastal region.

vodomerni postaji Kubed. Pregledane so bile tudi jame na območju med krajem nesreče in naštetimi izviri.

5.6.1 Pojav plinskega olja D2 v Rižani

Po izlitju plinskega olja v prometni nesreči 12 dni ni bilo padavin, ki bi pospešile pretakanje olja skozi vadozno kraško cono. Med padavinami, ki so sledile 14 dni po nesreči, pa je bil ob nekoliko povečanem pretoku zabeležen pojav plinskega olja v Rižani (80 μg/l), kar pomeni hitrost pretakanja 45 m/h (10). Ob nadaljnjih izdatnih padavinah (70 mm) se je 29. oktobra pretok Rižane povečal na 22,8 m^3/s in naslednji dan so bile zabeležene tudi višje koncentracije plinskega olja (*Kogovšek* idr. 1994; *Kogovšek* 1995b). Izvir Rižane je bil zato kar nekaj časa izključen iz vodovodnega omrežja.

Glede na razpoložljive podatke o srednjih dnevnih pretokih Rižane in analize koncentracije ogljikovodikov smo izračunali količino plinskega olja, ki je odtekla skozi Rižano. Ta znaša za čas meritev v zadnjem tednu oktobra 88 kg, kar je dobrega pol odstotka izlite količine. Sklepamo, da se je iztekanje nadaljevalo po vsakokratnih izdatnih in intenzivnih padavinah dlje časa, verjetno tudi skozi Osapsko reko, ko je bila aktivna.

for which a reliable connection with the spring of the rivers Rižana and Osapska reka was established by means of tracer test in 1986 (*Krivic* et al. 1989).

In 1986 the tracer was detected in the Rižana spring following a precipitation event 18 days after the injection. In one month after this first appearance, 10.6 % of the injected tracer was recovered in the spring and the apparent flow velocity was 35 m/h. In four-times lower concentrations and with similar flow velocity the tracer was detected in the spring of Osapska reka 21 days after injection. Already 11 days after injection, in a recession period, the tracer has appeared in low concentrations in the springs Ara near Mlini and Sv. Ivan near Buzet in Croatia. The apparent flow velocity towards the Ara spring was 67 m/h, and towards the Sv. Ivan spring 72 m/h. Due to low concentrations it was not possible to confirm or reject the groundwater connection with the Mirna river (*Krivic* et al. 1987).

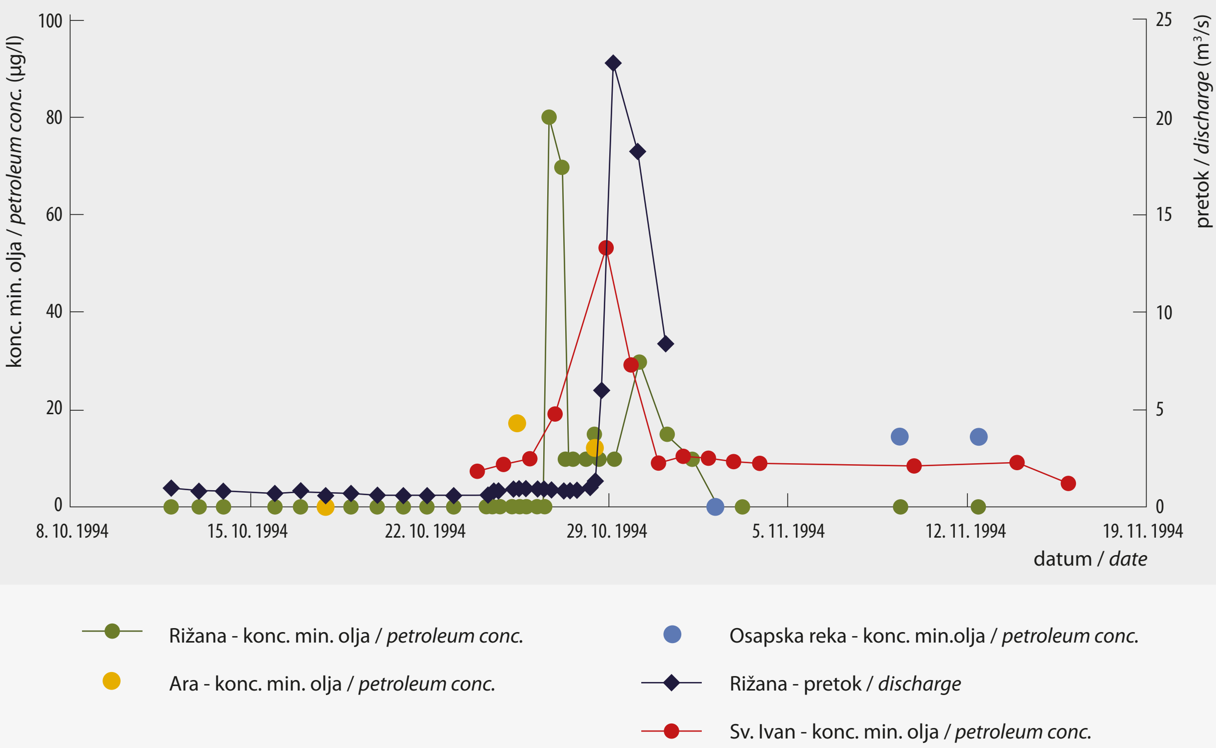
On the basis of this knowledge, during the accident near Obrov the view was taken that the spread of pollution would be affected by rainfall and increased discharges, and that it was therefore necessary to monitor closely the Rižana spring (9), and additionally the Osapska reka and Ara springs. The most frequent sampling was organized at the Rižana spring; the precipitation data for the nearby Podgrad precipitation

Kraško vodo, ki jo uporabljamo za pitje, je treba v večini primerov dezinficirati, preden prispe do uporabnikov. V Rižanskem vodovodu, ki upravlja z zajetjem Rižana, so jo v času opisanih nesreč pri Kozini in Obrovu klorirali s plinskim klorom. V strokovni literaturi opozarjajo na negativni vpliv kloriranja, kadar so v vodi navzoče organske snovi, ker s klorom nastajajo halogenirani ogljikovodiki, ki so rakotvorni. Njihova maksimalna dopustna meja je 30 µg/l. Pri kontroli pitne vode po nesreči so v končnih točkah rižanskega vodovoda ugotavljali koncentracijo halogeniranih ogljikovodikov – skupnih trihalogenmetanov 10 µg/l (*Ožbolt* 1994). Upravljavci so ugotovili, kakšno nevarnost pomenijo takšne nesreče v zaledju Rižane in poznejše kloriranje, zato vodo Rižane že nekaj časa čistijo z ultrafiltracijo brez dodanih kemikalij.

station and the discharge data for the Kubed gauging station were obtained. Several caves in the area between the accident location and the observed springs were also surveyed.

5.6.1 The appearance of D2 gas oil in the Rižana spring

For 12 days following the gas oil spillage there was no rainfall, which would accelerate the flow of the oil through the karst vadose zone. But then light rainfall 14 days after the accident caused an increase in discharge and the appearance of increased concentrations of gas oil (80 µg/l). The apparent flow velocity of 45 m/h was calculated (10). A further 70 mm of rain led to an increase of discharge of the Rižana spring to 22.8 m^3/s on 29 October, and the following day higher concentrations



10 Rezultati spremljanja pojava plinskega olja v opazovanih kraških izvirih.
Results of the gas oil monitoring in the observed karst springs.

5.6.2 Pojav plinskega olja D2 v Osapski reki in v izviru Ara

Osapska reka je bila do padavin na začetku novembra suha, ob pojavu vode 2. novembra pa nismo ugotovili povišanih vsebnosti mineralnih olj. Ob naraščajočem pretoku 9. in 12. novembra sta zajeta vzorca vsebovala 0,014 mg/l mineralnih olj (10). Možno je, da se je onesnaženje pojavilo že kak dan prej, ko nismo jemali vzorcev, zelo verjetno v višjih koncentracijah. Sklepamo, da je bila hitrost pretakanja v Osapsko reko okrog 30 m/h. Verjetno pa bi se ob visokem vodostaju mineralna olja pojavila v izviru prej, kar bi pomenilo večjo hitrost.

Izvir Ara je bil aktiven že v času izlitja. Med 18. oktobrom in 2. novembrom sta bila zajeta le dva vzorca in oba sta imela zvišano koncentracijo mineralnih olj (10). Prvo povišanje smo zabeležili že dan pred pojavom plinskega olja v Rižani. Ocenjena hitrost pretakanja s točke razlitja v izvir Ara bi bila ob sorazmerno nizkem vodostaju približno 50 m/h ali celo nekoliko večja. S sledilnim poskusom junija 1986 (*Krivic* idr. 1989) so zaradi neizrazitega pojava sledila v izviru Ara ugotavljali vprašljivo povezavo, ocenjena hitrost pa bi bila 67 m/s. Čeprav je tudi pojav izlitega olja po nesreči pri Obrovu v izviru Ara zaradi majhnega števila vzorcev in nizkih koncentracij vprašljiv, pa se zdi povezava verjetna. Zanesljivo bi jo lahko potrdili samo z dodatnim sledilnim poskusom.

Od 24. oktobra 1994 naprej so spremljali vsebnost mineralnih olj v izviru Sv. Ivan v Buzetu (*Vlahović* 2000). Iz njihovih podatkov je razvidno opazno povečanje vsebnosti mineralnih olj in skupnih maščob od 27. do 30. oktobra (10). Tako sklepamo, da je izlito plinsko olje verjetno odtekalo tudi v tej smeri, čeprav niso znane izhodne vrednosti merjenih parametrov pred nesrečo. V primeru sledenja iz Jezerine v juniju 1986 se je sledilo v tem izviru pojavilo podobno šibko kakor v izviru Ara.

Sklep

Nesreče, pri katerih odtečejo v kras večje količine nevarnih netopnih snovi (npr. naftni derivati), pomenijo nevarnost za naše okolje in kraške vode, saj lahko

of gas oil were detected (*Kogovšek* et al. 1994; *Kogovšek* 1995b). As a result, the spring was excluded from the water supply network for quite some time.

The quantity of gas oil calculated to have drained through the Rižana spring by the end of October was 88 kg, which is over half a percent of the total quantity spilled. The existing data on mean daily discharges of the Rižana river and measured concentrations of hydrocarbons were used for the assessment. It clearly indicates the gradual rate of discharge of such substances following each instance of heavier rainfall. When the Osapska reka spring was still active, it is highly probable that the oil also discharged through this spring.

Usually karst water has to be disinfected before it is used as a drinking water source. At the time of the described accidents near Kozina and Obrov the water in the Rižana water supply system was chlorinated with gas chlorine, which in the presence of organic substances leads to the formation of carcinogenic halogenated hydrocarbons. Their maximum allowed concentration is 30 µg/l. After the accidents, the concentrations of halogen hydrocarbons of 10 µg/l were measured in the final sections of the Rižana water supply system (*Ožbolt* 1994). The operators of the Rižana water supply system recognized the danger represented by accidents of this type in the catchment area of the Rižana river and by subsequent chlorination, and therefore for some time now its water has been purified by means of ultrafiltration without added chemicals.

5.6.2 The appearance of D2 gas oil in the Osapska reka and Ara springs

Until the precipitation occurred in the beginning of November, the spring of Osapska reka was dry, and no increased concentrations of mineral oils were detected in the spring activated on 2 November. The concentration 0.014 mg/l was measured in two samples taken on 9 and 12 November, in the time of the increase of discharge (10). It is possible that the tracer has appeared in higher concentrations already some day before when no samples were collected. The assessed flow velocity was approximately 30 m/h. At high waters the mineral oils would probably appear at the spring earlier, which would also give a higher flow velocity.

že majhne količine za dolga obdobja onesnažijo vodne vire. Še posebej so nevarna izlitja naftnih derivatov in podobnih snovi zato, ker o pretakanju nepolarnih snovi (kamor uvrščamo tudi naftne derivate, ki niso topni v vodi in so lažji od nje) skozi kraške vodonosnike vemo še zelo malo. Številne prometne nesreče z razlitji naftnih derivatov na krasu so sčasoma le prinesle spoznanje, da se je treba lotiti reševanja na strokoven način. Ob nesrečah konec prejšnjega stoletja je Inštitut za raziskovanje krasa ZRC SAZU pogosto sodeloval pri ugotavljanju, kateri izviri so ogroženi, kar je bila podlaga za spremljanje njihove kakovosti. Na podlagi dosedanjih opazovanj nesreč z izlitji naftnih derivatov na kraškem svetu vemo, da ti odtekajo po poteh, ki jih ubira s površja v kraško notranjost padavinska voda. Na prvi pojav v izvirih vplivajo predvsem razmere v prsti in vadozni coni ter padavine, ki sledijo. Opravljene primerjave prenosa naftnih derivatov in topnih sledil nakazujejo, da je poznejši način prenosa teh snovi skozi kraške vodonosnike bistveno drugačen od prenosa topnih snovi. Predvidevamo predvsem daljše zadrževanje ter le postopno spiranje naftnih derivatov zaradi možnosti zastajanja v sifonih in adsorpcije na sedimente. Kljub temu pa ostaja še veliko neznank.

V primeru pogostejših nesreč na nekem območju bi prav zaradi vsakokratnega akumuliranja snovi v zaledju lahko prišlo do trajnejšega onesnaženja izvira, kar bi lahko onemogočilo njegovo uporabo. Glede na današnje poznavanje pretakanja topnih snovi skozi vadozno cono pa vemo, da je to močno odvisno od predhodne namočenosti prsti in zapolnjenosti vadozne cone z vodo (*Kogovšek* 2010) ter od padavinskih razmer, ki sledijo. Lahko prihaja tudi do daljšega zadrževanja v vadozni coni in pojava v kraškem izviru z večjim časovnim zamikom (*Kogovšek* in *Šebela* 2004). Zato je ob nesrečah smiselno daljše opazovanje, še posebno v času po intenzivnejših in izdatnejših padavinah.

Omejevalni faktor pri ugotavljanju navzočnosti mineralnih olj je sorazmerno visoka meja določljivosti metode. Plinsko olje je verjetno iztekalo skozi izvir Rižane daljši čas in v zelo nizkih koncentracijah, pod 0,01 mg/l. Čeprav jih nismo mogli določiti, pa lahko ob dlje časa trajajočih pretokih pomenijo prenos večje količine snovi. Tako bi ob koncentraciji 0,005 mg/l in pretoku 20 m^3/s v enem mesecu izteklo 260 kg plin-

The Ara spring has already been active in the time of the spillage. Only two samples were taken between 18 October and 2 November, and in both increased concentrations of mineral oils were detected (10). The first rise occurred even before the gas oil was detected in the Rižana spring. The flow velocity from the spillage point to the Ara spring at relatively low waters was assessed to 50 m/h or even more. At the tracer test in June 1986 (*Krivic* et al. 1989) the concentrations of tracer in the Ara spring were low and the groundwater connection with the flow velocity of 67 m/s was characterized as uncertain. Although the appearance of oil from the spillage near Obrov is due to the low number of samples and low concentrations uncertain as well, the connection with the Ara spring seems possible. An additional tracer test is needed for confirmation.

Since 24 October 1994, mineral oil content has also been monitored in the Sv. Ivan spring in Buzet (*Vlahović* 2000). These data reveal a perceptible increase in mineral oil content and total fats between 27 and 30 October (10). Since measurements were not taken before the accident, we can only predict that gas oil also drained in this direction. Similar as for the Ara spring, only a weak connection was indicated by the tracer test in June 1986.

Conclusion

Traffic accidents involving the drainage of large quantities of hazardous substances into the karst represent a danger for our environment and for karst waters, since even small quantities can contaminate karst springs for long periods. Specially dangerous are spillages of substances which are insoluble in water and lighter than water (e.g. petroleum products) since we still know very little about how these contaminants behave in karst aquifers. Based on the experiences of several traffic accidents involving spillages of petroleum products on karst the need for the involvement of experts has been acknowledged in time. In the case of accidents towards the end of last century the Karst Research Institute frequently took part in identifying those springs that were at risk, which was the basis for the monitoring of their quality. By observing the accidents involving spillages of petroleum products in karst areas to date, we know that they drain along the routes that rainfall follows from the surface skega olja. In tako spiranje verjetno lahko traja nekaj mesecev ali celo več let.

Vsekakor je reševanje posameznih primerov, ko dejansko pride do izlitja nevarne snovi in je treba oceniti, kateri kraški izviri bodo onesnaženi, povezano s poznavanjem značilnosti pretakanja podzemnih voda na obravnavanem območju oz. z že predhodno opravljenimi raziskavami. Hidrogeološke in hidrokemične raziskave, predvsem pa sledilni poskusi (3, 7), nam omogočajo ugotavljanje podzemnih vodni poti.

Le majhen del trenutno izlite večje količine tekočin v sušnih obdobjih preide vadozno cono po najprepustnejših razpokah in se pojavi na izviru, medtem ko se pretežni del snovi akumulira v vadozni coni. Raziskave pretakanja vode skozi prst in vadozno cono (*Kogovšek* in *Šebela* 2004; *Kogovšek* 2010) so pokazale, da lahko prihaja v vodonosniku prav v vadozni coni do najdaljšega zadrževanja vode in morebitnih drugih tekočin na poti v bolj prepustne dele, kjer je pretakanje bistveno hitrejše. Zato se onesnaženje lahko pojavi v kraškem izviru tudi z večjim časovnim zamikom in traja daljši čas (nekaj let in več), saj lahko postopno iztekanje pričakujemo po vsakih izdatnejših padavinah v zaledju. V primeru nesreč je zato smiselno daljše opazovanje, skladno s hidrološkimi in padavinskimi razmerami.

Za vsak izvir, ki je zajet za oskrbo prebivalstva s pitno vodo, bi morali dobro poznati njegovo zaledje, da bi lahko varovali kakovost vode in primerno ukrepali, če bi že prišlo do nepričakovanega onesnaženja. Vendar to ni dovolj, da bi si zagotovili kakovostno vodo. Treba bi se bilo izogniti možnim posledicam nesreč in s primerno gradnjo cest preprečiti neposredni odtok nevarnih snovi v kras. Prvi korak je bil narejen že ob gradnji avtoceste Ljubljana–Razdrto, ko so na kraškem svetu zgradili lovilnike olj, v katere bi v primeru izlitij v prometnih nesrečah stekle nevarne snovi, lažje od vode (*Kogovšek* 1995c). Ob novejši gradnji avtocest na kraškem svetu postavljajo tudi nove generacije zadrževalnih in čistilnih objektov (*Kompare* idr. 2002).

Čeprav so v onesnaženem kraškem izviru koncentracije onesnažil pod mejnimi vrednostmi in celo pod mejo določljivosti ter se pojavljajo povišanja le občasno, ugotavljamo, da je v primeru onesnaženja z naftnimi derivati (Globočec) to dovolj, da je treba vodni vir izključiti iz uporabe. Tu se je kot omejitve-

into the karst interior. Their first appearance in springs is influenced by conditions in the soil and the vadose zone and by the rainfall that follows. Comparisons of the transmission of petroleum products and soluble tracers indicate that the subsequent mode of transfer of these substances through karst aquifers differs significantly. Above all it involves longer retention and gradual washing away of petroleum products due to their accumulation in siphons and adsorption on sediments. However, many other questions remain unsolved.

In the case of more frequent accidents in a given area, the accumulation of substances in the hinterland of a spring on each occasion could lead to more permanent pollution of the spring, which could render its use impossible for a long time. A modern understanding of the flow of soluble substances through the vadose zone recognizes an important influence of the previous saturation of soil and vadose zone (*Kogovšek* 2010) and of the precipitation regime on the characteristics of this flow. Longer retention in the vadose zone and appearance at the spring with a significant time lag are possible (*Kogovšek* and *Šebela* 2004). Therefore in the case of an accident a long-lasting monitoring is necessary, especially in the periods of intensive precipitation.

A limiting factor in the detection of mineral oils is a relatively high detection limit of the method. In the case of the Rižana spring, a long-lasting outflow of gas oil in very low concentrations below 0.01 mg/l was very likely. Although we were not able to detect them, a larger amount of these substances was probably transferred in the periods of higher discharges. In one month, the outflow with the concentration 0.005 mg/l and the discharge 20 m^3/s would wash out 260 kg of gas oil. And such outflow could last for several months or even years.

When taking action in concrete cases of spillage, it is necessary to predict what karst springs will be polluted. This is connected to the knowledge of flow in the area in question, in other words to researches already carried out. Hydrogeological and hydrochemical studies, and above all the tracer tests (3, 7) are efficient tools for assessing the characteristics of the groundwater flow.

In the case of currently spilled larger quantities of liquids in dry periods, only a small part passes through the vadose zone via the most permeable fractures and appears at the springs, while the largest part of the subni faktor pokazala sorazmerno visoka meja detekcije metode določevanja mineralnih olj.

V primerih, ko je tak izvir zajet za vodovod in se za dezinfekcijo vode uporablja klor, nastajajo halogenirani derivati, ki so rakotvorni. To je bil tudi razlog, da so v Rižani po omenjenih nesrečah prešli na čiščenje vode z ultrafiltracijo. Vendar pa se v Sloveniji za dezinfekcijo vode še vedno najpogosteje uporablja prav kloriranje.

stances accumulates in the vadose zone. Research of the flow of water through the soil and the vadose zone (*Kogovšek* and *Šebela* 2004; *Kogovšek* 2010) has shown that it is actually in the vadose zone of an aquifer that the longest retention of water and potential contaminants can occur, as they make their way to more permeable parts of the aquifer, where flow is significantly faster. The pollution can occur in the springs with a significant time lag and longer duration (several years or more) since it is later gradually pushed in the direction of springs by each more intensive precipitation event in the catchment. In the case of such accidents, longer observation is therefore necessary, in accordance with hydrological and precipitation conditions.

The characteristics of the recharge area of each spring, which is used for the water supply, should be well understood to properly protect the water quality and to take efficient measures in the cases of an unexpected pollution. However, this is not enough to ensure good water quality. Possible consequences of accidents should be avoided by adequate construction of roads, which would prevent direct infiltration of hazardous substances into the karst. The first step was made during the construction of the motorway Ljubljana–Razdrto. Oil collectors were designed to collect harmful substances lighter than water in the cases of traffic accidents involving spillages on karst terrains (*Kogovšek* 1995c). In the recent construction of motorways, new generations of retention ponds and purification facilities are being built (*Kompare* et al. 2002).

Although the concentrations of contaminants in a polluted karst spring are below the allowed values or even below the detection limits, and they only appear occasionally, in the case of pollution with petroleum products (e.g. the Globočec spring) this is a sufficient reason to exclude the spring from use. A limiting factor in this process is a relatively high detection threshold of mineral oils.

Disinfection of karst water sources with gas chlorine leads to the formation of carcinogenic halogenated hydrocarbons. This is the reason why after the described accidents the process of ultrafiltration was implemented in the Rižana water supply system. However, the chlorination is still the most often applied method of a drinking water treatment in Slovenia.

6

NAČRTOVANJE MONITORINGA PODZEMNE VODE V VPLIVNEM OBMOČJU ODLAGALIŠČ ODPADKOV NA KRASU NA PODLAGI REZULTATOV SLEDILNIH POSKUSOV

PLANNING OF GROUNDWATER MONITORING IN THE IMPACT AREAS OF LANDFILLS IN KARST BASED ON THE RESULTS OF TRACER TESTS

METKA PETRIČ, JANJA KOGOVŠEK

V številnih delih sveta uporaba in odlaganje odpadkov in celo strupenih snovi še vedno naraščata, s tem pa se povečuje tudi nevarnost onesnaženja. Odlagališča odpadkov so resna grožnja za okolje, zaradi odtekanja izcednih vod v podzemlje so ogrožene predvsem podzemne vode. Še posebej to velja za odlagališča na krasu, ki je zelo ranljiv za posledice različnih virov onesnaževanja. Sposobnost naravnega čiščenja onesnaževal v kraški vodi je majhna in možni negativni vplivi zelo verjetni. Za njihovo ustrezno ovrednotenje je treba vzpostaviti dobro načrtovan, dolgotrajen monitoring kakovosti vode. Za izbiro najbolj primernih točk za monitoring in izdelavo njegovega programa na kraških območjih so se kot zelo uporabna raziskovalna metoda pokazali sledilni poskusi.

6.1 Odlagališča odpadkov na krasu

Izbira točk za monitoring kakovosti kraških voda v vplivnem območju odlagališč odpadkov temelji na nekaterih posebnih značilnostih. Zaradi velike heterogenosti kraških vodonosnikov vrtine za monitoring, izvrtane na območju odlagališča, niso reprezentativne za zaznavanje morebitnega onesnaženja kraških voda (*Kaçaroğlu* 1999; *Vadillo* idr. 2005; *Kogovšek* in *Petrič* 2010a). Zato je treba ugotoviti glavne smeri podzemnega odtoka z območja odlagališča in določiti točke, kjer so ti tokovi dostopni. Običajno so to izviri ali vodni tokovi v jamah. Za določitev smeri in značilnosti podzemnega pretakanja so se poleg osnovnih hidrogeoloških metod kot zelo primerni pokazali sledilni poskusi (*Eiswirth* idr. 1999; *Zhou* idr. 2002; *Benischke* idr. 2007).

V zadnjih letih so bili uspešno uporabljeni v več študijah za izdelavo načrta monitoringa v vplivnem območju odlagališč na slovenskem krasu (*Kogovšek* idr. 1999; *Petrič* in *Šebela* 2005; *Kogovšek* in *Petrič* 2006, 2007, 2010a). Po slovenski zakonodaji gradnja novih odlagališč na tako imenovanih rizičnih območjih, med katera spada tudi kras, ni več možna. Za še obstoječa odlagališča na krasu (1) pa je predvideno zapiranje, nadaljnje vzdrževanje in varovanje. Upravljavci odlagališč morajo pripraviti program monitoringa kakovosti

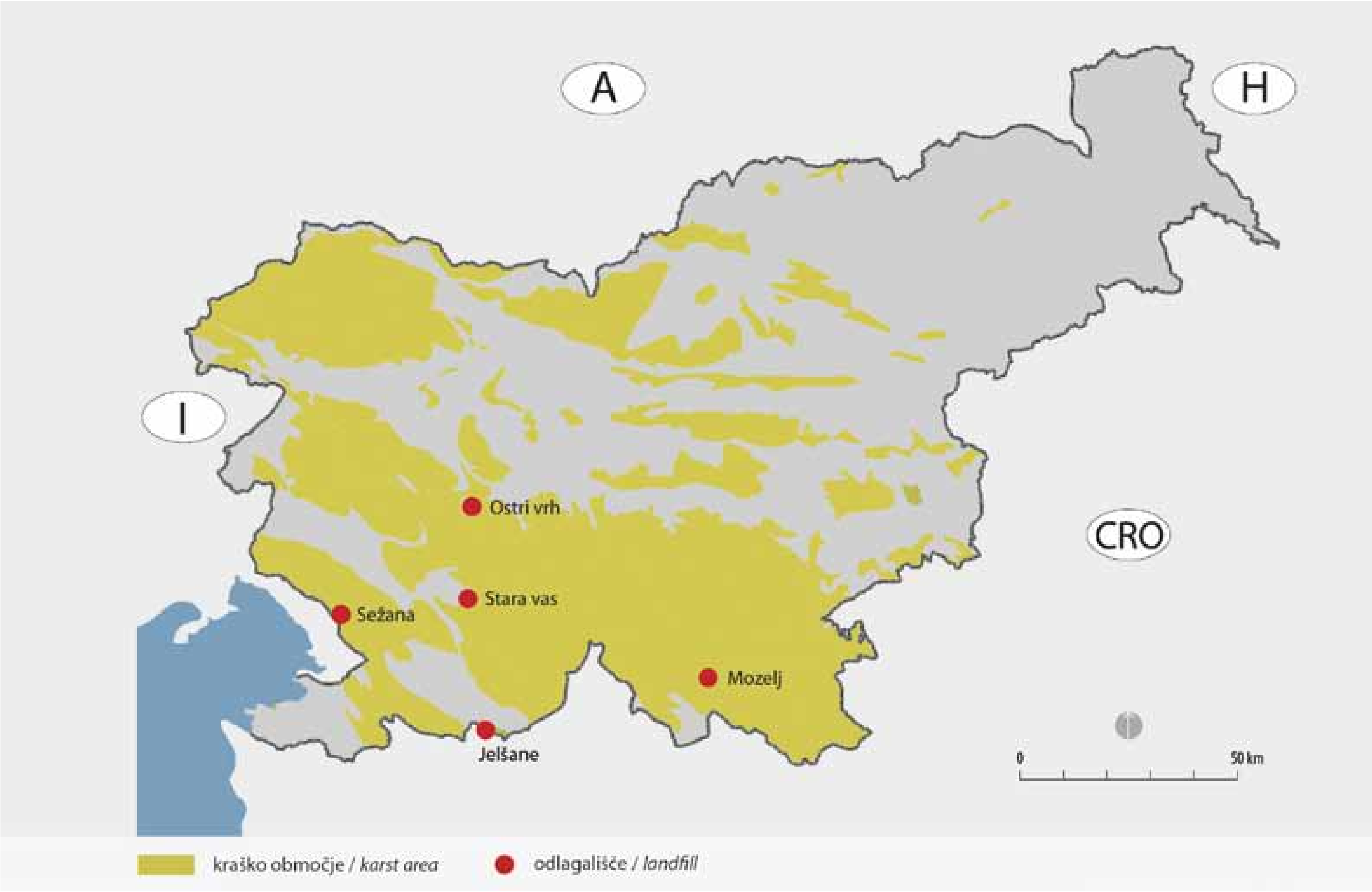
In many parts of the world the use and disposal of wastes and even toxic materials are still growing, therefore the danger of pollution is increasing, too. The landfills are a serious threat to environment, specially to groundwater due to percolation of leachates into the underground. This is especially true for the landfills in karst areas with very high intrinsic vulnerability. The capacity of natural treatment of waterborne contaminants in karst is relatively ineffective and the possible negative influences are very likely. To assess them properly, a well-planned, long-term water quality monitoring has to be implemented. In karst areas, tracer tests were proved a valuable research method for defining the most suitable monitoring points and preparing efficient monitoring plans.

6.1 Landfills in karst areas

For karst areas, the selection of monitoring points in the impact areas of landfills has some specific principles. Because of high heterogeneity of karst aquifers, the monitoring boreholes in the vicinity of the landfill are not representative for detecting the pollution of karst waters (*Kaçaroğlu* 1999; *Vadillo* et al. 2005; *Kogovšek* and *Petrič* 2010a). Therefore, the main paths of groundwater flow from the landfill area have to be defined and their accessible sections selected. Usually these are springs or water courses in caves. Additional to basic hydrogeological mapping, the tracer tests were proved a very useful method for detecting the directions and characteristics of the groundwater flow (*Eiswirth* et al. 1999; *Zhou* et al. 2002; *Benischke* et al. 2007).

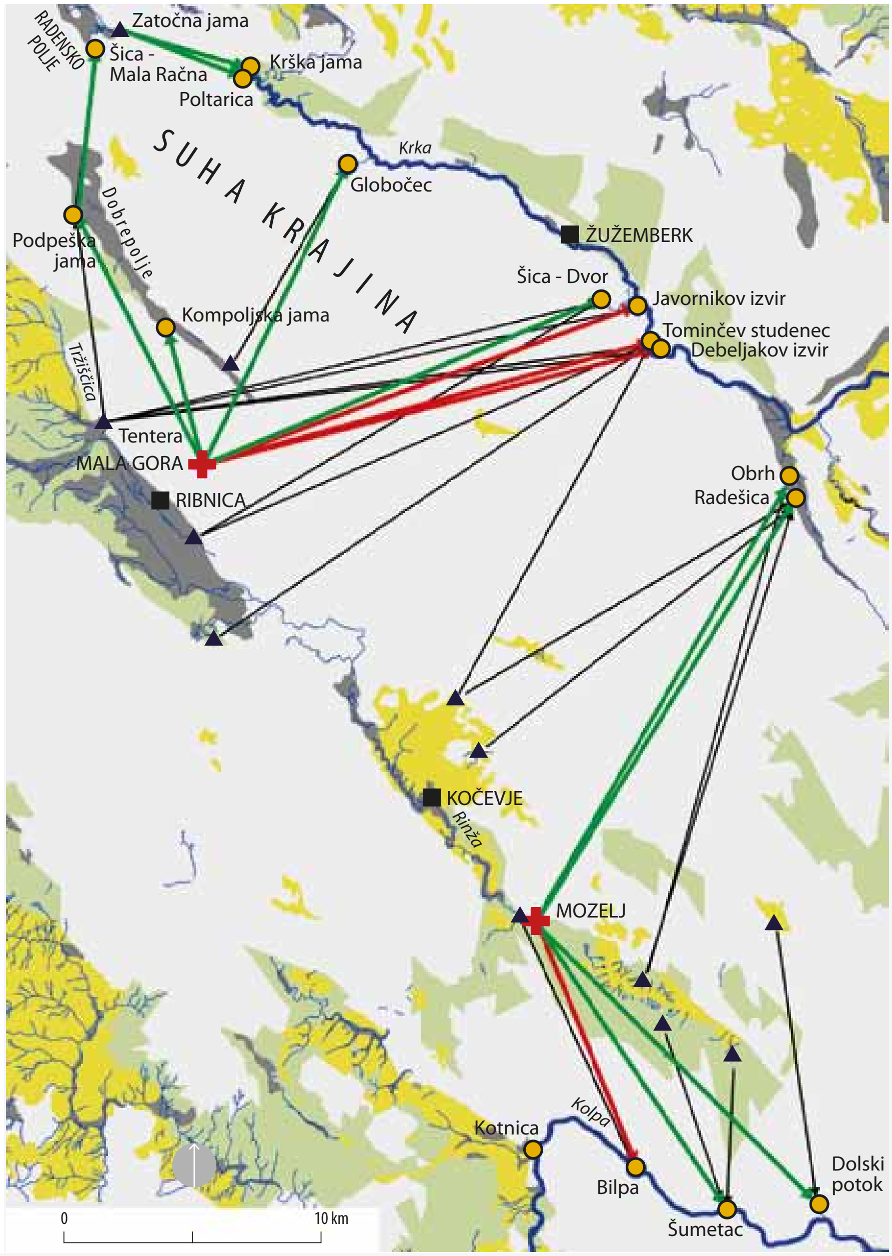
In recent years, the tracer tests were successfully applied in several case-studies of planning the water quality monitoring in the impact areas of landfills in the Slovene karst (*Kogovšek* et al. 1999; *Petrič* and *Šebela* 2005; *Kogovšek* and *Petrič* 2006, 2007, 2010a). According to the Slovene legislation it is not possible to plan new landfills on the so-called risky areas to which also the karst belongs. For the still existing ones (1), the closing as well as their further maintenance and protection are foreseen. Therefore, the landfill managers are obliged to prepare the programme of water quality monitoring, which should consider the vode v skladu s *Pravilnikom o obratovalnem monitoringu onesnaževanja podzemne vode* (*PrOM*, 2006). V programu so predstavljene hidrogeološke razmere in značilnosti podzemne vode pred izgradnjo odlagališča, ciljne hidrogeološke cone, določene so lokacije objektov za monitoring in opisani načini izgradnje in opreme teh objektov, prikazana opazovanja nivojev podzemne vode in smeri toka podzemne vode ter podan načrt testiranja ustreznosti točk monitoringa. Kot primerne raziskovalne metode so predlagani sledilni poskusi, strukturno kartiranje, hidrokemične analize in geofizikalne metode. Po naših izkušnjah dobimo najboljše rezultate z vzporedno uporabo teh metod, zlasti pa priporočamo izvedbo sledilnega poskusa.

requirements of the *Rules on the performance of operational monitoring of groundwater pollution* (*PrOM*, 2006). In the programme the hydrogeological conditions and characteristics of groundwater previous to the landfill construction, target hydrogeological zones, locations of monitoring points and description of the construction and equipment of these objects, observations of water table and groundwater flow directions, and the plan of testing the adequacy of monitoring points have to be described. As research methods the tracer tests, structural mapping, hydrochemical analyses and geophysical methods are suggested. According to our experiences, the best results are obtained by a parallel application of the listed methods, however,



1 Leta 2011 še aktivna odlagališča odpadkov na krasu v Sloveniji.
In 2011 still active landfills in the Slovene karst.

2 Hidrogeološka karta širšega območja odlagališč Mala gora in Mozelj.
Hydrogeological map of the broader area of the Mala gora and Mozelj landfills.



točka injiciranja / *injection point*	površinski tok / *surface stream*
odlagališče / *landfill*	kraški vodonosnik / *karst aquifer*
izvir / *spring*	medzrnski vodonosnik / *porous aquifer*
glavna zveza / *main connection*	zelo slabo prepustne kamnine / *very poorly permeous* rocks
stranska zveza / *secondary connection*	razpoklinski vodonosnik / *fissured aquifer*
ostala sledenja / *other tracer tests*	

V nadaljevanju so predstavljeni primeri opravljenih študij na treh odlagališčih na slovenskem krasu: na Mali gori, v Mozlju in Sežani.

6.2 Hidrogeološke značilnosti območij izbranih odlagališč

Odlagališči odpadkov Mala gora in Mozelj ležita na kraškem območju med rekama Krko in Kolpo v jugovzhodni Sloveniji (2). Osrednji kraški vodonosnik gradijo dobro prepustne jurske in kredne karbonatne kamnine. Jurski apnenci z vložki dolomita prevladujejo v južnem delu, v severnem pa najdemo predvsem kredne apnence prav tako z vložki dolomita. Na jugozahodnem robu kraškega platoja se na manj prepustnih triasnih karbonatnih kamninah ter slabo prepustnih permijskih in triasnih klastičnih kamninah, prekritih s kvartarnimi rečnimi in jezerskimi sedimenti, pojavljajo površinski tokovi. Med njimi je največja reka Rinža, ki odvisno od hidroloških razmer ponika na različnih mestih zahodno od odlagališča Mozelj in se pretaka podzemno proti izvirom v dolini reke Kolpe.

Podzemni tok v kraškem vodonosniku je usmerjen proti kraškim izvirom v obeh rečnih dolinah. Na severozahodni strani sta dva glavna izvira reke Krke s skupnim srednjim pretokom 8,3 m^3/s, minimalnim pretokom 0,8 m^3/s in maksimalnim pretokom 80 m^3/s (*Kolbezen* in *Pristov* 1998). V jugozahodnem delu zaledja obeh izvirov je nekaj občasnih izvirov, ki so aktivni le po močnejših padavinah, ob nizkih vodostajih pa je voda dostopna le v Podpeški in Kompoljski jami.

Dolvodno ob reki Krki je njen desni pritok izvir Globočec, ki je regionalno pomemben vir za oskrbo s pitno vodo. Njegovi srednji pretoki se gibljejo med 1 in 1,5 m^3/s (*Novak* 1985). Jugovzhodno od Žužemberka so trije izviri: Tominčev studenec, Debeljakov izvir in Javornikov izvir. Slednji je le občasno aktiven. Največji je Tominčev studenec z minimalnim pretokom 0,54 m^3/s, srednjim pretokom 1,6 m^3/s in maksimalnim pretokom 10 m^3/s (*Novak* 1992). Naprej proti vzhodu je potok Radešica, ki je še en pomemben desni pritok Krke. Napajajo ga številni izviri, največja med njimi sta Radešica in Obrh. V obdobju od aprila do septembra 1988, za katero razpolagamo s podatki, so se pretoki

we strongly recommend the use of tracer tests. Three examples of case-studies of the Mala gora, Mozelj and Sežana landfills in the Slovene karst are presented below.

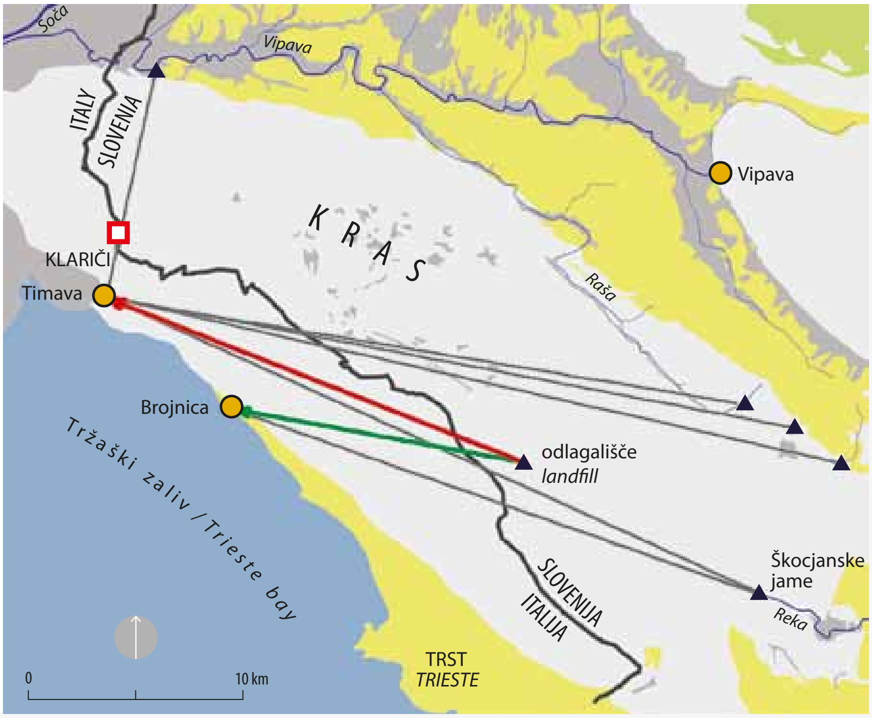
6.2 Hydrogeological characteristics of the selected landfill areas

The Mala gora and Mozelj landfills are situated in the karst area of south-eastern Slovenia between the Krka and Kolpa rivers (2). The main karst aquifer is composed of well permeable Jurassic and Cretaceous carbonate rocks. Jurassic limestone with inliers of dolomite is dominant in the southern part, while in the northern part Cretaceous limestone with inliers of dolomite prevails. On the south-western part of the karst plateau are less permeable Triassic carbonate rocks and poorly permeable Permian and Triassic clastic rocks covered with Quaternary river and lacustrine sediments, on which the surface drainage net has developed. The biggest is the Rinža river, which sinks at various locations (depending on hydrological conditions) west of the Mozelj landfill and flows underground towards the springs in the Kolpa valley.

The underground flow within the karst aquifer is directed towards several karst springs in the two river valleys. On the north-western side is the Krka river with two main springs. Their common mean discharge is 8.3 m^3/s, the minimum measured discharge 0.8 m^3/s and the maximum one 80 m^3/s (*Kolbezen* and *Pristov* 1998). South-west of the springs, within their catchment, some intermittent springs are active after heavy raining, while during low waters the underground water can only be reached in the caves Podpeška jama and Kompoljska jama.

The Globočec spring, a right tributary of the Krka river, is a regionally important source of drinking water with the mean discharge between 1 and 1.5 m^3/s (*Novak* 1985). South-east of Žužemberk there are three springs: Tominčev studenec, Debeljakov izvir and Javornikov izvir. The latter is only temporarily active. The biggest among them is Tominčev studenec with the minimum discharge 0.54 m^3/s, mean discharge 1.6 m^3/s and maximum discharge 10 m^3/s (*Novak* 1992). Further towards east runs the Radešica stream,

3 Hidrogeološka karta območja Krasa z odlagališčem Sežana.
Hydrogeological map of the Kras area with the Sežana landfill.



Radešice gibali med 0,5 in 23 m³/s, pretoki Obrha pa med 0,5 in 2,5 m³/s.

V zgornjem delu doline Kolpe je več izvirov na njenem levem bregu. Večji in stalni so Bilpa, Dolski potok, Šumetac in Kotnica. Po podatkih, ki nam jih je za obdobje od septembra 2005 do avgusta 2007 posredovala Agencija Republike Slovenije za okolje (ARSO), so se pretoki Bilpe gibali med 0,1 in 35,7 m³/s.

Odlagališče Sežana leži na območju Krasa v jugozahodni Sloveniji (3). Osrednji del Krasa gradijo zakraseli in dobro prepustni kredni apnenci in deloma dolomiti v debelini več kot 1000 m (*Kranjc* 1997). Proti severu, jugu in vzhodu prehajajo v ploščaste apnence terciarne starosti, ki so prav tako razpokani in zakraseli. Karbonatni masiv obdaja zelo slabo prepusten

another important right tributary of the Krka river. It is recharged by several karst springs, the biggest among them are the Radešica and Obrh springs. In the period from April to September 1988, the discharges of Radešica ranged from 0.5 to 23 m³/s, and of Obrh from 0.5 to 2.5 m³/s.

In the upper part of the Kolpa valley there are several springs on the left bank. Larger and permanent are the springs Bilpa, Dolski potok, Šumetac, and Kotnica. The discharge data of the Bilpa spring were provided by the Slovenian Environment Agency (ARSO). In the period from September 2005 to August 2007 they ranged from 0.1 to 35.7 m³/s.

The Sežana landfill is situated in the Kras area in south-western Slovenia (3). The central part of Kras is

4 Odlagališče Mozelj s točkama injiciranja T-1 in T-2 ter vrtinami za monitoring Mo-1, Mo-2 in Mo-3 (topografska osnova: ARSO 2010).
The Mozelj landfill with injection points T-1 and T-2 and monitoring boreholes Mo-1, Mo-2, Mo-3 (topographic base: ARSO 2010).

eocenski fliš, ki ima vlogo hidrogeološke pregrade. Površinski tokovi s fliša ponikajo na vzhodnem obrobju na stiku s karbonatnimi kamninami in napajajo kraški vodonosnik. Najpomembnejši je prispevek reke Reke, ki ponika v Škocjanske jame na jugovzhodnem robu Krasa. V obdobju 1961–1990 je bil najnižji izmerjeni pretok Reke na vodomerni postaji približno 7 km pred ponorom 0,18 m^3/s, srednji pretok pa 8,26 m^3/s (*Kolbezen* in *Pristov* 1998). V obdobju zelo visokih vod pa lahko pretoki celo presežejo 300 m^3/s. Manj pomemben je prispevek manjših ponikalnic, ki se nahajajo naprej proti severu.

Na severozahodnem robu je kraški vodonosnik v dinamičnem stiku z medzrnskim vodonosnikom aluvialnih sedimentov ob rekah Soči in Vipavi. Prazni

composed of well karstified and well permeable Cretaceous limestone and partly dolomite in the thickness of more than 1000 m (*Kranjc* 1997). To the north, south and east these pass into bedded and tabular limestone of Tertiary age, which is also fissured and karstified. The carbonate massif is surrounded with very poorly permeable Eocene flysch which acts as an important hydrogeological barrier. On the eastern side, the surface streams from flysch areas sink at the contact with carbonate rock and recharge the karst aquifer. The most important is the contribution of the Reka river which sinks into the Škocjan caves/ Škocjanske jame at the south-eastern border of Kras. In the period 1961–1990, the lowest measured discharge of the Reka river at the gauging station approxise skozi številne izvire v Tržaškem zalivu Jadranskega morja v Italiji. Največji je izvir Timava s pretoki med 9,1 in 127 m^3/s ter srednjim pretokom 30,2 m^3/s v obdobju 1972–1983 (*Civita* idr. 1995). Naprej proti notranjosti je še več manjših izvirov na nadmorskih višinah med 0,4 in 12 m. Med številnimi podmorskimi izviri vzdolž obale je najpomembnejši izvir Brojnica pri Nabrežini. V slovenskem delu vodonosnika ni izvirov, podzemna voda pa je dosegljiva le v nekaterih globokih jamah in vrtinah. V črpališču Klariči jo od leta 1983 črpajo za oskrbo s pitno vodo v petih kraških občinah.

6.3 Sledilni poskusi

Z namenom, da bi simulirali pretakanje izcednih vod iz opisanih odlagališč odpadkov na krasu, smo v obdobju 2004–2006 izvedli tri sledilne poskuse z injiciranjem fluorescentnih sledil (uranin na vseh treh lokacijah, na odlagališču Mozelj pa še dodatno eozin) v dobro prepustne površinske razpoke na območju odlagališč. Iskali smo odgovore na naslednja vprašanja: v kateri smeri in kako hitro odtekajo z odlagališča padavinske vode in z njimi škodljive snovi, kakšne so značilnosti dinamike transporta v odvisnosti od padavinskih razmer in v katerih izvirih ali vodnih jamah lahko pričakujemo pojav škodljivih snovi. Na osnovi teh podatkov je bilo možno izdelati program monitoringa kakovosti podzemnih voda v vplivnih območjih odlagališč. Na odlagališču Mozelj pa smo dodatno preizkusili reprezentativnost treh vrtin za monitoring, ki so bile predhodno izvrtane na obrobju odlagališča (4).

Injiciranja so bila izvedena v času po obilnih predhodnih padavinah, ko je bil velik del por in razpok v prsti in vadozni coni začasno napolnjen z vodo in hidravlično povezan. Takšne razmere omogočajo hitro infiltracijo in hitro odtekanje skozi vadozno cono. Dežemeri Onset RG2-M in Eijkelkamp e+ so bili uporabljeni za merjenje padavin na odlagališčih v 15-minutnih intervalih. Na izvirih Tominčev studenec in Globočec smo nivoje vode merili v urnih intervalih z Eijkelkamp CTD diverjem in modulom 750-ISCO 6700, pretoke pa izračunali na osnovi pretočnih krivulj. Za izvir Bilpa smo podatke o pretokih pridobili na Agenciji Republike Slovenije za okolje, za

mately 7 km upstream the ponor was 0.18 m^3/s and the mean discharge 8.26 m^3/s (*Kolbezen* and *Pristov* 1998). In the time of extremely high waters the discharge can reach up to more than 300 m^3/s. Less important is the contribution of the inflows from smaller sinking streams located further towards the north.

On the north-western part the karst aquifer is in a dynamic contact with a porous aquifer of alluvial sediments deposited along the Soča and Vipava rivers. The Kras area is discharged through several springs in the Trieste Bay of the Adriatic Sea in Italy. The biggest is the Timava spring with discharges from 9.1 m^3/s to 127 m^3/s, and the mean discharge 30.2 m^3/s in the period 1972–1983 (*Civita* et al. 1995). Several smaller springs are located further inland at the altitudes from 0.4 to 12 m above the sea level. Among numerous submarine springs along the coast the Brojnica spring near Nabrežina/Aurisina is the most important one. There are no springs in the Slovene part of the aquifer, and groundwater is only accessible in some deep caves and boreholes. In the pumping station Klariči it has been pumped out for the water supply of 5 municipalities in the Kras region since 1983.

6.3 Tracer tests

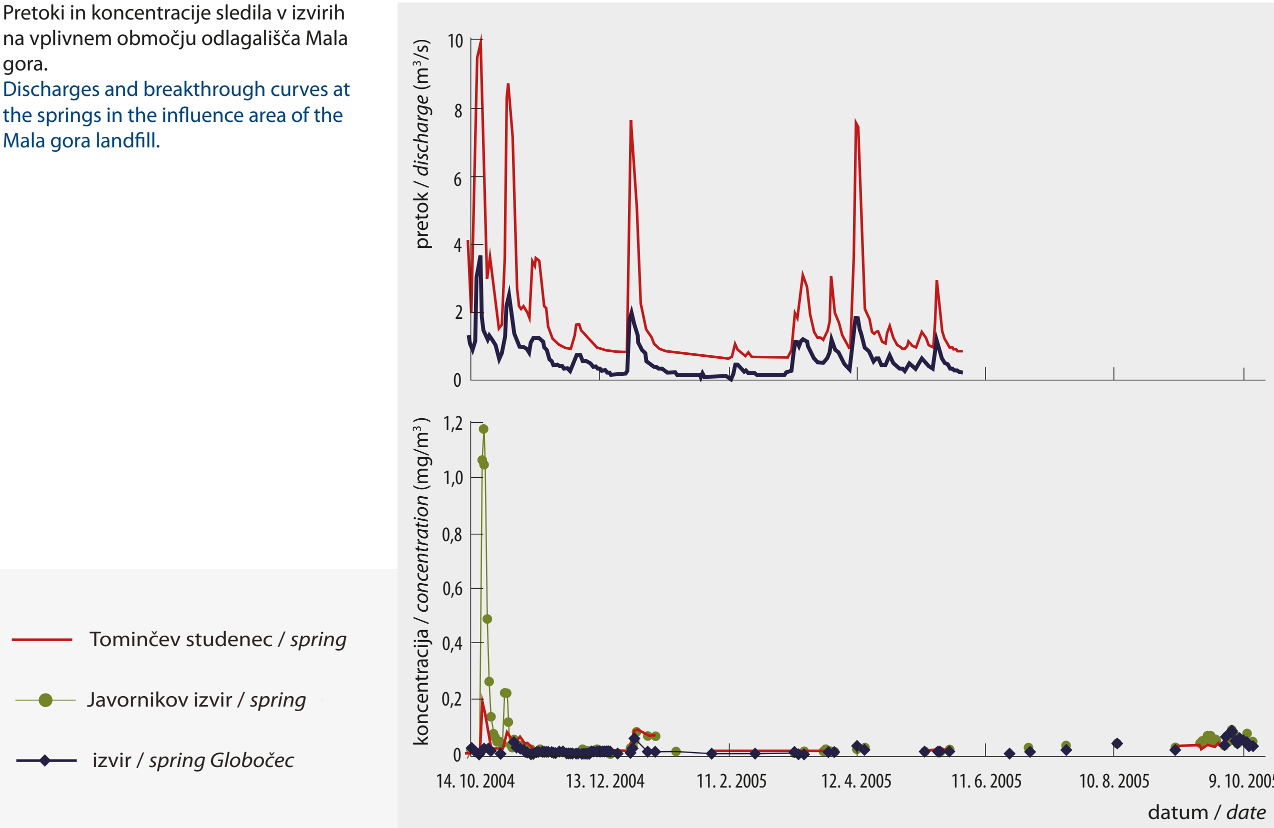
With the aim of simulating the flow of leachates from the described landfills in karst, three tracer tests with the injection of fluorescent tracers (Uranine at all three locations, and additionally Eosin at the Mozelj landfill) into well permeable fissures on the surface near the landfills were carried out in the period 2004–2006. The tests were aimed to answer the following questions: in which direction and how fast infiltrated precipitation water (and with water also harmful substances) from the landfill flows, which are the characteristics of transport dynamics in dependence of precipitation conditions, and in which springs or water caves the appearance of the harmful substances can be expected. Based on these data, it was possible to prepare the plans of groundwater quality monitoring in the impact areas of the landfills. An additional goal of the tracing at Mozelj was the testing of the functioning of three monitoring boreholes, which were previously drilled at the margins of the landfill (4).

Točka injiciranja (sledilo) ***Injection point (tracer)***	Datum injiciranja *Date of injection*	M (kg)	Dokazana zveza *Proved connection*	L (km)	t_{dom} (d)	v_{dom} (m/h)	R (%)	C_{max} (mg/m³)
Mala gora (*uranin*/Uranine)	14.10.2004	7	Tominčev studenec/*spring*	17.80	5	145		0.19
			Javornikov izvir/*spring*	17.70	6	122		1.18
			Debeljakov izvir/*spring*	18.00	6	126		0.08
			Globočec	12.70	5	102	3	0.09
			Podpeška jama/*cave*	10.70	17	26		0.13
Mozelj – T-1 (eozin/*Eosin*)	5.4.2006	18	Bilpa	10.30	9	48	79	12.00
			Šumetac	13.30	56	11		0.30
			Dolski potok/*spring*	15.30	56	10		0.18
			Radešica	18.70	56	14		0.10
			Vrtina/*Borehole* Mo-2	0.19	1.2	7		0.52
			Vrtina/*Borehole* Mo-3	0.46	1.9	10		0.68
Mozelj – T-2 (uranin/*Uranine*)	5.4.2006	18	Bilpa	10.30	9	48	92	19.00
			Šumetac	13.30	56	11		0.09
			Dolski potok/spring	15.30	56	10		0.04
			Radešica	18.70	56	14		0.03
			Vrtina/Borehole Mo-3	0.38	0.2	85		0.11
Sežana (uranin/*Uranine*)	20.4.2005	38	Timava	21.40	23	39	93	0.48
			Brojnica	14.20	31	19		0.14

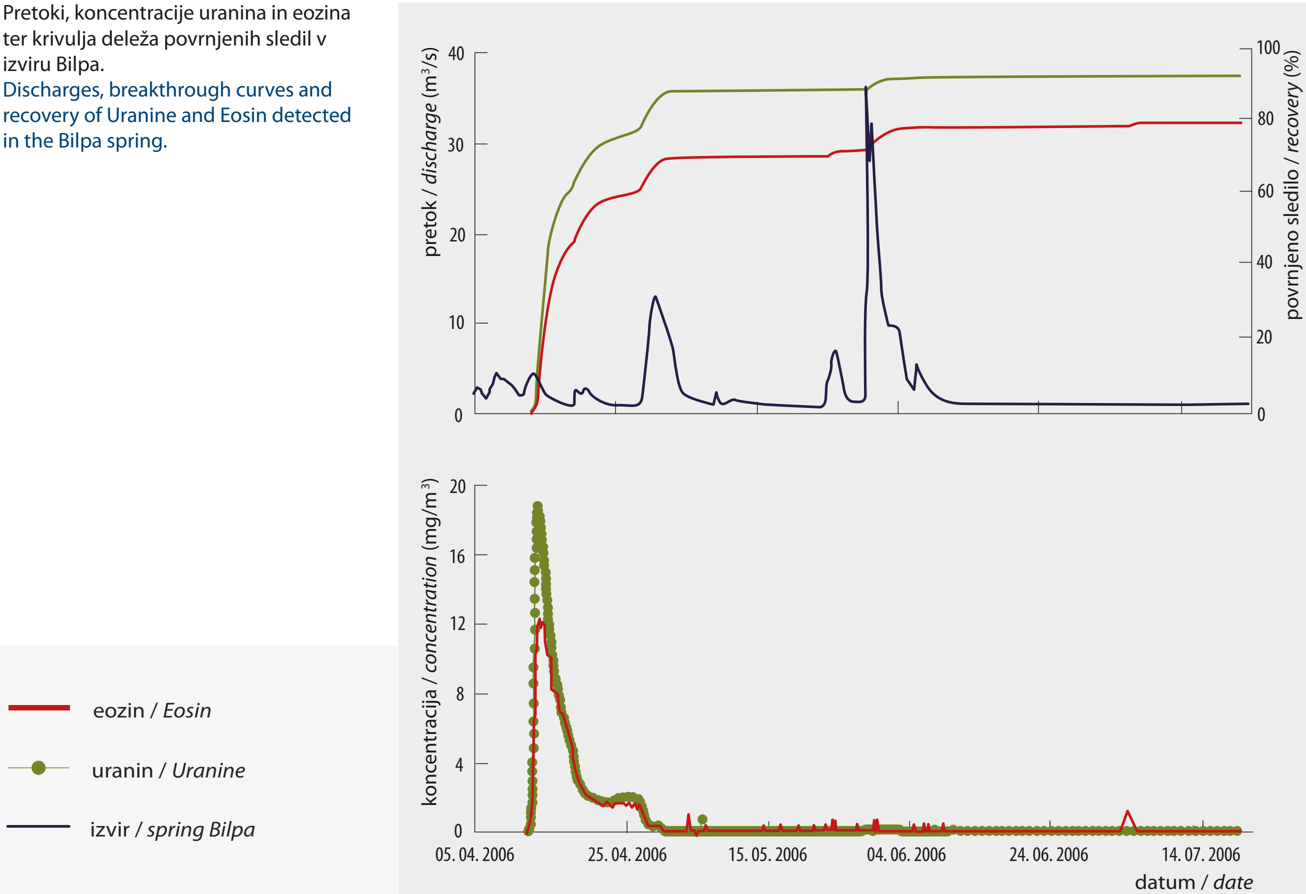
Tabela 1
Značilnosti in rezultati sledilnih poskusov (M – količina injiciranega sledila, L – zračna razdalja med točko injiciranja in izvirom, t_{dom} – čas od injiciranja do izmerjene najvišje koncentracije, v_{dom} – dominantna navidezna hitrost toka, R – delež povrnjenega sledila, C_{max} – maksimalna koncentracija).

Tabela 1
The characteristics and results of tracer tests (M – amount of injected tracer, L – air distance between the injection point and the spring, t_{dom} – time between injection and detection of the maximum concentration, v_{dom} – dominant apparent flow velocity, R – tracer recovery, C_{max} – maximum concentration).

5 Pretoki in koncentracije sledila v izvirih na vplivnem območju odlagališča Mala gora.
Discharges and breakthrough curves at the springs in the influence area of the Mala gora landfill.



6 Pretoki, koncentracije uranina in eozina ter krivulja deleža povrnjenih sledil v izviru Bilpa.
Discharges, breakthrough curves and recovery of Uranine and Eosin detected in the Bilpa spring.



izvir Timava pa pri podjetju ACEGAS, ki upravlja s tržaškim vodovodom.

Vzorce smo zajemali z avtomatskim zajemalnikom ISCO 6700 ali ročno na izbranih izvirih. Fluorescenco uranina (E_{ex} = 491 nm, E_{em} = 512 nm, meja detekcije 0,01 mg/m³) in eozina (E_{ex} = 516 nm, E_{em} = 538 nm, meja detekcije 0,05 mg/m³) smo merili v našem laboratoriju z luminiscenčnim spektrometrom LS 30, Perkin Elmer. Prve meritve smo izvedli takoj po zajemu vzorcev, ponovili pa smo jih pozneje z dekantiranimi vzorci. V izviru Bilpa in črpališču Klariči smo fluorescenco dodatno merili *in situ* s fibrooptičnim fluorimetrom LLF-M Gotschy Optotechnik v 30-minutnih intervalih.

6.4 Smeri in značilnosti podzemnega toka z območja odlagališč

S sledilnimi poskusi so bile ugotovljene glavne in stranske podzemne vodne povezave med odlagališči in kraškimi izviri (2, 3). Za vsako od dokazanih zvez smo izračunali dominantno navidezno hitrost toka v_{dom} glede na zračno razdaljo med točkama injiciranja in pojava sledila ter s časom t_{dom}, v katerem je bil zabeležen prvi višek na krivulji koncentracije sledila (tabela 1). Poleg tega smo na temelju podatkov o koncentraciji in pretoku ocenili še delež povrnjenega sledila.

6.4.1 Odlagališče Mala gora

Uranin, ki smo ga injicirali na odlagališču Mala gora, smo že po 5 dneh in v najvišjih koncentracijah do 1,18 mg/m³ zaznali v Javornikovem izviru (2, 5). Hkrati se je v koncentracijah do 0,19 mg/m³ pojavil v Tominčevem studencu, nekoliko kasneje pa še v Debeljakovem izviru. Velike oscilacije vsebnosti uranina v Podpeški jami kažejo na dotoke vode iz različnih delov vodonosnika. Prvi višek se je pojavil že po 3 dneh, najvišja koncentracija 0,135 mg/m³ pa po 17 dneh. V Kompoljski jami je bilo odvzetih le nekaj vzorcev, v katerih je bil signal občasno povečan.

Koncentracije uranina v izviru Globočec so bile le malenkost nad mejo detekcije, ker pa so se ta povečanja pojavila hkrati kakor v drugih izvirih, lahko ob

The injections were performed in conditions of abundant previous precipitation, when a major part of pores and fissures in the soil and vadose zone was temporarily filled with water and hydraulically connected. These conditions are favorable for rapid infiltration and quick flow through the vadose zone. Rain-gauges Onset RG2-M and Eijkelkamp e+ were used to measure precipitation at 15-minute intervals at the landfills. At the springs Tominčev studenec and Globočec the water levels were measured in hourly intervals with an Eijkelkamp CTD diver and ISCO 6700 with 750 Area-velocity flow module, and discharges were calculated based on the existing stage-discharge curves. For the Bilpa spring the discharge data were provided by the Slovenian Environment Agency, and for the Timava spring by the water supply company ACEGAS.

Samples were collected with automatic samplers ISCO 6700 or manually at the selected springs. Fluorescence of Uranine (E_{ex} = 491 nm, E_{em} = 512 nm, detection limit 0.01 mg/m³) and Eosin (E_{ex} = 516 nm, E_{em} = 538 nm, detection limit 0.05 mg/m³) was measured in our laboratory by a Luminescence Spectrometer LS 30, Perkin Elmer. First measurements were carried out immediately after the sampling and then later when possible suspended particles in the samples were decanted. In the Bilpa spring and at the Klariči pumping station, fluorescence was additionally measured *in situ* by a Fiber-optic Fluorometer LLF-M Gotschy Optotechnik at 30-minute intervals.

6.4 Directions and characteristics of groundwater flow from the landfill areas

The main and secondary directions of groundwater flow from the landfill areas to karst springs were defined by performed tracer tests (2, 3). For each of the proved connections the dominant apparent flow velocity v_{dom}—regarding the air distance between the injection and sampling points and the time t_{dom} at which the first peak of breakthrough curve C_{max} was detected—was calculated (table 1). Additionally, the recovery of injected tracer was assessed based on the discharge and tracer concentration data.

visokih vodostajih potrdimo stransko povezavo odlagališča s tem izvirom. Večinoma pa se Globočec napaja iz drugih delov kraškega vodonosnika. Povečane koncentracije uranina so se pojavljale tudi ob kasnejših padavinskih dogodkih, najvišja vrednost 0,085 mg/m³ je bila izmerjena šele oktobra 2005, skoraj eno leto po injiciranju. Po vsakih bolj intenzivnih padavinah pride do iztekanja sledila iz slabše prepustnih delov kraškega vodonosnika. V tako obsežnem in heterogenem sistemu je pojavljanje sledila v izvirih odvisno od hidroloških razmer, ki se značilno spreminjajo v prostoru in času. Ugotovitve o daljšem zadrževalnem času v smeri proti izviru Globočec je treba upoštevati pri načrtovanju monitoringa podzemne vode v vplivnem območju odlagališča.

Zaradi pomanjkanja ustreznih podatkov o pretokih smo delež povrnjenega sledila ocenili le približno. Na opazovanih izvirih se je pojavila več kot polovica injiciranega uranina, od tega približno 3 % na izviru Globočec (*Kogovšek* in *Petrič* 2006).

6.4.2 Odlagališče Mozelj

Dokazana je bila glavna smer podzemnega pretakanja z odlagališča Mozelj proti izviru Bilpa. Uranin in eozin sta se pojavila praktično sočasno, sedem dni po injiciranju, ko je pretok izvira upadal (6). Zaradi nizkih pretokov so bile koncentracije sledil visoke. Najvišje vrednosti so bile izmerjene 9 dni po injiciranju, potem pa so hitro upadale in ostajale nekoliko nad 1 mg/m³ do konca aprila. Po padavinskem dogodku, ki je sledil, je bila iztisnjena večja količina sledila, zaradi povečanih pretokov pa so bile izmerjene nižje koncentracije. Že v enem tednu po injiciranju je bilo povrnjenega 70 % uranina in 55 % eozina, v treh mesecih po injiciranju pa 92 % uranina in 74 % eozina (*Kogovšek* in *Petrič* 2010a).

V drugih opazovanih izvirih sta se sledili pojavili le v nizkih koncentracijah. V izvirih Dolski potok in Šumetac smo bolj izrazito povišanje zaznali vzporedno s povečanjem pretoka 30. maja 2006. Zvezno pojavljanje eozina in uranina v izviru Radešica smo po vsakem bolj intenzivnem padavinskem dogodku beležili od začetka maja 2006 do januarja 2007. Lahko sklepamo, da je povezava med odlagališčem in temi tremi izviri možna, a šibka.

6.4.1 The Mala gora landfill

Uranine injected at the Mala gora landfill was detected already after 5 days and in highest concentrations up to 1.18 mg/m³ at the spring Javornikov izvir (2, 5). At the same time it was detected in the spring Tominčev studenec in concentrations up to 0.19 mg/m³, and with a short delay also in Debeljakov izvir. Strong oscillations of Uranine concentrations measured in the cave Podpeška jama indicate inflows from various parts of the aquifer. The first peak has appeared already after 3 days, while maximum concentration 0.135 mg/m³ was detected after 17 days. In the cave Kompoljska jama only some separate samples were taken, in which the signal was occasionally increased.

Measured concentrations of Uranine in the Globočec spring were only slightly above the detection limit, however the signal was simultaneous to the one at all the other springs. We can conclude that additional to the main direction of the flow towards the springs near Žužemberk also the secondary connection with the Globočec spring was confirmed in the existing conditions of high waters. However, this spring is mainly recharged from other parts of the karst aquifer. Increased concentrations of tracer were detected at this spring also after later precipitation events, and the maximum value 0.085 mg/m³ was measured in October 2005, almost one year after the injection. After each more intensive precipitation event the tracer stored in the low-permeable parts of the karst water system is pushed out. In such extensive and heterogeneous system the appearance of tracers in the springs and the tracer concentrations are largely influenced by hydrological conditions which differ significantly in time and space. The information about longer retention time in the direction towards the Globočec spring should be considered in the planning of water quality monitoring in the impact area of the landfill.

Due to the lack or low accuracy of discharge data, the tracer recovery was estimated only roughly. More than a half of injected tracer was recovered in all the observed springs, approximately 3 % in the Globočec spring (*Kogovšek* and *Petrič* 2006).

Vzorčili smo tudi v vseh treh vrtinah za monitoring. V vrtini Mo-1 so koncentracije sledila ostajale okrog meje določljivosti. V vrtini Mo-2 smo zaznali le eozin s kratkim in neizrazitim vrhom krivulje koncentracije sledila (7). V vrtini Mo-3 sta se pojavili obe sledili v relativno nizkih koncentracijah. Ti rezultati kažejo, da je večji del injiciranih sledil odtekel po dobro prepustnih razpokah, ki jih vrtine za monitoring niso dosegle.

6.4.3 Odlagališče Sežana

Uranin, ki smo ga injicirali na odlagališču Sežana, se je najprej pojavil v izviru Timava po 12 dneh (8), maksimalna koncentracija 0,48 mg/m³ pa je bila izmerjena 23 dni po injiciranju. V izviru Brojnica smo sledilo zaznali šele mesec dni po injiciranju, z maksimalno koncentracijo 0,14 mg/m³. V celotnem obdobju opazovanja, ki je trajalo 17 mesecev, je bilo skozi izvir Timava povrnjenega 93 % injiciranega sledila (*Kogovšek* in *Petrič* 2007). Podatkov o pretokih izvira Brojnica nimamo, zato izračun deleža povrnjenega sledila skozi ta izvir ni bil mogoč. Terensko opazovanje pa je pokazalo, da so ti pretoki značilno manjši od pretokov Timave. Ker so bile v Brojnici nizke tudi koncentracije uranina, ocenjujemo delež povrnjenega sledila na manj kot 1 %.

Na črpališču Klariči so bile merjene vrednosti koncentracije sledila večinoma pod mejo določljivosti. Po intenzivnih padavinah konec novembra in v začetku decembra 2005 se je koncentracija sledila povišala na 0,015 mg/m³. Vrednosti so bile le malo nad mejo določljivosti, a so se pojavile v več zaporednih vzorcih. Na območju med odlagališčem in izviri v Tržaškem zalivu prevladuje tok v glavnih kraških kanalih, ob izrazitem dvigu nivoja podzemne vode pa se slednja preceja tudi po širšem območju z relativno slabšo prepustnostjo. Na podlagi rezultatov sledenja sklepamo, da lahko v izjemnih hidroloških razmerah zelo majhen del sledila s počasnim tokom skozi manjše razpoke v kratkem vodnem valu doseže črpališče Klariči. Izračunana količina povrnjenega sledila v črpališču (ob upoštevanju količine črpanja 140 l/s) je zelo majhna (približno 1 g uranina), kar pomeni, da je samo 0,003 % injiciranega sledila doseglo črpališče. Po drugi strani pa ne moremo izključiti možnosti, da so izmerjene

6.4.2 The Mozelj landfill

From the Mozelj landfill the main flow towards the Bilpa spring was proved. Uranine and Eosin were first detected practically simultaneously 7 days after the injection when the discharge of the spring was in recession (6). Due to low discharges the concentrations of tracers were high and the maximum values were measured 9 days after the injection. Afterwards concentrations decreased quickly, and persisted at the values slightly above 1 mg/m³ until the end of April. Then precipitation washed out an additional amount of tracer, however the measured concentrations decreased due to increased discharges. Approximately 70 % of injected Uranine and 55 % of Eosin were recovered within one week after the injection, and 92 % and 74 %, respectively, in three months after the injection (*Kogovšek* and *Petrič* 2010a).

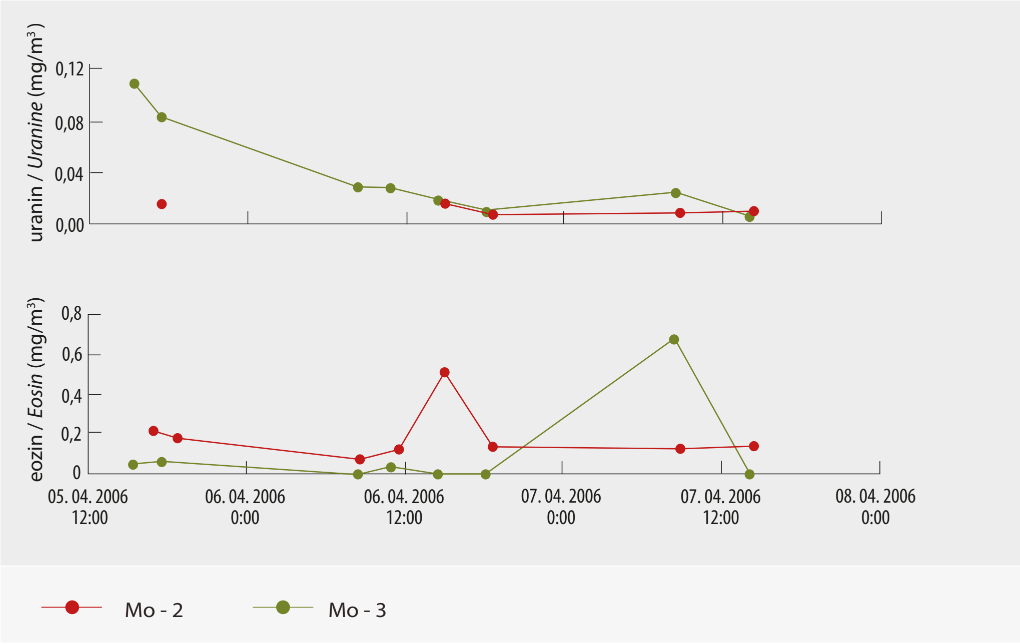
In the other observed springs the tracers appeared only in low concentrations. In the springs Dolski potok and Šumetac a more significant increase was detected parallel with the discharge increase on 30 May 2006. Continuous appearances of Eosin and Uranine were detected in the Radešica spring from the beginning of May 2006 to January 2007 after each more intensive precipitation event. We can conclude that the underground water connections between the landfill and these three springs are possible but weak.

The sampling was organized in all three monitoring boreholes, too. In the borehole Mo-1 the concentrations of tracers remained around the detection limit. In the borehole Mo-2 only Eosin was detected in one short and low peak of the breakthrough curve (7). Both tracers were detected in the borehole Mo-3 in relatively low concentrations. This indicates that a greater portion of injected tracers was washed through well permeable fissures which do not intersect the monitoring boreholes.

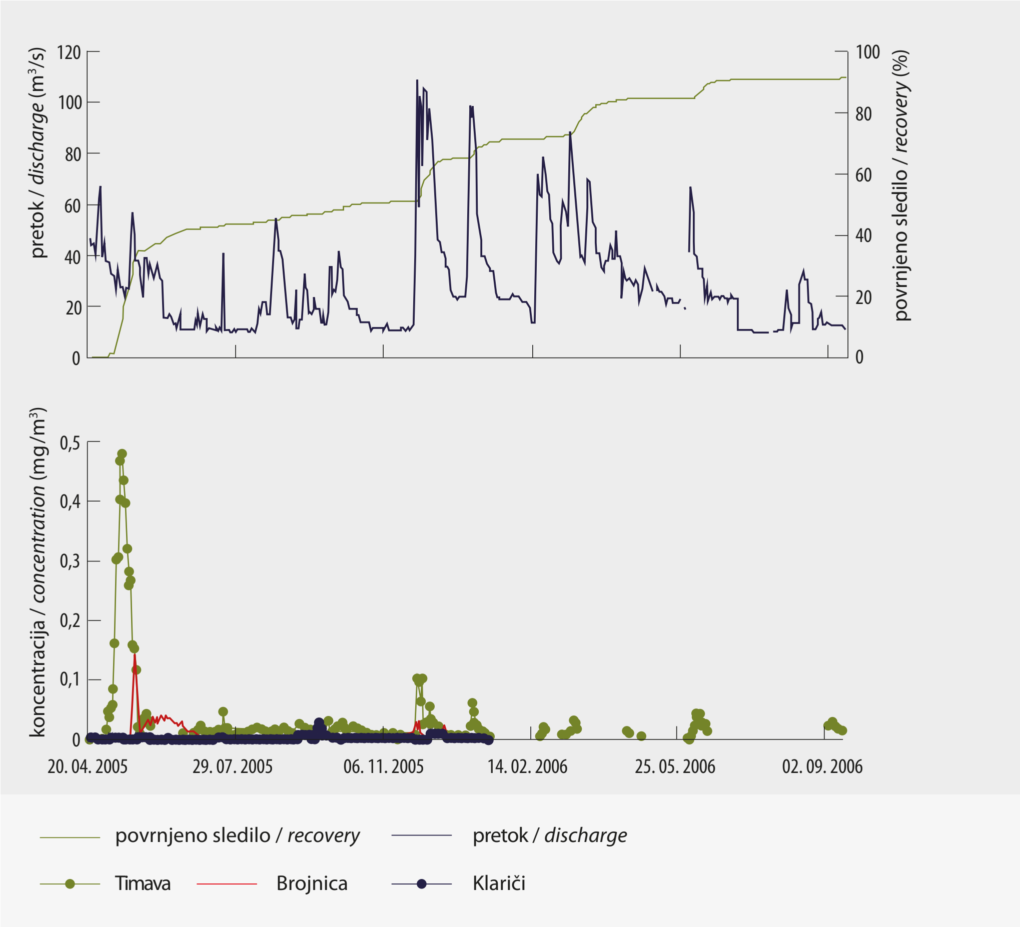
6.4.3 The Sežana landfill

The first traces of Uranine injected at the Sežana landfill were detected in the Timava spring 12 days after the injection (8). The breakthrough curve reached its maximum 0.48 mg/m³ 23 days after the injection. In

7 Koncentracije sledil v vrtinah Mo-2 in Mo-3.
Tracer concentrations in boreholes Mo-2 and Mo-3.



8 Pretoki in krivulja deleža povrnjenega sledila v izviru Timava ter koncentracije sledila v izvirih Timava in Brojnica ter v črpališču Klariči.
Discharges and recovery curves in the Timava spring, and the breakthrough curves of the Timava and Brojnica springs, and the Klariči pumping station.



povečane koncentracije posledica naravnega iztekanja onesnaženja iz zaledja. Za potrditev ali zavrnitev te hipoteze bi bila nujna analiza serije slepih vzorcev, odvzetih v podobnih razmerah visokih vodostajev.

6.5 Uporaba rezultatov sledilnih poskusov pri načrtovanju monitoringa kakovosti podzemnih voda

Visoke dominantne navidezne hitrosti toka s treh odlagališč proti glavnim izvirom kažejo, da v primeru obilnih predhodnih padavin (in posledično v razmerah, ko je velik del por in razpok v prsti in vadozni coni začasno zapolnjen z vodo in hidravlično povezan) prenos sledila ni zadržan niti v debelejši vadozni coni. To kaže na zelo veliko ranljivost in resno nevarnost onesnaženja s škodljivimi snovmi z odlagališč. Poleg tega smo povišanje koncentracij sledila zaznali po vsakem intenzivnejšem padavinskem dogodku. Čeprav se del sledila prenaša hitro po primarnih drenažnih poteh, se preostanek uskladišči v vadozni coni in ga potem v daljšem časovnem obdobju iztiska novo infiltrirana voda ob padavinskih dogodkih, ki sledijo.

6.5.1 Predlagane točke monitoringa

Za odlagališče Mala gora je bil za glavno točko monitoringa predlagan Tominčev studenec. Dodatno naj bi opazovali še Javornikov izvir, kjer lahko pričakujemo najbolj intenziven vpliv z odlagališča (značilno višje koncentracije ob prvem pojavu sledila kakor v drugih izvirih), in izvir Globočec, ki je regionalno pomemben vir za oskrbo s pitno vodo.

Rezultati sledenja z odlagališča Mozelj so pokazali, da tri vrtine ne ustrezajo objektom za monitoring. To se ujema s splošno ugotovitvijo, da zaradi izrazite heterogenosti kraških vodonosnikov monitoring v vrtinah večinoma ni primeren za kraška območja. Ustreznejša izbira so kraški izviri ali drugi naravni objekti.

Zaradi hitrega pretakanja proti izviru Bilpa in zaznanih visokih koncentracij sledila je ta izvir najprimernejša točka za oceno vpliva odlagališča Mozelj

the Brojnica spring the tracer was detected only one month after the injection with the peak concentration 0.14 mg/m³. During the total sampling period of 17 months, almost 93 % of injected Uranine was washed out through the Timava spring (*Kogovšek* and *Petrič* 2007). No data on discharges of the Brojnica spring are available therefore calculation of the recovered amount of tracer was not possible. However, according to our field observations the discharges of this spring were significantly smaller than the discharges of the Timava spring. As the measured concentrations of Uranine were low too, the assessed amount of recovered tracer in the Brojnica spring remains below 1 %.

At the Klariči pumping station the measured values were in general below the detection limit. After intensive precipitation at the end of November and in the beginning of December 2005 the tracer concentration increased to 0.015 mg/m³. These values were only slightly above the detection limit, but they were measured in several successive samples. In the studied karst area between the landfill and the springs in the Trieste Bay a water flow through the main conduits is dominant, while in conditions of a significant rise of water table the groundwater can spill over in a broader area of low-permeable parts. From the results obtained we can infer that in extreme hydrological conditions and flowing slowly through small fissures only a very small portion of injected tracer reached the Klariči pumping station in a short water pulse. The calculated amount of recovered tracer (considering the quantity of pumping 140 l/s) is very low (approximately 1 g of Uranine). This would mean that only 0.003 % of the injected quantity was detected at the Klariči pumping station. On the other hand, we can not exclude the possibility that the increased concentrations reflect a natural outflow of pollution from the catchment. To accept or reject this hypothesis we would need to analyse a series of blind samples taken in similar hydrological conditions of high waters.

na kraške vode. Ker pa se izvir napaja tudi iz ponikalnice Rinže, ki jo onesnažujejo različni onesnaževalci s kočevskega območja, je interpretacija rezultatov monitoringa zelo težka. Za ločevanje vplivov bi bil potreben vzporedni monitoring Bilpe in Rinže. Izbrati bi bilo treba značilne kontaminante in monitoring zasnovati predvsem na njih. Ker pa h glavnemu podzemnemu toku proti Bilpi dodatno prispeva avtogeno napajanje neonesnažene vode, to vodi k razredčenju onesnažil, na katero značilno vplivajo padavinske in hidrološke razmere. Posledica je boljša kakovost Bilpe v primerjavi z Rinžo. Zaradi naštetega sta za ustrezno interpretacijo rezultatov monitoringa pomembna spremljanje in primerjava dotokov iz različnih delov zaledja.

Za monitoring kakovosti podzemne vode v vplivnem območju odlagališča Sežana sta bila izbrana izvira Timava in Brojnica. Čeprav je možnost vpliva na črpališče Klariči zelo majhna, je bil zaradi izjemne pomembnosti za vodooskrbo Krasa tudi ta vir predlagan za monitoring.

6.5.2 Smernice za monitoring

Da bi povečali možnost zaznave onesnaženja, je smiselno vzorčiti v času, ko lahko pričakujemo najvišje koncentracije onesnažil. V vlažnih obdobjih so taki pogoji doseženi že po srednje intenzivnih padavinah, ob suši pa so potrebne močnejše padavine. V sušnih razmerah se padavinska voda najprej porabi za omočitev odloženih odpadkov in prsti, šele potem se izcedne vode infiltrirajo v vadozno cono in odtekajo naprej proti izvirom. Posebno ob dolgih poletnih sušah, ko se padavinska voda samo skladišči v smeteh, prsti in vadozni coni, izcedne vode z odlagališča ne dosežejo izvirov. Šele dovolj intenzivne padavine v nadaljevanju povzročijo izpiranje onesnažil iz odlagališča in iztiskanje predhodno uskladiščenih onesnažil iz vadozne proti freatični coni (*Kogovšek* 2010). Naprej proti izvirom je prenos zelo hiter.

Ker se razmere v kraških vodonosnikih hitro spreminjajo, se zdi najbolj učinkovit odvzem več zaporednih vzorcev v obdobju celotnega poplavnega vala: od začetka naraščanja pretoka, preko doseže-

6.5 The use of tracer tests results in planning of the groundwater quality monitoring

High dominant apparent flow velocities from the three landfills to the main springs indicate that in conditions of previous abundant precipitation (and consequently in conditions when a greater proportion of pores and fissures in the soil and the vadose zone is temporarily filled with water and hydraulically connected) the transport of tracers is not hindered even in a thicker vadose zone. This means a very high vulnerability and a serious danger of pollution with harmful substances from the landfill. Additionally, the increase of tracer concentrations was detected after each more intensive precipitation event. Even though one part of a soluble tracer flows rapidly through the primary drainage paths, the remainder is retained in the vadose zone and is pushed out by newly infiltrated water in the following precipitation events over a long time period.

6.5.1 Proposed monitoring points

As the main monitoring point of the Mala gora landfill the spring Tominčev studenec was suggested. The spring Javornikov izvir should be observed additionally because the influences from the landfill are the most intensive there (significantly higher concentration of tracer in the first peak than at the other springs), and the Globočec spring as the main regional source of water supply.

Results of the tracer test at the Mozelj landfill indicate that the three boreholes are not representative for monitoring. This confirms a general finding that the monitoring in boreholes is unsuitable in karst in the majority of cases due to a high heterogeneity of karst aquifers. Therefore karst springs or other natural objects with water flow should be a better choice.

A rapid flow towards the Bilpa spring and high concentrations of tracers confirmed that this spring was the best location to assess the impacts of the Mozelj landfill on karst waters. However, the interpretation of the monitoring results of this spring only would nega viška, v recesijskem delu do začetnega stanja. Da bi se izognili prevelikemu razredčenju, je bolje, da ne zajemamo v času zelo velikih pretokov.

Ker imajo številni izviri velika in kompleksno zgrajena zaledja, je možno prepletanje negativnih vplivov iz različnih virov onesnaževanja. Za ustrezno interpretacijo rezultatov monitoringa je zato potrebno dobro razumevanje delovanja kraških vodonosnikov. Vzporedno mora potekati merjenje padavin, pretokov in fizikalnih parametrov vode. Stalno vzdrževanje mreže monitoringa in primerjava dobljenih rezultatov zagotavljata izboljšanje njegove učinkovitosti.

Zahvala

Sledilne poskuse smo izvedli v sodelovanju z Inštitutom za rudarstvo, geologijo in geotehnologijo iz Ljubljane ter ob podpori javnih podjetij Komunala Ribnica, Komunala Kočevje in Komunalno stanovanjsko podjetje Sežana, ki so upravljavci odlagališč. Za brezplačno posredovanje podatkov o padavinah in pretokih se zahvaljujemo Agenciji Republike Slovenije za okolje in podjetju ACEGAS, za sodelovanje pri pripravi projektov pa Andreju Jurnu (GeoSi d.o.o., Inštitut za zemljeslovje).

be difficult, because the sinking Rinža river, polluted with various pollution sources from the Kočevje area, is also recharging the spring. To distinguish the influences, a simultaneous monitoring of the Bilpa spring and the Rinža stream is necessary. Some characteristic contaminants should have to be selected and the monitoring concentrated mainly on them. Furthermore, the main underground flow towards the Bilpa spring gets an additional contribution by autogenic recharge of unpolluted water. It leads to a dilution of contaminants, which is highly influenced by precipitation and hydrological conditions. As a consequence, the water quality of the Bilpa spring is better than the quality of the Rinža stream. Therefore, for interpreting properly the results of monitoring it is important to measure and compare the inflows from various contribution areas within this complex catchment.

The Timava and Brojnica springs were selected as the monitoring points in the impact area of the Sežana landfill. Even though a possible influence of the landfill on the Klariči pumping station is very low, this location was suggested as the monitoring point due to its exceptional importance for the water supply in the Kras region.

6.5.2 Guidelines for monitoring

With the aim of increasing the possibility of detecting the pollution, it is sensible to sample in the periods when the highest concentrations of pollutants can be expected. During wet periods these conditions are caused already by precipitation of a medium intensity, while during dry periods a more intensive precipitation is needed. In dry conditions rainwater is first used to saturate deposited waste and the soil; only then do leachates infiltrate into the vadose zone and then further on towards the springs. Especially during long summer droughts, when precipitation water is only stored in the wastes, soil and vadose zone, the leachates from the landfill do not reach the springs. Only sufficiently intensive precipitation in the following period induces the leaching of contaminants out of the landfill and pushing the previously stored contaminants out of the vadose zone towards the phreatic zone (*Kogovšek* 2010). From there to the springs the transport is very rapid.

As conditions in karst aquifers change quickly, it seems the most efficient to take several samples in the time of a complete flood wave: from the beginning of the increase of discharge, through the discharge peak, and in the recession phase back to the initial state. To avoid strong dilution, it is better not to sample in conditions of very high discharges.

As many karst springs have large catchment areas with a complex structure, the overlapping of negative influences from various pollution sources is possible and a good understanding of the functioning of karst aquifers is necessary to consistently interpret the monitoring results. Therefore, the monitoring should be supported by the measurements of precipitation, discharges and physical parameters of water. A permanent supervision of the monitoring net, as well as the comparison of the obtained results will help to improve the performance and efficiency of monitoring.

Acknowledgement

The tracer tests were supported by the Institute of Mining, Geology and Geotechnology from Ljubljana, and the public companies Komunala Ribnica, Komunala Kočevje, and Komunalno stanovanjsko podjetje Sežana, which are the managers of the landfills. We would like to thank the Slovenian Environment Agency and the ACEGAS company for giving us the precipitation and discharge data free of charge, and Mr. Andrej Juren (GeoSi d.o.o., Geological Institute) for co-operation in the preparative arrangements.

7

OCENA VPLIVA VOJAŠKEGA VADIŠČA POČEK NA KRAŠKE VODE

ASSESSMENT OF IMPACT OF THE POČEK MILITARY TRAINING AREA ON KARST WATERS

MOJCA BOLE, SAMAR AL SAYEGH-PETKOVŠEK, POLONCA DRUKS GAJŠEK, JANJA KOGOVŠEK, METKA PETRIČ, BOŠTJAN POKORNY

Kljub mnogim pozitivnim spremembam v svetu in Sloveniji ostaja uporaba vojaške sile v miru in vojni stalnica v naših življenjih in našem okolju. Oborožene sile vojaško sposobnost ohranjajo z urjenjem svojih vojakov in testiranjem vojaške opreme. Slednje se izvaja na vojaških vadiščih (poligonih), ki imajo pomembno vlogo pri vzdrževanju usposobljenosti in pripravljenosti oboroženih sil. Pomen vojaških poligonov se ne zmanjšuje, ampak v nekaterih primerih celo povečuje, saj uporaba sodobnih oborožitvenih sistemov mnogokrat narekuje povečanje površine vadišč (zaradi povečane mobilnosti in ognjene moči orožja) ali celo spremembo njihovih lokacij (*Prebilič* 2004). V zgodnjih devetdesetih letih prejšnjega stoletja so članice Severnoatlantske zveze NATO razširile svoj koncept nacionalne varnosti tako, da so vanj vključile tudi varnost okolja in začele sistematično preučevati tudi spremembe naravnega okolja, nastale zaradi onesnaževanja, ki ga povzročajo oborožene sile oziroma uporaba najrazličnejšega orožja in oborožitvenih sistemov (*Prebilič* in *Ober* 2004).

7.1 Vojaški poligoni kot vir onesnaževanja

Dejavnosti, ki se izvajajo na vojaških območjih, vplivajo na okolje kot celoto. Spremeni se raba prostora, pride do izgube in degradacije habitatov, biotska pestrost se zmanjša; verjetna je onesnaženost vodnih virov, tal in rastlin; pogostokrat prihaja do obremenjenosti s hrupom in do zapraševanja okolice; nikakor ne gre zanemariti niti velikega sociološkega vpliva na okoliško prebivalstvo. Najpomembnejša onesnažila so vse vrste naftnih derivatov (še posebej ob izlitjih), sulfati in nitrati (posledica eksplozivov), težke kovine ter plastični ostanki orožja in streliva. Po nekaterih ocenah so vojske na svetu odgovorne za 6–10 % svetovnega onesnaženja, po drugih pa celo za 20 % (*Mekina* 2002; *Myrttinen* 2002).

V svetu je znanih kar nekaj okoljskih raziskav in programov za zmanjšanje vpliva vojaške aktivnosti na okolje na vojaških vadiščih (*Trame* in *Harper* 1997; *Kress* 2001; *Bleise* idr. 2003; *Hynes* in *Ibragimov*

Despite many positive changes in the world and in Slovenia, the use of military force in peace and in war remains a constant of our lives and in our environment. Armed forces maintain their military capability by training their soldiers and testing military equipment. The latter takes place in military training areas, which therefore have an important role in maintaining the level of training and readiness of armed forces. The importance of military training areas shows no signs of diminishing. In some cases it is even increasing, since the use of modern weapons systems often requires an increase in the size of training areas (because of increased mobility and the increased firepower of weapons) or even a change of location (*Prebilič* 2004). In the early 1990s the members of NATO expanded their concept of national security so as to incorporate security of the natural environment and began to systematically study the changes to the natural environment that occurred as a result of pollution caused by armed forces or the use of a wide range of weapons and weapons systems (*Prebilič* and *Ober* 2004).

7.1 Military training areas as a source of pollution

Activities that take place in military areas affect the environment as a whole. Land use changes, loss and degradation of habitats occurs, and biodiversity is reduced; pollution of water sources, soil and plants is likely; noise pollution and dust are a frequent problem; the significant sociological impact on the population of the surrounding area should not be overlooked. The most important pollutants are petroleum derivatives of all types (particularly in the case of spillages), sulfates and nitrates (a by-product of explosives), heavy metals and plastic debris from weapons and ammunition. According to some estimates, armies around the world are responsible for between 6–10 % of global pollution, while other estimates even place this figure as high as 20 % (*Mekina* 2002; *Myrttinen* 2002).

Quite a number of environmental research projects and programmes to reduce the impact of military activity on the environment in military training areas have taken place around the world (T*rame* and *Harper* 1997; *Kress* 2001; *Bleise* et al. 2003; *Hynes* and *Ibragimov*

2003; *Clausen* idr. 2004; *Barnes* idr. 2005; *Bennet* idr. 2007). V Evropi je problematika sanacije opuščenih vojaških baz in poligonov zelo aktualna; še zlasti so problematična območja, ki jih je upravljala bivša Sovjetska zveza. Ponekod je onesnaženost zraka in podtalnice dosegla katastrofalne razsežnosti. V sedanji Ruski federaciji je 12,800.000 ha nekdanjih vojaških površin, za katere predvidevajo, da jih bo treba sanirati. Na Madžarskem (na bivših sovjetskih vojaških območjih in na območjih, ki jih je uporabljala madžarska vojska) pomeni največje tveganje onesnaženje tal in podtalnice z naftnimi derivati, kot so kerozin, dizel in bencin. Druga najpomembnejša skupina onesnažil so težke kovine, še posebej baker in svinec, medtem ko na območjih strelišč in delavnic za popravilo prevoznih sredstev najdemo velike količine kadmija, kroma in arzena. Tretjo skupino onesnažil predstavljajo različni kemijski agensi v odpadnih vodah. Omenjenim onesnažilom se pogostokrat pridružujeta še problematika radioaktivnosti in radioaktivnih odpadkov ter navzočnost neeksplodiranih topniških izstrelkov (npr. v Belorusiji). Mnoge države bivše Sovjetske zveze (Ukrajina, Armenija, Azerbajdžan, Kazahstan, Tadžikistan in Uzbekistan) poskušajo rešiti problem skladiščenja oksidantov goriv raketnih motorjev, ki so zelo strupeni in hkrati korozivni ter prestavljajo veliko tveganje za okolje in javno zdravje (*Science, Society, Security News* 2005).

Vprašanje varovanja okolja postaja čedalje pomembnejše v vojaški sferi. Konec šestdesetih let 20. stoletja je NATO ustanovil Odbor za preučevanje izzivov sodobne varnosti (CCMS), ki vodi in organizira okoljske raziskave, povezane z delovanjem vojaških sil. Primer sodelovanja Republike Slovenije s Severnoatlantsko zvezo NATO na področju varovanja okolja je izvedba projekta »Določitev vpliva vojaškega poligona Krivolak na okolje z namenom njegove ekološke sanacije«, ki je v letih 2006–2007 potekal na območju vojaškega poligona Krivolak v Makedoniji (*Al Sayegh Petkovšek* idr. 2007). Določili smo onesnaženost posameznih okoljskih segmentov na omenjenem poligonu in ocenili vpliv vojaških dejavnosti nanje; opravili smo meritve radioaktivnosti in ugotavljali navzočnost

2003; *Clausen* et al. 2004; *Barnes* et al. 2005; *Bennet* et al. 2007). In Europe the issue of the remediation of abandoned military sites and training areas is a very current one; areas that were managed by the former Soviet Union are particularly problematic. In places, air pollution and groundwater pollution have reached catastrophic proportions. In the present Russian Federation there are 12,800,000 hectares of former military areas for which remediation is expected to be necessary. In Hungary (in former Soviet military areas and areas used by the Hungarian armed forces), the biggest risk is presented by pollution of the soil and groundwater with petroleum derivatives (e.g. kerosene, diesel and petrol). The second most important group of pollutants consists of heavy metals, in particular copper and lead; in the areas of firing ranges and vehicle workshops we find large quantities of cadmium, chromium and arsenic. The third group of pollutants is represented by various chemical agents in waste-water. These pollutants are often joined by the problem of radioactivity and radioactive waste and the presence of unexploded artillery projectiles (for example in Belarus). Many of the countries of the former Soviet Union (Ukraine, Armenia, Azerbaijan, Kazakhstan, Tajikistan and Uzbekistan) are attempting to resolve the problem of storage of rocket fuel oxidizers, which are highly toxic and at the same time corrosive and represent a serious risk to the environment and human health (*Science, Society, Security News* 2005).

The issue of environmental protection is becoming increasingly important in the military sphere. In the late 1960s NATO set up the Committee on the Challenges of Modern Society (CCMS), which leads and organizes environmental research connected with the operations of military forces. An example of the cooperation of the Republic of Slovenia with NATO in the field of environmental protection is the implementation of a project entitled »Determination of the environmental impact of the Krivolak military training area for the purpose of its environmental remediation« (*Al Sayegh Petkovšek* et al. 2007), which took place in the years 2006–2007 in the Krivolak military training area in Macedonia. We determined the level of pollution of individual segments of the environment in the above military training area and assessed the impact of military activities on them;

osiromašenega urana v različnih tipih vzorcev; obravnavali smo ravnanje z odpadki ter izvedli meritve hrupa na poligonu in v okolici. Posebej nas je zanimala naravovarstvena vrednost območja; s tem namenom smo opravili inventarizacijo rastlinskih vrst in njihovih habitatov. Na podlagi kemijskih analiz v različnih tipih vzorcev smo ugotovili, da tamkajšnja vojaška dejavnost na splošno ne vpliva na onesnaženost okolja. Še najbolj problematično je širjenje erozijskih procesov, do katerih prihaja zaradi fizične degradacije tal kot posledice antropogenih vplivov oz. vojaških aktivnosti, in v omejenem obsegu tudi širjenje hrupa med vojaškimi vajami. Vojaška dejavnost oziroma navzočnost vojaškega poligona na tem območju Makedonije ima lahko na okolje celo pozitiven vpliv, in sicer predvsem v smislu ohranjanja biotske pestrosti rastlin in živali zaradi relativne nedostopnosti in zaprtosti območja ter njegove ekstenzivne rabe (*Al Sayegh Petkovšek* idr. 2007).

Vojaške dejavnosti v Republiki Sloveniji morajo biti usklajene z ekološkimi normami ter okoljsko zakonodajo Slovenije (Direktiva o varstvu okolja v Slovenski vojski) in zveze NATO, ki predpisuje izhodišča za varstvo okolja. V Sloveniji imamo sicer kar nekaj območij, ki jih uporablja Slovenska vojska, manj pa je kompleksnih raziskav o vplivih njene dejavnosti na okolje. Potreba po tovrstnih raziskavah obstaja tako z vidika uporabnika kakor tudi okoliškega prebivalstva. Prva kompleksna raziskava o celovitih vplivih vojaške dejavnosti na okolje v Sloveniji je potekala v letih 2004–2006. Projekt z naslovom »Določitev vpliva vojaškega poligona na okolje kot modelna študija za varovanje in sanacijo okolja na območjih delovanja Slovenske vojske«, ki ga je vodil ERICo Velenje, Inštitut za ekološke raziskave, in sta ga financirala Ministrstvo za obrambo Republike Slovenije in Agencija za raziskovalno dejavnost, je obravnaval območje osrednjega vojaškega poligona v Sloveniji – območje Počka (*Al Sayegh Petkovšek* idr. 2006). Z izvedbo tega projekta smo določili stanje onesnaženosti posameznih segmentov okolja (zrak, tla, rastline, živalstvo, vodni viri) na vojaškem vadišču Poček in skušali oceniti vpliv vojaške dejavnosti nanje.

we measured radioactivity and detected the presence of depleted uranium in samples of various types; we also addressed the management of waste and carried out measurements of noise in the military training area and the surrounding area. We were particularly interested in the nature protection value of the area; to this end we made an inventory of plant species and their habitats. On the basis of chemical analyses using different types of samples we discovered that in general terms military activity in this area has no effect on the level of pollution of the environment. The most problematic issue is the spread of erosion processes that occur as a result of physical degradation of the soil as a consequence of anthropogenic impacts or military activities and, to a limited extent, the problem of noise during military exercises. Military activity or the presence of a military training area in this part of Macedonia can even have a positive impact on the environment, above all in the sense of the conservation of biodiversity of plants and animals owing to the relative inaccessibility and closed nature of the area and its extensive use (*Al Sayegh Petkovšek* et al. 2007).

Military activities in the Republic of Slovenia have to be harmonized with the ecological norms and environmental legislation of Slovenia (Directive on environmental protection in the Slovenian armed forces) and of NATO, which set out starting points for environmental protection. Although in Slovenia we have quite a number of areas that are used by the armed forces, there has not been much complex research into the effects of this activity on the environment. A need for research of this kind exists from the point of view of both the user (the Slovenian armed forces) and the local population. The first complex research into the overall effects of military activity on the environment in Slovenia took place between 2004 and 2006. The project, entitled »Determination of the impact of the military training area on the environment as a model study for the protection and remediation of the environment in the areas of operation of the Slovenian armed forces«, was led by the environmental research institution ERICo, Velenje, and financed by the Ministry of Defence of the Republic of Slovenia and the Slovenian Research Agency. The project covered the area of the main military training area in Slovenia, the Poček area (*Al Sayegh*

Hkrati smo obravnavali ravnanje z odpadki in izvedli študijo ranljivosti okolja. Slednja je z vrednotenjem naravnih pokrajinskih virov opozorila na najšibkejša pokrajinska vira – matično podlago in relief, ki pogojujeta majhno do kritično majhno samočistilno sposobnost preučevanega območja, še zlasti na zahodnem robu Javornikov. Pričakovano je bil največji negativni vpliv ugotovljen na tleh. Na podlagi ugotovitve, da so bila tla najbolj onesnažena na pehotnem strelišču, smo oblikovali projektno nalogo »Pehotna strelišča kot dejavnik tveganja za okolje s poudarkom na ekološki sanaciji pehotnega strelišča na vojaškem poligonu Poček«, v kateri smo obravnavali pehotna strelišča Slovenske vojske (*Al Sayegh Petkovšek* idr. 2009). V sklopu omenjenega projekta smo dodatno raziskali še vplive vojaškega poligona Poček na vodne vire.

V pričujočem prispevku predstavljamo sintezo rezultatov, ki smo jih pridobili z obema raziskavama (*Al Sayegh Petkovšek* idr. 2006, 2009), z namenom oceniti potencialne vplive vojaškega poligona Poček na vodne vire njegovega vplivnega območja. V talnih vzorcih s poligona smo namreč ponekod izmerili povečane vsebnosti težkih kovin (npr. prekoračene kritične imisijske vrednosti za svinec in baker v tleh pehotnega strelišča), ki bi se lahko ob spremembi mobilnosti v tleh izpirale v vodne vire. Zaenkrat so vrednosti mobilnega dela svinca relativno nizke. Z raziskavo njegove mobilnosti je bilo namreč ugotovljeno, da delež mobilnega dela ne presega 0,1 % celotne vsebnosti svinca v talnih vzorcih pehotnega strelišča (*Al Sayegh Petkovšek* idr. 2009). Obenem smo predlagali ukrepe za zaščito kraških voda in ustrezne monitoringe, ki bi prepoznali oz. preprečili širjenje potencialnega onesnaženja s Počka v vodne vire, ki so tudi vir pitne vode.

Petkovšek et al. 2006). With the implementation of this project we determined the state of pollution of individual segments of the environment (air, soil, plants, animals, water sources) in the Poček military training area and attempted to assess the impact of military activity on these segments. At the same time we looked at the management of waste and carried out an environmental vulnerability study. By means of evaluation of natural landscape resources, the latter drew attention to the two weakest landscape resources—bedrock and relief—which condition the low to critically low self-cleaning ability of the area being studied (in particular on the western margin of the Javorniki). As expected, the biggest negative impact was identified in the soil. On the basis of the finding that the highest level of soil pollution was in the infantry firing range, we developed a project entitled »Infantry firing ranges as an environmental risk factor with an emphasis on the ecological remediation of the infantry firing range in the Poček military training area«, in which we covered the infantry firing ranges used by the Slovenian armed forces (*Al Sayegh Petkovšek* et al. 2009). As part of the above project we additionally researched the impacts of the Poček military training area on water sources.

This chapter contains a synthesis of the results that we obtained during the course of the two research projects (*Al Sayegh Petkovšek* et al. 2006, 2009) for the purpose of assessing the potential impact of the Poček military training area on the water sources of the area of influence. Increased heavy metal contents were in fact measured in soil samples from parts of the Poček military training area (e.g. exceeded critical thresholds for lead and copper in the soil of the infantry firing range) which, with a change in mobility in the soil, could be washed into water sources. For the time being, values for the mobile component of lead are relatively low. Research into Pb mobility in fact showed that the proportion of its mobile component does not exceed 0.1 % of the total lead content in soil samples from the infantry firing range (*Al Sayegh Petkovšek* et al. 2009). At the same time we proposed measures for the protection of karst waters or appropriate monitoring that would identify or prevent the spread of potential pollution from Poček to water sources that are also a source of drinking water.

7.2 Ogroženost vodnih virov na vplivnem območju vojaškega poligona Poček

7.2.1 Hidrogeološki opis vplivnega območja poligona

Območje vojaškega vadišča zajema severni del Javornikov, ki so 11 km široko in 30 km dolgo hribovje, razpotegnjeno v smeri severozahod–jugovzhod (1). Na zahodni strani mejijo na Pivško kotlino, na severovzhodu pa na Cerkniško in Planinsko polje. Površje večinoma prekrivajo tanke rjave prsti tipa redzina, katerih debelina v povprečju ne presega 20 cm. Pogosto pa plast prsti ni sklenjena. Na najbolj kamnitih površinah se je ohranil gozd, drugod je bil gozd spremenjen v travnike in pašnike, ki se v zadnjih letih intenzivno zaraščajo. Na dnu depresij ali vrtač so ponekod nastale debelejše plasti koluvialne prsti. Na območju vojaškega vadišča je 39 kraških jam (Kataster jam JZS), kjer prevladujejo brezna. Le Brezno v Kobiljih grižah (kat. št. 166), ki je 72 m globoko, je vodna jama (*Kogovšek* idr. 1999).

Celotno območje Javornikov je zgrajeno iz krednih apnencev, ki ponekod prehajajo v dolomit ali apnene breče. Eocenski fliš pokriva skoraj vso Pivško kotlino, razteza se tudi v Vipavsko dolino. Ob površinskih tokovih in na kraških poljih na obrobju so odloženi kvartarni sedimenti. Karbonatne kamnine so zakrasele, z razvitimi tipičnimi površinskimi in podzemnimi kraškimi oblikami, značilno kraški pa je tudi podzemni način pretakanja vode. Padavinska voda hitro in relativno neovirano odteka v podzemlje, z njo se prenašajo tudi kontaminanti. Na obravnavanem območju je bilo ugotovljeno, da padavinska voda po izdatnih in intenzivnih padavinah preide 150 m debele apnence že v 6 urah (*Kogovšek* in *Habič* 1981), medtem ko se v sušnih poletnih obdobjih z manjšimi, neintenzivnimi padavinami lahko pojavi šele po dveh do treh mesecih (*Kogovšek* idr. 1999). V slabše prepustnih conah vodonosnikov pa se lahko vode zadržijo tudi dlje časa. Snovi, ki jih voda nosi s seboj, se tako kopičijo v podzemlju, predvsem v vadozni coni, dokler jih intenzivni padavinski dogodki postopno ne iztisnejo iz podzemlja. Ta proces lahko traja tudi več let.

7.2 Threat to water sources in the area of influence of the Poček military training area

7.2.1 Hydrogeological description of the area of influence of the training area

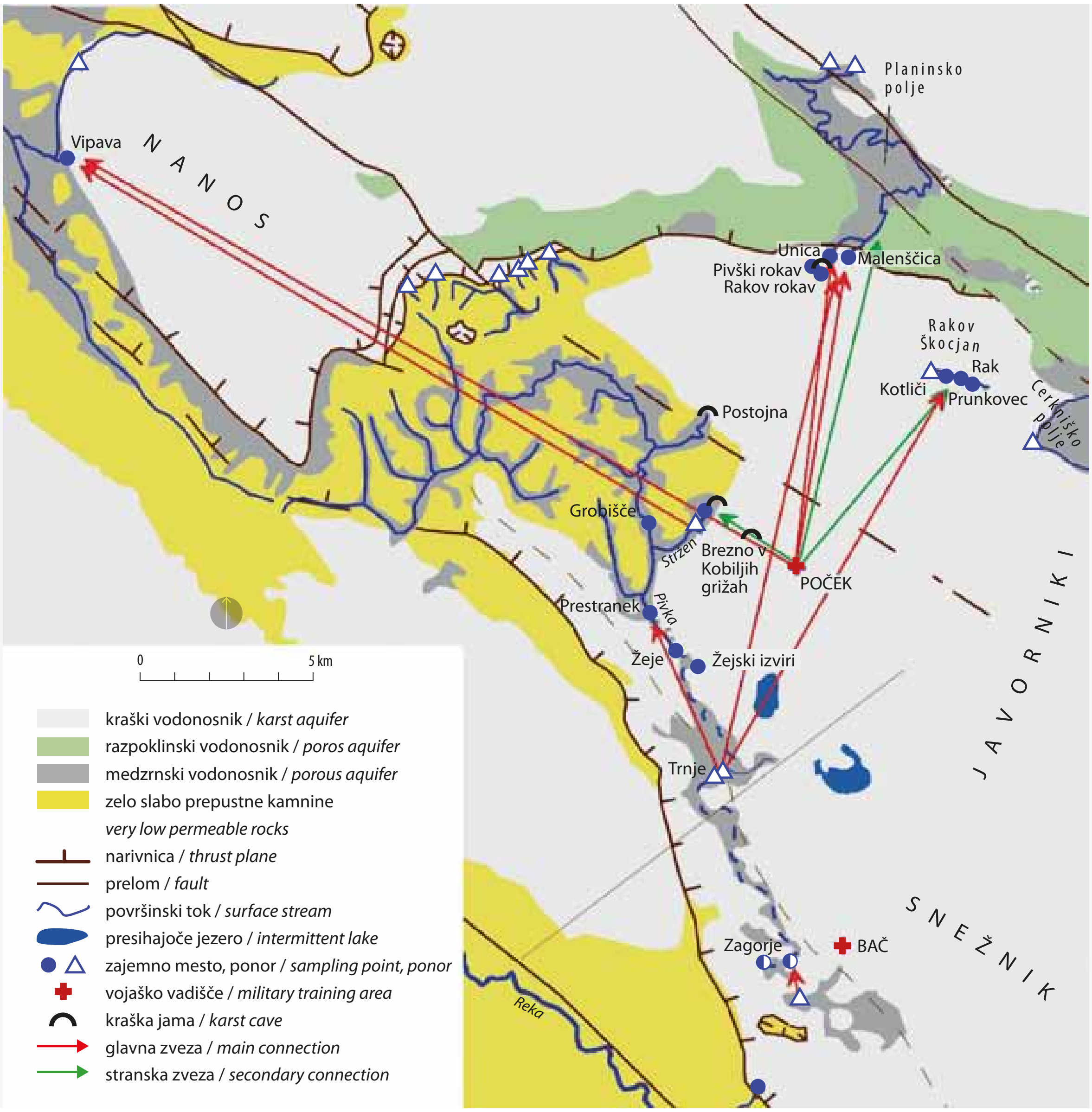
The military training area covers the northern part of the Javorniki, a range of hills 11 km wide and 30 km long extending in a NW–SE direction (1). They are bounded to the west by the Pivka basin and to the northeast by two karst poljes—Cerkniško polje and Planinsko polje. The surface is for the most part covered by thin layers of brown soil of the redzine type, with an average thickness of less than 20 cm. The soil layer is frequently unconsolidated. Forest survives in the rockiest areas, while elsewhere it has given way to meadows and pastures, which however in recent years have become increasingly overgrown. In places, thicker layers of colluvial soil have formed at the bottom of depressions or dolines. There are 39 karst caves within the military training area (Caves Register of the Caving Association of Slovenia), the majority of them of the pothole type. The only water cave is Brezno v Kobiljih grižah (cat. no. 166), which is 72 m deep (*Kogovšek* et al. 1999).

The entire area of the Javorniki hills is composed of Cretaceous limestones that in places transition to dolomite or limestone breccias. Eocene flysch covers almost the whole of the Pivka basin and also extends into the Vipava valley. Quaternary sediments are deposited along surface streams and in the karst poljes at the margins. The carbonate rocks are karstified, with well-developed typical surface and underground karst formations. Groundwater flow is also typical of karst areas. Rainwater drains underground quickly and relatively unimpeded, carrying contaminants with it. In the area in question it has been established that following abundant and heavy rainfall rainwater passes through 150 m of limestone in just 6 hours (*Kogovšek* and *Habič* 1981), while in dry summer periods when rainfall is less and lighter, it can take up to two to three months to appear (*Kogovšek* et al. 1999). In the less permeable zones of aquifers, water can be retained for a considerable time.

V zasičeni coni se podzemna voda pretaka večinoma po razširjenih razpokah in kraških kanalih v različnih smereh proti kraškim izvirom, značilnosti pretakanja pa se spreminjajo v različnih hidroloških razmerah. Z opravljenim sledilnim poskusom so bile dokazane smeri odtekanja s Počka proti izvirom na Planinskem polju (Malenščica, Unica) in v Rakovem Škocjanu (Kotliči, Prunkovec), proti izviru

The substances carried by this water thus accumulate underground, above all in the vadose zone, until they are gradually driven out of the underground by intense rainfall events. This process can last several years.

In the saturated zone, groundwater mainly flows through widened fissures and karst conduits in different directions towards karst springs, while the flow characteristics change with different hydrological conditions.



1 Hidrogeološka karta širšega območja vojaškega poligona Poček z rezultati sledenj.
Hydrogeological map of the broader area of the Poček military training area with the results of tracer tests.

Stržen pri Postojni, pa tudi proti izvirom Vipave v Vipavski dolini (*Kogovšek* idr. 1999; *Kogovšek* 1999; *Kogovšek* in *Petrič* 2004). Predhodna sledenja so potrdila tudi podzemno vodno povezavo med ponori v strugi Stržena in izvirom Vipave (*Habič* 1989). Pretoki izvira Malenščica, ki je zajet za vodooskrbo občin Postojna in Pivka, se po podatkih za obdobje 1961–1990 gibljejo med 1,1 in 9,9 m^3/s, srednji pretok je 6,7 m^3/s (*Kolbezen* in *Pristov* 1998). Izvir Unice iz Planinske jame je največji ob visokih vodah, ko preseže 70 m^3/s, precej manjši pa je pretok ob suši z le nekaj sto litri v sekundi. V Planinski jami se združita vodotoka iz Rakovega in Pivškega rokava. Prvi zbira podzemno vodo predvsem iz smeri Rakovega Škocjana in Cerkniškega jezera, drugi pa iz Pivške kotline. Poleg tega Unico tudi neposredno napajajo podzemne vode iz Javornikov. V Rakovem Škocjanu sta najpomembnejša leva pritoka Raka iz izvirov Kotliči in Prunkovec.

Sedem stalnih izvirov Vipave je razporejenih ob zahodnem vznožju Nanosa v mestu Vipava na nadmorski višini 98 m. Eden izmed njih je zajet za vodooskrbo zgornje Vipavske doline. Njihov skupni pretok se po podatkih za obdobje 1961–1990 giblje med 0,7 in 70 m^3/s, srednji pretok je 6,78 m^3/s (*Kolbezen* in *Pristov* 1998).

Stržen napajajo kraške vode iz izvirov ob robu Javornikov južno od Postojne. Ko kraški dotok presahne, ga hranijo manjši dotoki s fliša in iztok iz komunalne čistilne naprave. Na različnih točkah na dnu struge ponika voda v podzemlje.

7.2.2 Značilnosti pretakanja podzemnih vod in prenosa snovi v vplivnem območju poligona

S sledilnim poskusom smo določili smeri in značilnosti pretakanja podzemnih voda in prenosa snovi z območja vojaškega vadišča Poček. Ob nizkem vodostaju junija 1997 smo v dnu skalne vrtače injicirali 4 kg fluorescentnega sledila uranin. Ugotovljena je bila glavna smer pretakanja proti izviru Malenščica, pa tudi dobra povezava s Pivškim rokavom v Planinski jami in z izviri Vipave. Uranin se je pojavil še v izviru Stržen in v izvirih

A tracer test revealed the directions of drainage from Poček towards springs on Planinsko polje (Malenščica, Unica) and in Rakov Škocjan (Kotliči, Prunkovec), towards the Stržen spring near Postojna, and also towards the Vipava stream in the Vipava valley (*Kogovšek* et al. 1999; *Kogovšek* 1999; *Kogovšek* and *Petrič* 2004). Earlier tracer tests also confirmed an underground water connection between ponors in the bed of the Stržen stream and the Vipava spring (*Habič* 1989). The discharges of the Malenščica spring, which is used to supply water to the Postojna and Pivka municipalities, range from 1.1 m^3/s to 9.9 m^3/s, with a mean discharge of 6.7 m^3/s, according to figures for the period 1961–1990 (*Kolbezen* and *Pristov* 1998). The spring of the Unica river from the cave Planinska jama has the highest discharge at high water levels, when it exceeds 70 m^3/s, while the discharge falls to just a few hundred litres per second in dry periods. Watercourses from the Rak and Pivka underground streams merge in the Planinska jama. The former collects groundwater above all from the direction of Rakov Škocjan and the Cerknica lake, and the latter from the Pivka basin. The Unica river is also directly fed by groundwater from the Javorniki hills. In Rakov Škocjan the most important water sources are the two left tributaries of the river Rak from the Kotliči and Prunkovec springs.

The seven permanent springs of the Vipava river are distributed along the western foot of the Nanos mountain in the town of Vipava at a height 98 m a.s.l. One of them is used to supply water for the upper Vipava valley. According to figures for 1961–1990, their total discharge ranges from 0.7 m^3/s to 70 m^3/s with a mean discharge of 6.78 m^3/s (*Kolbezen* and *Pristov* 1998).

The Stržen spring is fed by karst waters from springs on the edge of the Javorniki hills, south of Postojna. When the karst inflow dries up, it is fed by smaller inflows from the flysch and by outflow from the municipal treatment plant. Water percolates underground at various points in the bed of the stream.

v Rakovem Škocjanu: v Raku pred Prunkovcem, v Prunkovcu in Kotličih. Sledilo, ki je iztekalo skozi izvire v Rakovem Škocjanu, smo delno zaznali v Malenščici, delno pa v Rakovem rokavu v Planinski jami. Glede na pojav prvega sledilnega vala (navidezna dominantna hitrost v_{dom}, izračunana za zračno razdaljo med točko injiciranja in izviri, ter čas pojava maksimalne koncentracije sledila) se je voda s sledilom najhitreje pretakala v Malenščico (v_{dom} = 26 m/h) in Vipavo (v_{dom} = 26 m/h), najpočasneje pa v izvir Stržena (v_{dom} = 10 m/h) (*Kogovšek* 1999; *Kogovšek* in *Petrič* 2004).

Spiranje in iztekanje injiciranega uranina skozi opazovane izvire je trajalo skoraj eno leto, ko je na območju padlo 1400 do 1500 mm padavin. Glavnina uranina je bila sprana skozi izvir Malenščica v 7 mesecih (55 % injiciranega sledila), ko je od začetka poskusa padlo več kot 1000 mm dežja. Kar 33 % uranina se je pojavilo v Malenščici šele 5 mesecev po injiciranju, ko je ob intenzivnem jesenskem deževju padlo 550 mm padavin. Skozi Malenščico in Vipavo je skupaj priteklo približno 80 % sledila. Količin povrnjenega uranina v drugih izvirih ni bilo možno ovrednotiti, ker pretoki niso bili merjeni. Predvidevamo pa, da je bil celokupni povrnjeni delež sledila blizu 100 %.

Zgradba sorazmerno plitve vadozne cone na območju Počka (ocenjujemo jo na do 40 m) pogojuje pretežno le počasno pretakanje vode in z njo sledila oz. daljše zadrževanje v njej. Občasne intenzivnejše padavine v poletnem sušnem obdobju so tako sprale le del injiciranega uranina. Šele intenzivne in izdatne padavine, ki na tem območju nastopijo predvsem jeseni, kot se je to zgodilo novembra 1997, so popolneje sprale in iztisnile sledilo iz vadozne cone proti kraškim izvirom. Prenos sledila je torej zelo odvisen od padavinskih razmer.

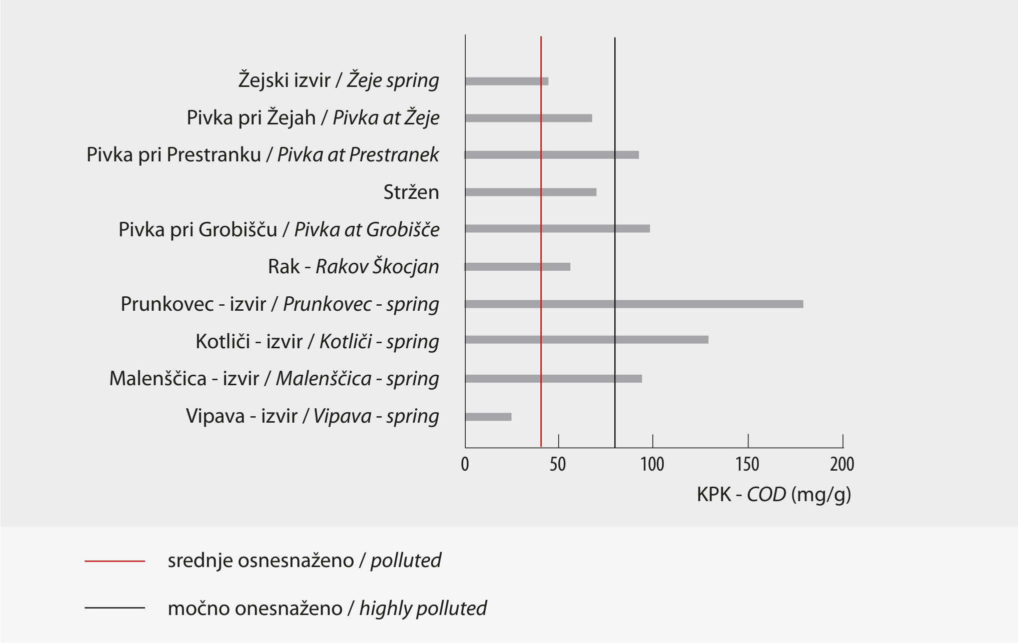
Podobno sklepamo za prenos topnega onesnaženja, ki ga prenašajo padavine. Manjše in manj intenzivne padavine potisnejo onesnaženje le delno v smeri proti izvirom, lahko pa ta prenos celo izostane, ker se večina onesnaženja zadrži v vadozni coni. Tam lahko nekaj mesecev in več čaka na dovolj izdatne in intenzivne padavine, ki ga začnejo spirati proti izvirom. Seveda pa lahko v tem času,

7.2.2 Groundwater flow characteristics and the transport of substances in the area of influence of the military training area

We conducted a tracer test to determine the directions and characteristics of groundwater flow and the transport of substances from the Poček military training area. In June 1997, when the water level was low, we injected 4 kg of the fluorescent tracer Uranine at the bottom of a rocky doline. The main direction of flow towards the Malenščica spring was identified, along with a good connection with the Pivka branch of the cave Planinska jama and with the springs of the Vipava river. Uranine also appeared in the Stržen spring and in the Rak, Prunkovec and Kotliči springs in Rakov Škocjan. The tracer that flowed out through springs in Rakov Škocjan was partly detected in the Malenščica spring and partly in the Rak branch of Planinska jama. Regarding the appearance of the first tracer peak (apparent dominant velocity v_{dom} calculated for the crow line between the injection point and the springs and the time of appearance of the maximum concentration of the tracer), water containing tracer flowed most quickly into the Malenščica spring (v_{dom} = 26 m/h) and the Vipava spring (v_{dom} = 26 m/h), and most slowly into the Stržen spring (v_{dom} = 10 m/h) (*Kogovšek* 1999; *Kogovšek* and *Petrič* 2004).

It took almost a year for the injected Uranine to be washed out through the observed springs, in which time precipitation in the area was between 1400 and 1500 mm. The bulk of Uranine was washed out through the Malenščica spring in a period of 7 months (55 % of the injected tracer), when more than 1000 mm of rain had fallen since the start of the test. Up to 33 % of Uranine did not appear in the Malenščica spring until 5 months after injection, in which time heavy autumn rain produced 550 mm of precipitation. A total of approximately 80 % of the injected tracer flowed through the Malenščica and Vipava springs. It was not possible to evaluate the quantity of recovered Uranine in the other springs because discharges were not measured. We do, however, envisage that the total share of recovered tracer was close to 100 %.

2 Koncentracija KPK v odvzetih vzorcih sedimenta na vplivnem območju vojaškega poligona Poček (maksimalna dovoljena koncentracija ali MDK – po priporočilih za klasificiranje sedimentov v ZDA).
COD concentration in samples of sediment taken in the area of influence of the Poček military training area (maximum allowable concentration or MAC—after recommendations for the classification of sediments in the USA).



posebno še v vadozni coni, potekajo različni fizikalni in kemijski procesi, kar lahko zadrževanje še znatno podaljša.

7.2.3 Obremenjenost voda in sedimentov z onesnažili

7.2.3.1 Posnetek stanja kakovosti voda in sedimentov na vplivnem območju Počka

Vzorčna mesta za fizikalno-kemijske analize vodnih vzorcev in sedimentov smo izbrali glede na rezultate sledilnih poskusov. Vsi vodotoki (izviri) so izbrani v širšem vplivnem območju, saj na vojaškem poligonu zaradi kraškega terena površinskih voda ni. Vzorčenje je potekalo v času upadanja pretokov, kar pomeni, da je že pred tem prišlo do intenzivnejšega spiranja zaledja pa tudi sedimentov na izvirih. Vsa vzorčenja in vse kemijske analize so bili opravljeni v skladu z zahtevami ustreznih standardov.

V odvzetih vzorcih vode so bile na splošno izmerjene nizke koncentracije organsko razgradljivih in nerazgradljivih snovi (izražene kot kemijska potreba po kisiku – KPK), medtem ko so bile v odvzetih vzorcih sedimenta, upoštevajoč priporočila za

The structure of the relatively shallow vadose zone in the area of Poček (estimated depth of up to 40 m) conditions the predominantly slow flow of water and, with it, tracer, in other words a longer period of retention in the vadose zone. Occasional heavy rainfall during the dry summer period thus only washed out part of the injected Uranine. It took heavy and plentiful rainfall, which in this area mainly occurs in autumn, as happened in November 1997, to wash the tracer more completely out of the vadose zone and drive it towards karst springs. The transport of the tracer is therefore very dependent on precipitation conditions.

A similar conclusion may be reached for the transport of soluble pollution carried by precipitation. Smaller quantities of rainfall and lighter rainfall only partially push pollution towards springs, and this transport can even be absent because the majority of the pollution remains in the vadose zone. It can wait there for several months or longer for sufficiently copious and heavy rainfall that begins to wash it towards the springs. During this time, of course, and in particular in the vadose zone, various physical and chemical processes can take place that can significantly extend the period of retention.

klasificiranje sedimentov v ZDA, izmerjene visoke vsebnosti KPK (2). Glede na omenjeno klasificiranje je bil v času vzorčenja močno onesnažen sediment na lokacijah Prunkovec–izvir, Kotliči–izvir, Malenščica–izvir in Pivka pri Prestranku. Izmerjena koncentracija razgradljivih organskih snovi (izražena kot biokemijska potreba po kisiku – BPK_5) je bila v vseh odvzetih vzorcih vode pod mejo določljivosti metode.

V nobenem odvzetem vzorcu vode niso izmerjene koncentracije nitratov presegale vrednosti MDK, določenih v *Uredbi o kemijskem stanju površinskih voda* (*UrKSPV*, 2002). Največje koncentracije nitratov v vodi v času vzorčenja so bile izmerjene na lokacijah Kotliči–izvir in Pivški rokav v Planinski jami ter so lahko posledica tako kmetijske dejavnosti kakor tudi vpliva vojaškega območja (ostanki streliv). Prav tako ni bila v času vzorčenja na nobeni lokaciji presežena priporočena vrednost celotnega dušika v vodi glede na *Uredbo o kakovosti površinskih voda, ki se jih odvzema za oskrbo s pitno vodo* (*UrKPV*, 2000). V odvzetem sedimentu je bila izmerjena najvišja vsebnost celotnega dušika na lokacijah Kotliči–izvir, Prunkovec–izvir in Pivka pri Žejah. Na vseh lokacijah smo izmerili zelo nizke koncentracije celotnega fosforja v vodi. Enako velja za kloride in sulfat. Izmerjene vsebnosti celotnega fosforja v odvzetih sedimentih pa so nihale in so se gibale med 454 mg/kg na lokaciji Vipava–izvir do 1350 mg/kg na lokaciji Prunkovec–izvir. Na posameznih lokacijah (Pivka pri Prestranku, Kotliči–izvir in Stržen) so bile izmerjene večje koncentracije adsorbljivih organskih halogenov (AOX) v vodi, ki pa niso presegale predpisane MDK, medtem ko so bile na drugih lokacijah izmerjene koncentracije AOX v vodi pod mejo določljivosti metode.

V času vzorčenja vode niso bile obremenjene s kovinami in niso presegale predpisanih mejnih vrednosti v že omenjenih Uredbi o kemijskem stanju površinskih voda in Uredbi o kakovosti površinskih voda, ki se jih odvzema za oskrbo s pitno vodo. Izmerjene koncentracije niklja (Ni), svinca (Pb), kroma (Cr), živega srebra (Hg), arzena (As), selena (Se) in kadmija (Cd) v vodi so bile pod mejo določljivosti za posamezno kovino.

7.2.3 Pollutants in water and sediments

7.2.3.1 Quality of water and sediments in the area of influence of Poček

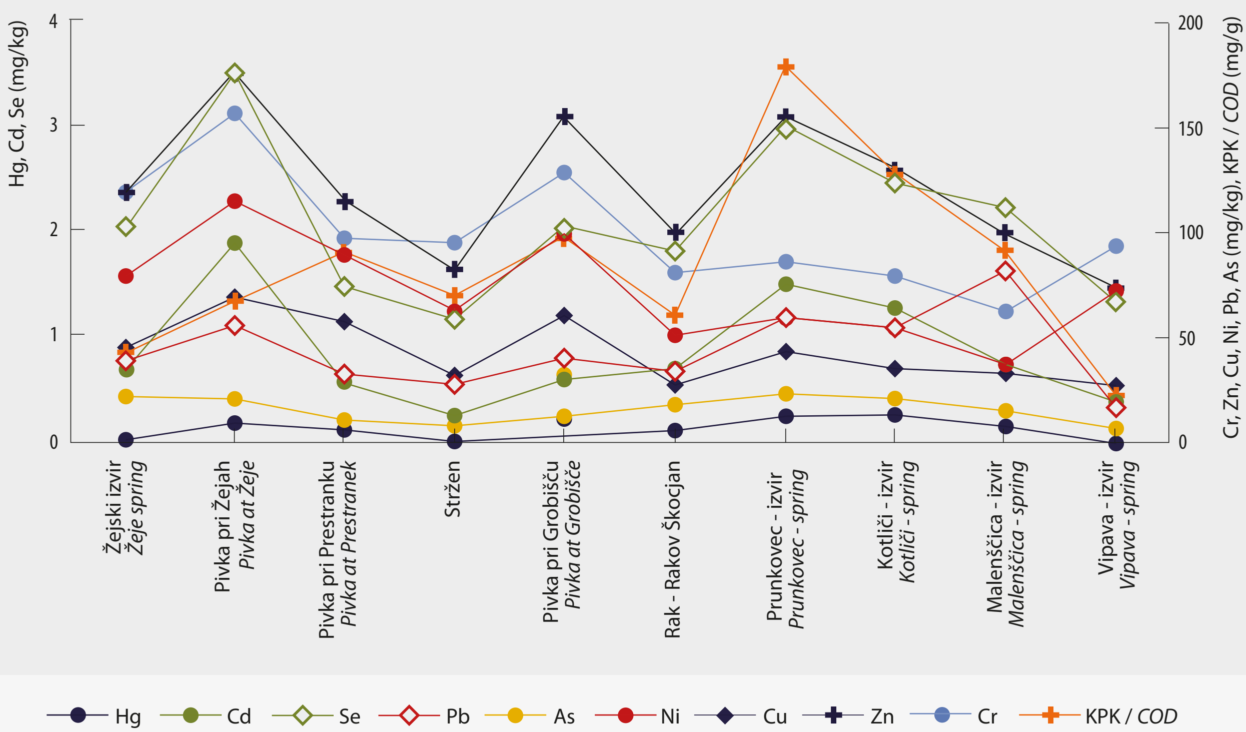
Sampling points for physical-chemical analyses of water samples and sediments were selected on the basis of the results of the tracer tests. All the selected watercourses (springs) are in the wider area of influence because the karst terrain means that there are no surface streams in the military training area itself. Sampling took place in the period of diminution of flow, which means that the intensive washing-out of the catchment area, and also of sediments in springs, had already taken place. All sampling and all chemical analyses were done in accordance with the requirements of the relevant standards.

In the water samples taken, generally low concentrations of organically degradable and non-degradable substances (expressed as chemical oxygen demand—COD) were measured, while in the samples of sediments COD contents that were high in terms of the recommendations for the classification of sediments in the USA were measured (2). In terms of this classification, there was heavily polluted sediment at the time of sampling at the Prunkovec, Kotliči, and Malenščica springs and in the Pivka river at Prestranek. The measured concentration of degradable organic substances (expressed as biochemical oxygen demand—BOD_5) was below the limit of quantification of the method in all the water samples taken.

In none of the water samples did the measured concentrations of nitrate exceed the maximum allowable concentration or MAC set out in the *Decree on the chemical status of surface waters* (*UrKSPV,* 2002). The highest concentrations of nitrate in water at the time of sampling were measured at the locations Kotliči spring and Pivka branch of the cave Planinska jama and could be the consequence both of agricultural activity and of the impact of the military area (ammunition residues). Furthermore, the recommended value of total nitrogen in water with regard to the *Decree on the quality of surface water abstracted for drinking water supply* (*UrKPV,* 2000) was not exceeded in any location at

Parameter ***Parameter***	Razporeditev po razredih (koncentracija kovin v mg/kg) *Classification into quality classes (concentration of metals in mg/kg)*			
	I.	II.	III.	IV.
Baker / *Copper (Cu)*	< 40	**40–100**	100–340	> 340
Krom / *Chromium (Cr)*	< 50	**50–150**	150–540	> 540
Nikelj / *Nickel (Ni)*	< 50	**50–100**	100–360	> 360
Cink / *Zinc (Zn)*	< 200	**200–1300**	1300–4600	> 4600
Svinec / *Lead (Pb)*	< 50	**50–120**	120–1000	> 1000
Kadmij / *Cadmium (Cd)*	< 1	**1–12**	12–40	> 40

Tabela 1 Kriteriji za razporeditev vodotokov v kakovostne razrede glede na vsebnost kovin v sedimentu (*MOP* 1997).
Table 1 Criteria for the classification of watercourses into quality classes with regard to metals content in sediment (*MOP* 1997).



3 Vsebnosti kovin v vzorcih sedimenta v izvirih na vplivnem območju poligona Poček (enkratni zajem 9. in 13. decembra 2005).
Metals content in samples of sediment in springs in the area of influence of the Poček military training ground (one-off samples taken on 9 and 13 December 2005).

Parameter *Parameter*	*Enota* *Unit*	Mesto vzorčenja / *Sampling location*									
		Žejski izvir *Žeje spring*	Pivka pri Žejah *Pivka at Žeje*	Pivka pri Prestranku *Pivka at Prestranek*	Stržen	Pivka pri Grobišču *Pivka at Grobišče*	Rak v Rakovem Škocjanu *Rak in Rakov Škocjan*	Prunkovec-izvir *Prunkovec-spring*	Kotliči-izvir Kotliči-spring	Malenščica-izvir Malenščica-spring	Vipava-izvir Vipava-spring
pH_{H20}		7.98	7.60	7.44	6.58	6.71	7.44	7.14	7.21	7.97	8.34
Suha snov *Dry matter*	%	98.6	97.4	98.4	98.4	94.2	98.8	96.9	81.8	98.8	98.9
Žarina *Anneal product*	%	92.0	81.1	78.6	89.8	84.5	90.4	73.4	59.3	88.2	96.1
Živo srebro *Mercury* (Hg)	mg/kg	< 0.10	0.16	0.10	< 0.10	0.20	0.10	0.24	0.27	0.13	< 0.10
Svinec *Lead* (Pb)	mg/kg	37.6	**55.5**	31.4	26.7	39.5	32.5	59.0	54.8	81.7	16.9
Arzen *Arsenic* (As)	mg/kg	21.10	20.40	10.20	7.16	11.70	17.50	23.20	21.00	15.10	6.80
Nikelj *Nickel* (Ni)	mg/kg	**78.9**	**114**	**88.7**	**62.2**	**98.5**	**50.7**	**59.7**	**55.1**	37.6	**72.3**
Kadmij *Cadmium* (Cd)	mg/kg	0.67	**1.88**	0.55	0.25	0.59	0.69	**1.51**	**1.28**	0.75	0.38
Selen *Selenium* (Se)	mg/kg	2.03	3.50	1.47	1.16	2.02	1.81	3.01	2.48	2.23	1.34
Baker *Copper* (Cu)	mg/kg	**44.4**	**68.6**	**57.0**	31.8	**59.9**	26.8	**43.2**	34.8	33.1	26.1
Cink Zinc (Zn)	mg/kg	118	175	114	81.6	155	99.5	155	130	100	73.2
Krom *Chromium* (Cr)	mg/kg	**118**	**156**	**96.5**	**94.5**	**128**	**80.7**	**85.7**	**79.3**	**62.4**	**93.5**
Dušik (celotni) *Nitrogen (total)*	%	0.170	0.620	0.396	0.288	0.340	0.188	0.818	0.848	0.289	0.073
Fosfor (celotni) *Phosphorus (total)*	mg/kg	628	1120	636	564	654	524	1350	1250	820	454

Tabela 2 Rezultati fizikalno-kemijskih preiskav odvzetih vzorcev rečnega sedimenta na vplivnem območju poligona Poček (9. in 13. decembra 2005). S krepkim tiskom so označene vrednosti, ki uvrščajo sediment glede na vsebnost kovin v sedimentu v II. ali III. kakovostni razred (*MOP* 1997).

Table 2 Results of physical-chemical investigations of samples of the river sediment taken in the area of influence of the Poček military training ground (9 and 13 December 2005). Bold print indicates values that classify the sediment in terms of metals content in quality classes II or III (*MOP* 1997).

V tabeli 1 so zbrani kriteriji za razporeditev vodotokov v kakovostne razrede glede na vsebnost kovin v sedimentih, ki jih je določilo Ministrstvo za okolje in prostor 1997 (*MOP* 1997). Zakonski predpisi sicer teh kriterijev ne vsebujejo, vendar smo kljub temu pridobljene rezultate primerjali z njimi, da bi ustrezno ovrednotili izmerjene vsebnosti kovin. S krepkim tiskom poudarjene vrednosti pomenijo razmejitev med naravnimi vrednostmi in onesnaženjem.

V tabeli 2 in na sliki 3 prikazujemo vsebnosti posameznih kovin v odvzetih vzorcih sedimentov, ki jih v nadaljevanju obravnavamo z vidika ugotovljenih povezav med Počkom in ostalimi izviri, še zlasti pa z izviri Malenščice in Vipave, kjer so povezave najboljše. Hkrati smo upoštevali tudi že omenjene kriterije za razporeditev vodotokov v kakovostne razrede. Iz opravljenih analiz je razvidno, da je bil sediment v času vzorčenja na posameznih lokacijah obremenjen s težkimi kovinami: svincem (Pb), nikljem (Ni), bakrom (Cu), kromom (Cr) in kadmijem (Cd).

Upoštevaje zgornji kriterij ugotavljamo, da je bil v času vzorčenja najbolj obremenjen sediment na lokaciji Pivka pri Žejah, kjer je znašala izmerjena vsebnost Cr v sedimentu 156 mg/kg (III. kakovostni razred), Ni 114 mg/kg (III. kakovostni razred), Pb 55,5 mg/kg (II. kakovostni razred), Cu 68,6 mg/kg (II. kakovostni razred) in Cd 1,88 mg/kg (II. kakovostni razred). Povečane koncentracije Cr in Ni v vzorcih Pivke (pri Žejskih izvirih in nižje) so lahko posledica vpliva vadišča na Baču. Ker pa so možni še drugi viri, bi bilo vzorec sedimenta dobro vzeti še na ostalih izvirih ob Pivki, kjer še ni možnosti onesnaženja iz drugih virov. Še primernejše pa bi bilo sledenje s strelišča Bač, ki bi konkretno pokazalo, kateri izviri so neposredno povezani z njim in katere so možne smeri prenosa onesnažil.

Prav tako so bile izmerjene povečane vsebnosti posameznih kovin v odvzetih vzorcih sedimenta na lokacijah Malenščica–izvir, kjer je znašala vsebnost Pb v sedimentu 81,7 mg/kg (II. kakovostni razred) in Cr 62,4 mg/kg (II. kakovostni razred), ter na lokaciji Kotliči-izvir, kjer je znašala vsebnost Pb v sedimentu 54,8 mg/kg (II. kakovostni

the time of sampling. The highest total nitrogen content in sediment samples was measured at the Kotliči spring, Prunkovec spring, and Pivka river at Žeje. Very low concentrations of total phosphorus in water were measured at all locations. The same applies to chlorides and sulfate. The measured total phosphorus contents in sediment samples fluctuated, ranging from 454 mg/kg at the Vipava spring to 1350 mg/kg at the Prunkovec spring. At individual locations (Pivka at Prestranek, Kotliči and Stržen springs) higher concentrations of adsorbable organically bound halogens (AOX) were measured in the water, but did not exceed the prescribed MAC, while at other locations the AOX concentrations measured in the water were below the limit of quantification of the method.

At the time of sampling the water was not polluted with metals and did not exceed the prescribed limit values from the already mentioned Decree on the chemical status of surface waters and the Decree on the quality of surface water abstracted for drinking water supply. Measured concentrations of nickel (Ni), lead (Pb), chromium (Cr), mercury (Hg), arsenic (As), selenium (Se) and cadmium (Cd) in the water were below the limit of quantification for the individual metal.

Table 1 shows the criteria for the classification of watercourses into quality classes with regard to the metals content of sediments defined by Ministry of the Environment and Spatial Planning in 1997 (*MOP* 1997). Although the statutory regulations do not contain these criteria, we compared our results with the criteria in order to evaluate appropriately the metals content measured. The values shown in bold indicate a divergence between natural values and pollution.

Table 2 and figure 3 show the contents of individual metals in sediment samples, which are considered below from the point of view of established connections between Poček and other springs, in particular the Malenščica and Vipava springs, where the connections are best. At the same time we took into account the criteria for the classification of watercourses mentioned above. On the basis of the analyses carried out, it is clear that at the time of sampling the sediment in individual locations was polluted with heavy metals (Pb, Ni, Cu, Cr, Cd).

razred), Cd 1,28 mg/kg (II. kakovostni razred), Cr 79,3 mg/kg (II. kakovostni razred) in Ni 55,1 mg/kg (II. kakovostni razred). Tudi na vseh drugih lokacijah so bile v času vzorčenja izmerjene povečane vsebnosti Cr v sedimentu (II. kakovostni razred), občasno pa tudi Cu (II. kakovostni razred: Žejski izvir, Pivka pri Grobišču, Prunkovec-izvir in Pivka pri Prestranku), Ni (II. kakovostni razred: Žejski izvir, Stržen, Pivka pri Grobišču, Prunkovec-izvir, Pivka pri Prestranku in Vipava-izvir) in Cd (II. kakovostni razred: Prunkovec-izvir).

Izvir Vipave v primerjavi z Malenščico dosega večje vrednosti Cr in Ni ter nekoliko nižje vrednosti Cu, Cd in Pb, kar nakazuje veliko verjetnost vpliva strelišča na Počku, saj se tudi Vipava delno napaja s tega območja. Dodaten vpliv na Vipavo predstavlja s sledilnim poskusom dokazan dotok iz Stržena, ki je onesnažen z istimi kovinami. V Stržen pritekajo voda s Počka, pa še očiščene odpadne vode iz Postojne, tudi iz obrata kovinske industrije. Da bi preverili ta možni vpliv iztoka iz čistilne naprave, bi bilo smiselno pregledati sestavo sedimenta za čistilno napravo.

Povečane koncentracije Cr v izvirih v Rakovem Škocjanu so lahko odraz vpliva dejavnosti na Počku, možno pa je tudi, da priteka s Cerkniškega polja, ki dobiva vodo še z Babnega in Loškega polja s poselitvijo in industrijo, tudi kovinsko. Enako velja za Ni. Možen vpliv s Cerkniškega polja bi se dalo preveriti z ustreznimi referenčnimi vzorci sedimenta in vode na Cerkniškem polju izven vplivnega območja Počka.

Poleg že obravnavanih fizikalno-kemijskih parametrov smo v vodnih vzorcih in sedimentu analizirali tudi vsebnosti organskih onesnažil. V času vzorčenja so bile izmerjene koncentracije lahkohlapnih halogeniranih ogljikovodikov (LHCH) in lahkohlapnih aromatskih ogljikovodikov (BTX) v vodi pod mejo zaznavnosti metode za posamezen parameter. Enako velja za celotne ogljikovodike, le v vodi na lokaciji Stržen je koncentracija 2,14 mg/l presegala predpisano mejno vrednost, ki po *Uredbi o kemijskem stanju površinskih voda* (*UrKSPV*, 2002) znaša za celotne ogljikovodike 0,05 mg/l. Tudi izmerjene koncentracije tenzidov in fenolov v vodi so bile pod mejo zaznavnosti metode.

Taking into account the above criterion, we can state at the time of sampling the most polluted sediment was at the location Pivka at Žeje, where the Cr content measured in the sediment was 156 mg/kg (quality class III), content of Ni 114 mg/kg (quality class III), Pb 55.5 mg/kg (quality class II), Cu 68.6 mg/kg (quality class II) and Cd 1.88 mg/kg (quality class II). The increased concentrations of Cr and Ni in samples from the Pivka river (at the Žeje springs and further downstream) could be the result of the impact of the military training area at Bač. Since, however, other sources are possible, it would be a good idea to take a sample of sediment from other springs along the Pivka river where the possibility of pollution from other sources does not yet exist. Tracing from the Bač firing range would be even more suitable, since this would clearly show what springs are directly connected to it and reveal the possible directions of transport of pollutants.

Increased contents of individual metals were also measured in sediment samples at the Malenščica spring, where the Pb content in the sediment was 81.7 mg/kg (quality class II) and Cr content 62.4 mg/kg (quality class II), and at the Kotliči spring where the content of Pb in the sediment was 54.8 mg/kg (quality class II), of Cd 1.28 mg/kg (quality class II), Cr 79.3 mg/kg (quality class II) and Ni 55.1 mg/kg (quality class II). Increased Cr contents in sediment (quality class II) were also measured at all other locations at the time of sampling, and occasionally also increased contents of Cu—quality class II (Žeje-spring, Pivka at Grobišče, Prunkovec-spring and Pivka river at Prestranek), Ni—quality class II (Žeje-spring, Stržen, Pivka at Grobišče, Prunkovec-spring, Pivka at Prestranek, Vipava-spring) and Cd—quality class II (Prunkovec-spring).

The Vipava spring has higher Cr and Ni values than the Malenščica spring and slightly lower Cu, Cd and Pb values, which indicates the high probability of the influence of the firing range at Poček, since the Vipava river is also partly fed from this area. An additional influence on the Vipava spring is represented by inflow from the Stržen spring—proved by the tracer test—which is polluted with the same metals. Water from Poček flows into Stržen, but also treated waste water from Postojna, including water from a metal industry plant. In order to verify this possible impact of outflow

7.2.3.2 Kakovost vodnih valov Malenščice po padavinah

Do največjih sprememb sestave kraške vode prihaja po padavinah, ki sledijo daljšemu sušnemu obdobju, zato smo podrobneje spremljali kakovost Malenščice v dveh zaporednih vodnih valovih septembra 2007. Meritve pretokov Malenščice smo dopolnili z zveznimi meritvami temperature in specifične električne prevodnosti (EC). Vzporedno smo zajemali vodne vzorce Malenščice v dveurnem intervalu za kemijske analize. Določili smo naslednje parametre: kalcij (Ca), magnezij (Mg), kloridi, nitrati, o-fosfati, sulfati, aluminij (Al), antimon (Sb), arzen (As), baker (Cu), barij (Ba), berilij (Be), bor (B), cink (Zn), kadmij (Cd), kobalt (Co), kositer (Sn), krom (Cr), mangan (Mn), molibden (Mo), nikelj (Ni), selen (Se), srebro (Ag), stroncij (Sr), svinec (Pb), talij (Tl), telur (Te) in vanadij (V).

V prvem vodnem valu sta ob naraščanju pretoka do maksimalne vrednosti (7,6 m^3/s) 19. septembra 2007 ostali temperatura (8,9 °C) in specifična električna prevodnost (370 µS/cm) Malenščice nespremenjeni (4). Tedaj je bil pretok vodotokov na Cerkniškem polju minimalen in sklepamo, da je iztekala v zaledju shranjena voda, predvsem infiltrirana voda z območja Javornikov. Ob prvem povečanju pretoka Malenščice izstopa višja vrednost Sn (39,6 µg/l), ki je ob nadaljnjem naraščanju pretoka najprej upadla na 5,8 µg/l, nato pa celo pod mejo določljivosti. Sočasno je bil nekoliko povečan Mo (0,6 µg/l). Od kovin smo ves čas meritev beležili povečane koncentracije Ba (okoli 6 µg/l) in Sr (113 µg/l), ki verjetno odražata naravne značilnosti zaledja izvira, kar pa bi bilo treba še preveriti. Vse druge merjene kovine so bile pod mejo določljivosti uporabljenih metod.

Do bolj izrazitega dogajanja je prišlo v drugem vodnem valu konec septembra (4), ko so bile padavine izdatnejše. Nekoliko višja temperatura Malenščice pred začetkom naraščanja pretoka v omenjenem valu je nakazovala tudi dotok toplejše vode s Cerkniškega polja v primerjavi z začetkom prvega vala. Koncentracija nitratov v Malenščici je ves čas upadala. Kloridi so sočasno z naraščanjem

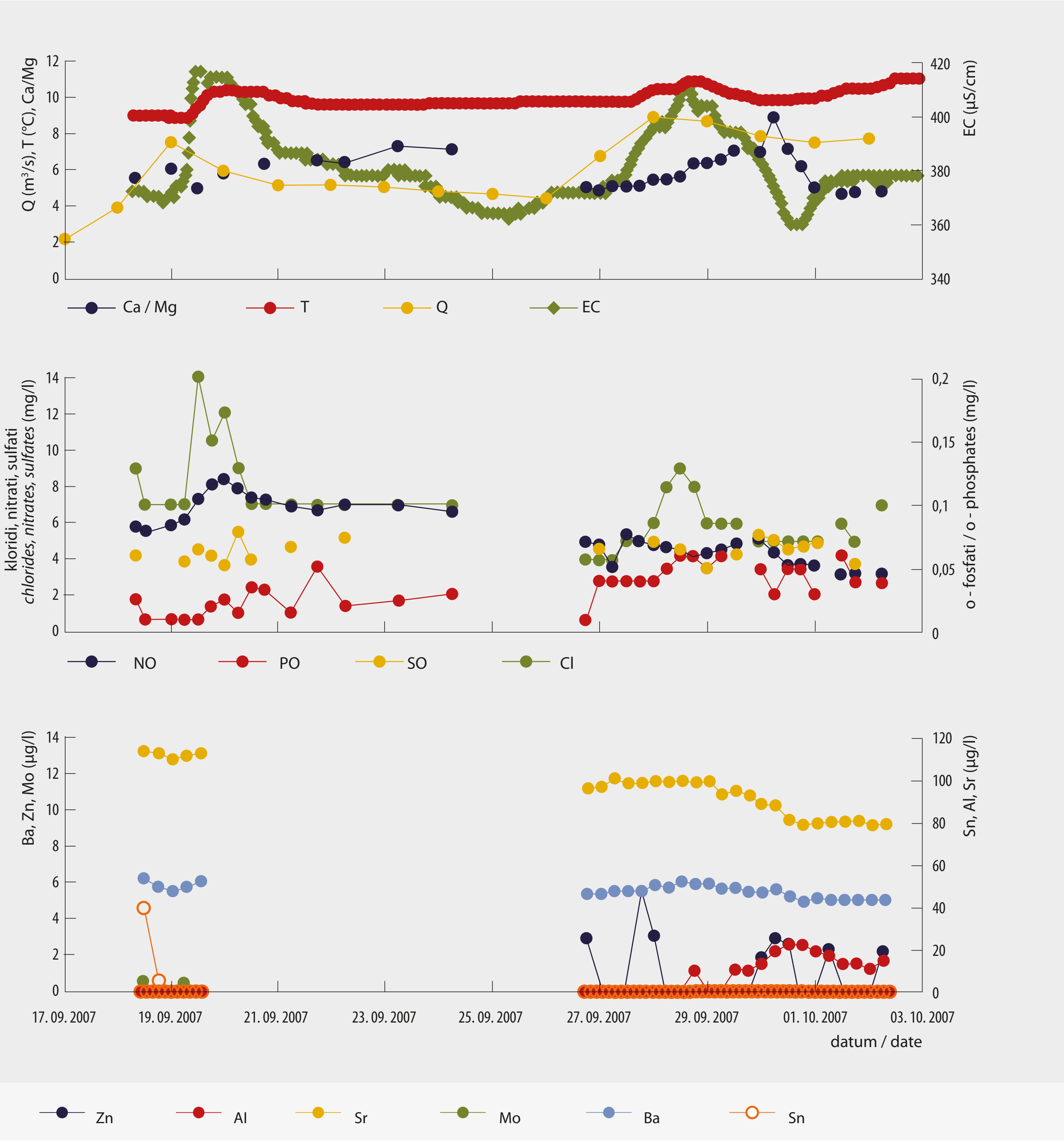
from the treatment plant, it would be a good idea to verify the composition of sediment at the outflow from the treatment plant.

Increased concentrations of Cr in the springs in Rakov Škocjan could be a reflection of the impact of activities in Poček but it is also possible that it comes from Cerkniško polje, which also receives water from Babno polje and Loško polje, the areas of habitation and industrial activity (including the metal industry). The same applies to Ni. A possible impact from Cerkniško polje could be checked by means of suitable reference samples of sediment and water in Cerkniško polje outside the area of influence of Poček.

In addition to the physical-chemical parameters already covered, we also analysed the organic pollutants content of the water samples and sediment. At the time of sampling, the measured concentrations of highly volatile halogenated hydrocarbons (HVHHC) and highly volatile aromatic hydrocarbons (BTX) were below the detection limit of the method for the individual parameter. The same applies to total hydrocarbons, except in water at the Stržen spring, where a concentration of 2.14 mg/l exceeded the prescribed limit value, which for total hydrocarbons is 0.05 mg/l (*Decree on the chemical status of surface waters – UrKSPV,* 2002). Measured concentrations of tenzids and phenols in the water were likewise below the detection limit of the method.

7.2.3.2 Quality of the Malenščica spring during the water pulses following rainfall

The biggest changes in the composition of karst water occur after rainfall that follows a long dry period. Therefore we closely monitored the water quality of the Malenščica spring in two successive water pulses in September 2007. Measurements of the discharges of the spring were complemented by continuous measurements of temperature and electrical conductivity (EC). At the same time we took water samples from the spring at a two-hour interval for chemical analysis. We determined the following parameters: calcium (Ca), magnesium (Mg), chlorides, nitrates, o-phosphates, sulfates, aluminium (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), molybdenum



4 Merjeni parametri v opazovanih vodnih valovih: pretok (Q), temperatura (T), specifična električna prevodnost (EC), razmerje Ca/Mg, kloridi (Cl^-), nitrati (NO_3^-), sulfati (SO_4^{2-}), o-fosfati (PO_4^{3-}) in kovine (Ba, Zn, Mo, Al, Sn in Sr).
Measured parameters in the observed water pulses: discharge (Q), temperature (T), electrical conductivity (EC), Ca/Mg ratio, chlorides (Cl^-), nitrates (NO_3^-), sulfates (SO_4^{2-}), o-phosphates (PO_4^{3-}), and metals (Ba, Zn, Mo, Al, Sn and Sr).

temperature in specifične električne prevodnosti dosegli maksimalno vrednost (9 mg Cl^-/l), kar verjetno odraža povečan dotok s Cerkniškega polja in spiranje onesnaženja. Tudi koncentracije o-fosfatov so se povečale do 0,07 mg PO_4^{3-}/l. Ob poznejšem nižanju temperature v upadajočem delu vodnega vala je naraščalo razmerje Ca/Mg, iz česar sklepamo na povečan dotok vode z območja Javornikov, morda pa gre tudi za vpliv Pivke iz ponora pri Trnju. Povečanja koncentracije kovin (Pb, Cr, Cd, Ni, Cu in Co), navzočih v tleh na pehotnem strelišču vojaškega poligona Poček (*Al Sayegh Petkovšek* idr. 2009), pa v vodnih vzorcih nismo določili oz. so bile koncentracije pod mejo določljivosti metod. Zaznali smo le večkratna občasna povečanja Zn (do 5,6 µg/l) in zvezno pojavljanje Al z maksimalno vrednostjo 22,5 µg/l, doseženo v času največjih vrednosti Ca/Mg in ob padcu temperature. Velja opozoriti, da so se v tleh vojaškega poligona Poček vsebnosti Zn praviloma nahajale v okviru normalnih vrednosti (*Al Sayegh Petkovšek* idr. 2006).

7.2.4 Ocena ogroženosti kraških vodnih virov v vplivnem območju

Iz rezultatov fizikalno-kemijskih preiskav odvzetih vzorcev vode je razvidno, da je bila med vzorčenjem voda obremenjena s celotnimi ogljikovodiki (mineralna olja) na lokaciji Stržen. Povsod drugod so bile izmerjene koncentracije organskih in anorganskih snovi nizke. V odvzetih vzorcih sedimenta so bile glede na priporočila za klasificiranje sedimentov v ZDA izmerjene visoke vsebnosti KPK. V času vzorčenja so bili tako močno onesnaženi sedimenti na lokacijah Prunkovec–izvir, Kotliči–izvir, Malenščica–izvir in Pivka pri Prestranku. Rezultati analize sedimenta so pokazali tudi onesnaženje rečnega sedimenta z določenimi kovinami (Pb, Ni, Cu, Cr, Cd). Na splošno je bil med vzorčenjem s kovinami najbolj obremenjen sediment na lokaciji Pivka pri Žejah (Cr in Ni v III. kakovostnem razredu; Pb, Cu in Cd v II. kakovostnem razredu). Prav tako so bile izmerjene povečane vsebnosti posameznih kovin v odvzetih vzorcih sedimenta na lokacijah Malenščica–izvir (Pb in Cr v II.

(Mo), nickel (Ni), selenium (Se), silver (Ag), strontium (Sr), thallium (Tl), tellurium (Te), tin (Sn), vanadium (V) and zinc (Zn).

In the first water pulse, with an increase of discharge to the maximum value (7.6 m^3/s) on 19 September 2007, the temperature (8.9 °C) and electrical conductivity (370 µS/cm) of the Malenščica spring remained unchanged (4). At that time the flow of watercourses on Cerkniško polje was minimal and we conclude that water stored in the catchment area, above all infiltrated water from the area of the Javorniki hills, was draining out. With the first increase in discharge of the Malenščica spring, a higher value is noticeable for Sn (39.6 µg/l), which as the discharge continued to grow first fell to 5.8 µg/l and then even dropped below the detection limit. At the same time there was a slight increase in the value for Mo (0.6 µg/l). With regard to the metals, throughout the period of measurements, we noted increased concentrations of Ba (around 6 µg/l) and Sr (113 µg/l), which are probably a reflection of the natural characteristics of the catchment area of the spring, although this would need to be checked further. All the other measured metals were below the detection limit of the methods used.

The situation was more marked during the second water pulse, at the end of September (4), when rainfall was more plentiful. The slightly higher temperature of the Malenščica spring before the start of the increase of discharge in the second water pulse also indicated the inflow of warmer water from Cerkniško polje in comparison to the start of the first water pulse. The concentration of nitrates in the Malenščica spring fell steadily. Simultaneous with the increases in temperature and electrical conductivity, chlorides reached their maximum value (9 mg Cl^-/l), which probably reflects the increase in flow from Cerkniško polje and the washing out of pollution. Concentrations of ortophosphates also increased to 0.07 mg PO_4^{3-}/l. With the subsequent fall in temperature in the recession period, the Ca/Mg ratio increased, from which we can conclude an increased flow of water from the area of the Javorniki hills, and perhaps also the influence of the Pivka river from the ponor near Trnje. Increases in the concentrations of the metals present in the soil in the infantry firing range of the Poček military training area (Pb, Cr, Cd, Ni, Cu and Co; *Al Sayegh Petkovšek* et al. 2009) were not identified kakovostnem razredu) in Kotliči–izvir (Pb, Cd, Cr, Ni v II. kakovostnem razredu). Poudariti moramo, da smo vode in sediment vzorčili le enkrat, pa še to ob upadajočih pretokih po izdatnejših padavinah, kar je za dejansko določitev vpliva vojaškega poligona na vodne vire premalo.

Na temelju podrobnih analiz v obdobju dveh vodnih valov sklepamo, da je začetnemu intenzivnemu spiranju onesnaženja, ki se je akumuliralo v predhodnem sušnem obdobju, sledil dotok čistejše vode s Cerkniškega polja, pa tudi delež vode z območja Javornikov se je povečeval. Ob koncu opazovanega prvega vodnega vala je pritekalo v izvir Malenščice tudi nekaj vode s Cerkniškega polja.

V drugem vodnem valu konec septembra 2007 je bilo dogajanje izrazitejše. Takrat so bile padavine izdatnejše in je bila prst omočena, vadozna cona vodonosnika na območju Javornikov pa bolj zapolnjena z vodo kakor v predhodnem valu. V takšnih razmerah prihaja po padavinah do spiranja tal ter pretakanja vode po celotni hierarhiji razpok skozi vadozno cono in nato po sklenjenih kanalih do izvira. Zaznan je bil dotok toplejše vode s Cerkniškega polja. V upadajočem delu vodnega vala se je povečal dotok vode z Javornikov, lahko pa bi šlo tudi za vpliv Pivke iz ponora pri Trnju. Vsebnosti nekaterih kovin (Pb, Cu, Cr, Cd, Ni in Co) so bile v vodnih vzorcih iz Malenščice pod mejo določljivosti analitske metode.

V vodnih vzorcih izvirov z vplivnega območja vojaškega poligona Poček so bile sicer izmerjene zelo nizke vsebnosti kovin, vendar pri vrednotenju vpliva poligona na vodne vire velja upoštevati, da so bile izmerjene povečane vsebnosti kovin v sedimentih. Slednje nakazuje možen vpliv Počka na izvira Malenščice in Vipave, ki sta zajeta za oskrbo prebivalstva s pitno vodo. Ker pa obstaja tudi možnost vplivov iz drugih virov, bi bilo treba napraviti še nekaj referenčnih preiskav na Cerkniškem polju in na ponoru Pivke pri Trnju. Tako bi ugotovili morebiten vpliv drugih dejavnosti še pred vplivnim območjem Počka. Glede na znano vodno povezavo med ponorom pri Trnju in izvirom Malenščice ugotavljamo, da bi v primeru potrjenega vpliva strelišča Bač na Pivko in ob izključitvi vpliva drugih

in the water samples or the concentrations were below the detection limit of the methods. We merely observed several occasional increases in Zn (up to 5.6 μg/l) and the continuous appearance of Al with a maximum value of 22.5 μg/l, which was reached at the time of the highest Ca/Mg values and with the fall in temperature. It is worth pointing out that concentrations of Zn in the soil of the Poček military training area were situated within normal values (*Al Sayegh Petkovšek* et al. 2006).

7.2.4 Estimate of the threats to karst water sources in the area of influence

It is clear from the results of physical-chemical investigation of the water samples taken that at the time of sampling the water was polluted with total hydrocarbons (mineral oils) at the location Stržen. At all other locations the measured concentrations of organic and inorganic substances were low. In the sediment samples taken, COD values that were high with regard to recommendations for the classification of sediments in the USA were measured. At the time of sampling, there were highly polluted sediments at the Prunkovec spring, Kotliči spring, Malenščica spring and Pivka at Prestranek. The results of analyses of the sediment also showed pollution of the river sediment with specific metals (Pb, Ni, Cu, Cr, Cd). In general, at the time of sampling the sediment was most polluted with metals at the Pivka river at Žeje (Cr and Ni in quality class III; Pb, Cu and Cd in quality class II). Increased contents of individual metals were likewise measured in the samples of sediment taken at the Malenščica (Pb and Cr in quality class II) and Kotliči springs (Pb, Cd, Cr, Ni in quality class II). It is worth emphasising that we only sampled the water and sediment once, at a time of recession following abundant rainfall, which is too little to actually determine the impact of the military training area on water sources.

On the basis of detailed analysis at the time of two water pulses we conclude that the initial intensive flushing of the pollution accumulated during the previous dry period was followed by the inflow of clean water from Cerkniško polje, while the proportion of water from the Javorniki area also increased. At the end of the dejavnosti na območju od izvira Pivščice do ponora v Trnju, morali tudi strelišče Bač obravnavati znotraj območja vpliva na Malenščico. Vsekakor je v tako občutljivem okolju, kot je kras, in še posebej, če gre za zaledje izvirov, zajetih za oskrbo prebivalcev s pitno vodo, nujna sodobna gradnja vojaških objektov, ki onemogoča nekontroliran vstop onesnažil v kraške vodne vire.

7.3 Ukrepi za zaščito kraških voda

Na podlagi opisanih splošnih značilnosti in rezultatov opravljenega sledilnega poskusa lahko potrdimo, da obremenjenost tal s kovinami na posameznih območjih vojaškega poligona Poček (zlasti na pehotnem strelišču) lahko ogroža kakovost zajetih izvirov Malenščice in Vipave, izvira Unice iz Planinske jame, izvirov v Rakovem Škocjanu in izvira Stržen pri Postojni, značilnosti pojava onesnažil v teh izvirih pa so odvisne od padavinskih in hidroloških razmer. Kljub temu da delež mobilnega dela Pb ne presega 0,1 % celotne vsebnosti Pb v talnih vzorcih pehotnega strelišča, kjer so bile izmerjene največje vsebnosti te kovine (*Al Sayegh Petkovšek* idr. 2009), pa sprememba razmer v tleh (na poligonu nastajajo namreč tudi nitrati in sulfati) lahko sproži intenzivnejše spiranje Pb in drugih kovin, ko s padavinami hitro in neovirano prodirajo globlje v kraški vodonosnik. Ko so kovine vezane v tleh, je z njihovo odstranitvijo še možna sanacija, ko pa vstopijo v vodonosnik, sanacija ni več mogoča. Tudi sanacija v primeru razlitja nevarnih snovi je na takem kraškem terenu praktično nemogoča, kar so dokazala razlitja naftnih derivatov v raznih nesrečah (*Kogovšek* 1995b; *Kogovšek* in *Petrič* 2002a, b). Vse napore je zato potrebno usmeriti v preventivo. Nevarnost predstavlja onesnaženje voda tako zaradi spiranja onesnaženih tal s padavinami kakor tudi zaradi aktivnosti, ki spremljajo nastanitev in oskrbo vojaških enot na vadišču (npr. komunalne odpadne vode). Tudi sama degradacija okolja s povečano erozijo prsti vpliva na vodne vire.

Pri načrtovanju aktivnosti na vojaškem poligonu so zato potrebni zaščitni in varovalni ukrepi na njem. Ker vode s tega območja odtekajo tudi proti

observed first water pulse, some water from Cerkniško polje also flowed to the Malenščica spring. The situation was more marked during the second water pulse, at the end of September 2007, when rainfall was more plentiful and the soil was damp, and the vadose zone of the aquifer in the area of the Javorniki contained more water than in the previous water pulse. In such conditions, rainfall is followed by a flow of water through the soil and the entire hierarchy of fissures through the vadose zone and then along conduits to springs. An inflow of warmer water from Cerkniško polje was noted. In the recession period, there was an increased inflow of water from the Javorniki area, and perhaps also the influence of the Pivka river from the ponor near Trnje. Contents of metals (Pb, Cu, Cr, Cd, Ni and Co) that showed increased values in the soil of the infantry firing range in Poček (*Al Sayegh Petkovšek* et al. 2006) were below the detection limit of the analytical method in the water samples from the Malenščica spring.

Although very low metals contents were measured in the water samples from springs from the area of influence of the Poček military training area, in evaluating the impact of the military training area on water sources it is worth taking into account the fact that the increased metal contents were measured in sediments. The latter indicates a possible impact of Poček on the Malenščica and Vipava springs, which are used to supply the population with drinking water. Since, however, there also exists a possibility of impacts from other sources, it would be necessary to carry out a number of reference investigations on Cerkniško polje and in the ponor of the Pivka river near Trnje. In this way we would establish the potential impact of other factors even before the area of influence of Poček. Given the known water connection between the ponor near Trnje and the Malenščica spring, we can state that in the case of a confirmed impact of the Bač firing range on the Pivka river, and with the exclusion of the impact of other factors in the area from the spring of the Pivka river to the ponor in Trnje, we would also have to treat the Bač firing range as being within the area of influence on the Malenščica spring. In any case, in such a sensitive environment as the karst, and in particular in the case of the catchment area of springs that are used to supply the population with drinking water, the modern construcvirom pitne vode, je treba upoštevati vse vodovarstvene predpise.

Na območju vojaških vadišč zato predlagamo naslednje ukrepe:

- padavinske vode z utrjenih površin je treba voditi preko usedalnikov in oljnih lovilcev;
- zaradi večjih količin ostankov streliva je nujen stalen pregled kakovosti vodnih izvirov in zajetij;
- uporabo streliva je treba prostorsko omejiti in tako fizično preprečiti vplive na podzemno vodo (strokovno odstranjevanje ostankov streliva z območja poligona);
- zagotoviti je treba pravilno ravnanje z naftnimi derivati in olji;
- pod vozila, parkirana na neutrjenih površinah, je treba podstaviti lovilne posode ali pivnike, z namenom, da se prepreči onesnaženje tal in vode z naftnimi derivati in olji;
- pretakanje naftnih derivatov in olj mora potekati na utrjenih površinah, da ne pride do nekontroliranih izpustov v okolje (urejene lovilne posode);
- treba je primerno urediti odvajanje in čiščenje vode iz nastanitvenih objektov.

7.4 Smernice za monitoring kakovosti kraških voda v vplivnem območju vojaških vadišč

Za spremljanje negativnih vplivov vojaških vadišč na vodne vire je treba vzpostaviti ustrezen monitoring. Na kraških območjih vstopajo onesnažila s površja neposredno v kraški vodonosnik, vode pa se nato pretakajo podzemno na večjih razdaljah in jih običajno lahko zajamemo šele v izvirih. Za določanje primernih točk monitoringa in za izbiro najbolj učinkovitega režima vzorčenja moramo zato dobro poznati hidrogeološke značilnosti območja. Dosedanje raziskave (*Kogovšek* 2010) so pokazale, da je smiselno vzorčenje po padavinah ob naraščanju pretokov, saj v sušnih obdobjih prenos skozi vadozno cono krasa skoraj popolnoma izostane.

Zbrani podatki kažejo na nujnost izvajanja monitoringa voda in sedimenta v vplivnem območju vojaškega vadišča Poček večkrat na leto (predvsem

tion of military facilities that prevents the uncontrolled access of pollutants to karst water sources is vital.

7.3 Measures for the protection of karst waters

On the basis of the general characteristics described above and the results of the tracer test, we can confirm that the pollution of soil with metals in individual parts of the Poček military training area (in particular the infantry firing range) can threaten the quality of the captured Malenščica and Vipava springs, the Unica spring from the cave Planinska jama, the springs in Rakov Škocjan and the Stržen spring near Postojna, while the characteristics of the appearance of pollutants in the springs are dependent on rainfall and hydrological conditions. Despite the fact that the mobile component of Pb does not exceed 0.1 % of the total Pb content in the soil samples from the infantry firing range where the highest contents of this metal were measured (*Al Sayegh Petkovšek* et al., 2009), changing conditions in the soil (nitrates and sulfates also occur in the training area) can trigger the more intensive flushing of Pb and other metals, when with rainfall they penetrate quickly and without obstruction deeper into the karst aquifer. When metals are bound within soil, remediation is still possible through removal of the soil, but when they enter an aquifer, remediation is no longer possible. In the karst terrain of this kind, remediation is also practically impossible in the case of the spillage of hazardous substances, something that has been demonstrated by spillages of petroleum derivatives in various accidents (*Kogovšek* 1995b; *Kogovšek* and *Petrič* 2002a, b). All efforts therefore need to be directed towards prevention. The danger comes from both the pollution of water as the result of wash-off of polluted soil with rainfall, and from activities that accompany the quartering and supply of military units in the training area (e.g. communal waste water). Degradation of the environment through increased soil erosion also has an impact on water sources.

In planning activities in the military training area, protective measures are therefore necessary within the area itself. Because waters from this area also drained monitoring kakovosti na izvirih Malenščice in Vipave, ki sta zajeta za vodooskrbo, občasno pa tudi na izvirih Prunkovec in Kotliči ter izviru reke Pivke), v odvisnosti od hidroloških razmer. Poleg takega stalnega monitoringa v določenih intervalih je smiselno tudi podrobno spremljanje izbranih parametrov v času vodnih valov, ki nastopijo ob izdatnejših padavinah po daljših sušnih obdobjih. Pri tem je treba podrobno preučiti način prenosa vseh onesnažil, posebno kovin, ki dosegajo na posameznih območjih na Počku velike vsebnosti tudi globlje (5–20 cm) v tleh (*Al Sayegh Petkovšek* idr. 2006, 2009), torej neposredno na vstopu v dobro prepustno kraško kamnino. Morda prav nevtralnost karbonatnih kamnin v vadozni coni zaenkrat onemogoča intenzivnejši nadaljnji prenos. Vendar pa druge dejavnosti na poligonu vplivajo tudi na kislost oz. alkalnost tal, ki pa je pomembna za prenos nekaterih kovin (svinec). Zato lahko zaenkrat, dokler ne bodo opravljene podrobnejše raziskave prenosa, le predpostavljamo, da pride tudi v vadozni coni do spremenjenih pogojev in preboja v prenosu teh nevarnih snovi. Iz dosedanjih raziskav krasa (*Kogovšek* in *Habič* 1981) pa vemo, da se lahko s površja globlje v kras po bolj prepustnih razpokah prenašajo tudi majhni trdni delci, na katere se vežejo kovine, pa tudi mikroorganizmi. Torej lahko kovine tudi v takšni obliki dosežejo kraške izvire.

Podobne smernice veljajo za načrtovanje monitoringa v vplivnih območjih vseh vojaških vadišč na krasu, vendar bi jih bilo treba prilagoditi ugotovljenim hidrogeološkim značilnostim posameznih območij. Osnova izdelave vsakega programa monitoringa je torej ustrezna predhodna hidrogeološka študija, ki lahko temelji na že obstoječih podatkih ali pa jo je ob pomanjkanju ustreznih podatkov treba dopolniti z novimi terenskimi raziskavami. V naši dosedanji praksi so se kot ena od najbolj primernih metod za tovrstne raziskave na krasu pokazali sledilni poskusi.

towards sources of drinking water, all water protection regulations must be observed.

We propose the following measures in the military training areas:

- rainwater from paved surfaces should be channelled via sedimentation basins and oil traps;
- owing to the large quantities of ammunition residues, the quality of springs and catchworks needs to be subject to constant inspection;
- the use of ammunition should be restricted to a specific area, in this way physically preventing impacts on groundwater (professional removal of ammunition residues from the training area);
- the correct management of petroleum derivatives and oils should be ensured;
- drip trays should be placed under vehicles parked on non-paved surfaces in order to prevent soil and water pollution with petroleum derivatives and oils;
- siphoning of petroleum derivatives and oils must take place on paved surfaces in order to prevent uncontrolled discharges into the environment (use of drip trays);
- the drainage and treatment of waters from accommodation facilities should be arranged appropriately.

7.4 Guidelines for monitoring the quality of karst waters in the area of influence of the military training areas

In order to monitor the negative impacts of the military training areas on water sources, an appropriate form of monitoring needs to be set up. In karst areas pollutants enter the karst aquifer directly from the surface. Waters then flow underground over large distances and can usually only be sampled in springs. In order to identify suitable monitoring points and choose the most effective sampling regime, we therefore need good knowledge of the hydrogeological characteristics of the area. Research to date (*Kogovšek* 2010) has shown that it makes sense to carry out sampling following rainfall when discharges increase, since in dry periods transport through the vadose zone of the karst ceases almost entirely.

The collected data point to the necessity of carrying out monitoring of waters and sediments in the area of influence of the Poček military training area several times a year (above all monitoring of water quality in the Malenščica and Vipava springs, which are used for water supply, and periodically of the Prunkovec and Kotliči springs and the spring of the Pivka river), depending on hydrological conditions. In addition to this constant monitoring at specific intervals, detailed monitoring of selected parameters during the water pulses that occur at times of abundant rainfall following longer dry periods is also a good idea. Here it is necessary to study in detail the method of transport of all pollutants, particularly metals, that in individual parts of the Poček military training area also reach high levels deeper down in the soil (5–20 cm) (*Al Sayegh Petkovšek* et al. 2006, 2009), in other words directly at the entrance to the highly permeable karst rock. It may be that the neutrality of carbonate rocks in the vadose zone for the time being prevents more intensive further transport. Other factors in the training area, however, also affect the acidity or alkalinity of the soil, which is important for the transport of some metals (lead). For the time being, then, until more detailed research of transport is carried out, we can only assume that conditions also change in the vadose zone and that there is a breakthrough in the transport of these hazardous substances. We know, in fact, from previous research of the karst (*Kogovšek* and *Habič* 1981) that small solid particles to which metals bind, and also microorganisms, can be carried from the surface deeper into the karst along more permeable fissures. Metals can therefore also reach karst springs in this form.

Similar guidelines apply to the planning of monitoring in the areas of influence of all military training areas in the karst areas, although it would be necessary to adapt them to the identified hydrogeological characteristics of these areas. The basis for drawing up each monitoring program is therefore a suitable preliminary hydrogeological study which can be based on existing data or, in the case of a lack of suitable data, supplemented as necessary by new field research. In our activities to date, tracer tests have proved to be one of the most suitable methods for this kind of research in the karst.

8

PRILAGAJANJE SLOVENSKE ZAKONODAJE POSEBNIM ZNAČILNOSTIM KRAŠKIH VODONOSNIKOV

ADJUSTMENT OF THE SLOVENE LEGISLATION TO THE SPECIAL CHARACTERISTICS OF KARST AQUIFERS

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Za učinkovito varovanje kraških vodnih virov pred negativnimi posledicami različnih človekovih dejavnosti so zelo pomembne odgovarjajoče zakonske podlage. Te vsebujejo pravila, ki omejujejo ali prepovedujejo aktivnosti z možnimi škodljivimi učinki in nalagajo izvajanje ukrepov za preprečevanje in omejevanje negativnih posledic. Slovenska zakonodaja na tem področju je prilagojena evropski zakonodaji in direktivam, v katerih pa kraški vodonosniki niso ustrezno izpostavljeni kot poseben tip z zelo specifičnimi značilnostmi. Posledično tudi prvotno sprejeti zakoni, uredbe in pravilniki, ki urejajo varovanje voda pri nas, večinoma niso posebej omenjali kraških območij. V nadaljnjih letih je praksa pokazala pomanjkljivosti tovrstnega pristopa in pojavile so se številne težave pri obravnavanju posameznih primerov vodnih virov, onesnaževalcev ali onesnaženj na krasu. Pripravljavci zakonodaje so se na to odzvali s postopnim vključevanjem sprememb in dopolnil v osnovnih uredbah, vendar pa gre za relativno počasen proces in za številne probleme še ni bila najdena primerna rešitev.

V nadaljevanju poglavja je najprej izpostavljenih nekaj značilnosti in osnovnih načel varovanja kraških vodnih virov, ki jih je treba upoštevati pri postavitvi zakonskih osnov za njihovo zaščito. Nato so predstavljeni deli vsebine pravnih podlag, ki upoštevajo posebne značilnosti krasa. V zaključku komentiramo ta posebna določila in jih primerjamo z izsledki naših raziskav o značilnostih pretakanja vode in prenosa snovi v krasu.

8.1 Osnovna načela varovanja kraških vodnih virov

Posebnosti krasa in kraških vodonosnikov se v smislu njihove ranljivosti kažejo predvsem v: odsotnosti varovalnega pokrova (npr. prst, sediment), hitri infiltraciji vode v podzemlje (ponori, razpokana kamnina), hitrem podzemnem pretakanju po kraških kanalih z možnostmi širjenja onesnaženja v različnih smereh ter v možnostih daljšega podzemnega uskladiščenja in kumulativnega kopičenja onesnaženja v conah slabše prepustnosti, ki ga lahko nato voda ob ustreznih

An adequate legal frame is essentially important for efficient protection of karst water resources against negative impact of various types of human activities. It defines the rules which limit or prohibit the activities with possible harmful influences and impose the implementation of measures for prevention and reduction of negative consequences. The Slovene legislation is adapted to the European legislation and directives. As in the latter the karst aquifers are not adequately treated as an environment with very specific characteristics, the particularities of karst areas were practically ignored in the first adopted Slovene laws, regulations and rules dealing with the water protection. In the following years many deficiencies of such approach were encountered in the practice of dealing with the problems of water resources, contaminants and pollution in karst. The legislator responded with a gradual incorporation of changes in the existent regulations. However, the process is relatively slow and still many problems remain unsolved.

In this chapter some basic characteristics and principles of karst water protection, which should be considered in preparation of the legislation, are recapitulated and in the existing regulations included articles dealing specially with karst are described. We comment these provisions and compare them with the results of our studies of groundwater flow and transport of substances in karst.

8.1 The basic principles of karst water protection

The specific characteristics of karst and karst aquifers in the sense of their vulnerability are: absence of efficient protective cover (e.g. soil, sediments), rapid infiltration of water into the underground (ponors, fissured rock), rapid groundwater flow through karst channels, quick spreading of pollution in various directions and long residence times and accumulation of contaminants in the low-permeability parts. Depending on the hydrological conditions, these pollutants may be washed out later through karst springs. The consequences of these characteristics are the following:

hidroloških pogojih iztisne skozi kraške izvire.

Posledice teh značilnosti so naslednje:

- velika ranljivost kraških vodonosnikov in močno zmanjšana samočistilna sposobnost;
- zaradi velikih hitrosti toka se lahko onesnaženje hitro razširi daleč proč od mesta vnosa v vodonosnik;
- možno dlje časa trajajoče uskladiščenje škodljivih snovi je razlog za dolgotrajno onesnaženost vodnega vira;
- najpomembnejši dejavnik zmanjševanja onesnaženja je razredčenje.

V procesu varovanja kraških voda je prvi korak njihovo ustrezno ovrednotenje, ki je tesno povezano z vrednotenjem celotnega kraškega sistema. Pri tem moramo upoštevati, da je kraška voda bistveni del ekosistema, naravni vir ter javno in ekonomsko dobro, katerega kakovost in količina določata njegovo uporabo. Kraški vodni viri morajo biti zaščiteni, upoštevati pa je treba tudi odzivanje vodnih ekosistemov in obnovljivo naravo virov. Pomembni so predvsem trije glavni vidiki:

- poznavanje naravnih značilnosti: v tem okviru moramo opredeliti obseg in način napajanja kraških vodonosnikov, značilnosti pretakanja in uskladiščenja podzemne vode, značilnosti izvirov ali površinskih tokov in podobno; posebej je treba izpostaviti podatke o razporeditvi in količini vode;
- kakovost voda: nanjo poleg naravnega ozadja v veliki meri vplivajo tudi človekove dejavnosti;
- sedanje in načrtovane potrebe po vodi ter možnosti njihove izrabe: kraški vodonosniki so pomemben vodni vir, pri načrtovanju njihovega izkoriščanja pa moramo upoštevati tako potrebe kot možnosti njihove izrabe.

V drugi fazi je potrebna ocena ogroženosti kraških voda, ki je odvisna od naravne ranljivosti vodonosnika in njegove obremenjenosti. Ranljivost opisuje naravne značilnosti kraških vodonosnih sistemov z vidika njihovega varovanja (*Vrba* in *Zaporozec* 1994). Določamo jo na podlagi geoloških in hidrogeoloških raziskav ter analize občutljivosti za vplive človeka in narave. Običajno jo predstavljamo v obliki kart ranljivosti, s katerimi lahko tudi grafično ponazorimo različne in kompleksne hidrogeološke značilnosti. Obremenjenost okolja je odvisna od različnih oblik in obsega človekovih dejavnosti. Dejanska obremenjenost

- high vulnerability of karst aquifers and much reduced self-purification;
- the contamination may spread rapidly and far away from the pollution source due to high flow velocities;
- long residence times and accumulation of harmful substances lead to long-term pollution of the water source;
- dilution may be the main form of pollution attenuation.

An adequate evaluation of karst waters, which is closely connected with the evaluation of the karst system as a whole, is the first step in the process of their protection. Karst waters are an essential part of the ecosystem, a natural source and a public and economic good. The use of water is conditioned by its quality and quantity. The karst water sources have to be protected, and the response of water ecosystems and their renewable nature considered. The following three aspects are the most important:

- understanding of natural characteristics: e.g. we should study the extent and type of recharge of karst aquifers, the characteristics of groundwater flow and storage, and the characteristics of springs and surface streams; the distribution and quantity of water are two significant parameters;
- water quality: additional to natural background the human activity largely affect the quality;
- present and future needs for water and feasibility of their use: karst aquifers are an important source, and it is essential to consider the needs as well as the feasibility of their consumption while planning their use.

In the second phase the risk assessment including the intrinsic vulnerability and pollution hazards should be implemented. The intrinsic vulnerability describes the natural characteristics of karst aquifers from the protection point of view (*Vrba* and *Zaporozec* 1994). It takes into account the result of geological and hydrogeological researches and the sensibility analyses of human and natural influences. Various and complex hydrogeological characteristics are usually presented graphically on vulnerability maps. The analysis of hazard depends on various types and extent of human activities. The existing hazard includes all vključuje vse vire onesnaževanja, opredelimo pa lahko tudi potencialno obremenjenost. Ocena ogroženosti temelji na identificiranju nevarnosti in oceni verjetnosti pojavljanja negativnih vplivov, ki je odvisna od ranljivosti in obremenjenosti. Pri tem je treba opredeliti možne posledice, tudi v povezavi s pomenom posameznih vodnih virov za vodooskrbo.

Naslednja faza je priprava strategije ter načrta primernega varovanja in gospodarjenja z vodami. Na temelju pripravljenih strokovnih podlag je treba za vodne vire določiti način njihove zaščite in sprejeti ustrezne ukrepe za njihovo varovanje. Zelo velik pomen pri tem ima zakonodaja, ki mora postaviti odgovarjajoče pravne okvire za izvajanje zaščite. Zagotoviti je treba učinkovit nadzor nad uresničevanjem predvidenih ukrepov.

K uspešni zaščiti lahko bistveno pripomoreta vzgoja in izobraževanje ljudi. Ljudje se moramo namreč zavedati življenjskega pomena podzemne vode in njene občutljivosti za onesnaževanje s kraškega površja.

Če torej povzamemo, mora varovanje kraških vodnih virov temeljiti na:

- dobrem poznavanju značilnosti krasa (izdelava ustreznih strokovnih podlag);
- sprejetju uredb o varovanju (območja in načini zaščite: določitev vodovarstvenih pasov, znotraj njih pa opredelitev omejenih in prepovedanih aktivnosti);
- razumni izrabi;
- stalnem monitoringu kakovosti;
- ozaveščenosti prebivalcev o pomenu in ranljivosti kraških voda ter o ukrepih za njihovo zaščito.

8.2 Prilagajanje slovenske zakonodaje posebnim značilnostim kraških vodonosnikov

Temeljno pravno podlago na področju voda predstavlja ***Zakon o vodah*** (*ZV-1*, 2002), *ki ureja upravljanje z morjem, celinskimi in podzemnimi vodami ter vodnimi in priobalnimi zemljišči*. (V celotnem poglavju 8.2 so v poševnem tisku zapisane navedbe ali povzetki navedb iz zakonskih aktov, v navadnem tisku pa naši komentarji.) V zakonu izraza 'kras' in 'kraški' nista omenjena. Med drugim *predvideva tudi izdelavo območij in režimov varovanja vodnih virov, ki se*

the pollution sources, and additionally the potential hazard may be defined. The risk assessment is based on the identification of hazard and the assessment of probability of negative impacts occurring, which depends on vulnerability and hazard. The idea is to predict the possible consequences, also with regard to the importance of individual water sources.

The next phase is preparation of the water resources protection and management strategies and plans. Based on the prepared expert basis the adequate methods and measures for the protection of water sources have to be implemented. The legislation is an important legal frame for efficient protection, and it should ensure a proper control over implementation of the prescribed measures.

Education and training of public can significantly contribute to efficient protection. People need to be aware of the importance of groundwater to their lives and the vulnerability of this resource to pollution from the karst surface.

Therefore, the protection of karst water resources should be based on:

- good understanding of the characteristics of karst (setting up the adequate expert basis);
- legal acts of protection (designation of water protection zones, and within them definition of controlled or prohibited activities);
- reasonable consumption;
- permanent quality monitoring;
- public awareness of the importance and vulnerability of karst waters and of the measures for their protection.

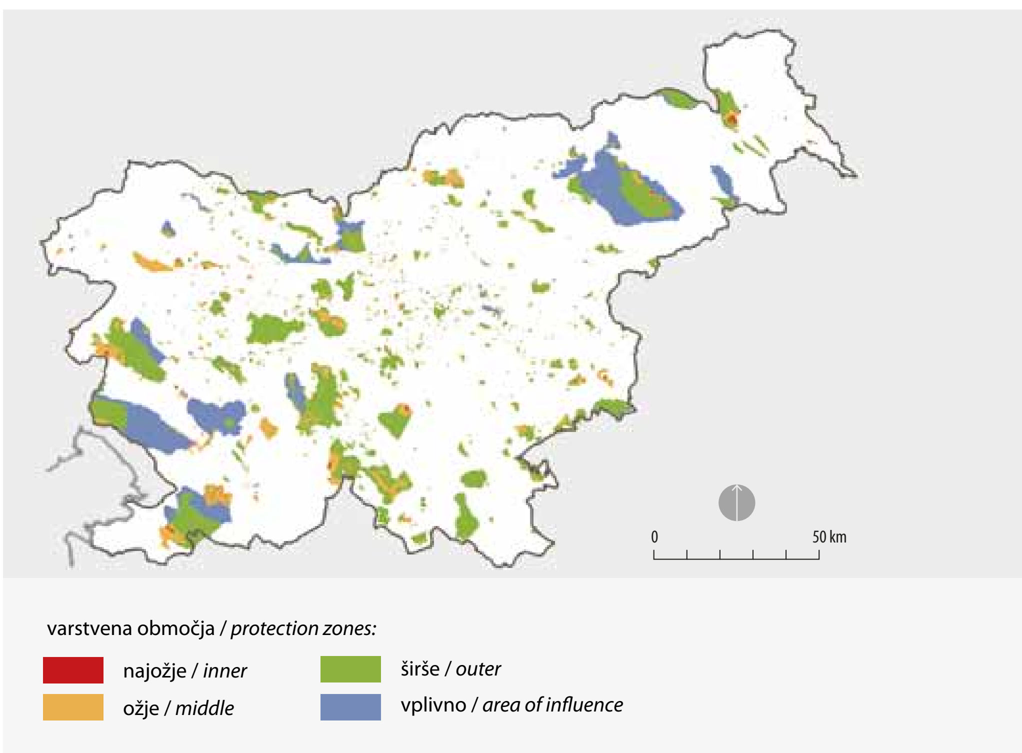
8.2 Adjustment of the Slovene legislation to the special characteristics of karst aquifers

The ***Waters Act*** (*ZV-1*, 2002) *governs the management of marine, inland and groundwaters, and the management of water and waterside land.* (In the whole chapter 8.2 the text or summary of the text of the legal acts is cited in italic, and our comments in regular font style). In this Act the terms 'karst' and 'karstic' are not mentioned. *The government shall designate* *uporabljajo za javno vodooskrbo* (1). *Za določanje varstvenih pasov in za nadzor nad izvajanjem predpisanih ukrepov so odgovorne pristojne državne ustanove.* Po prejšnji zakonodaji je bilo to v pristojnosti občinskih uprav. Največji problemi so se pojavljali tam, kjer so bili vodovarstveni pasovi določeni izven meja občine, ki vodni vir izrablja. Zato predvsem pri večjih kraških izvirih z velikim obsegom zaledja ustrezni odloki niso bili sprejeti. Stanje se s prenosom tega pooblastila na državo izboljšuje, vendar pa smo zaenkrat večinoma še v prehodni fazi pripravljanja ustreznih odlokov.

Način določitve vodovarstvenih območij predpisuje ***Pravilnik o kriterijih za določitev vodovarstvenega območja*** (*PrKDVO*, 2004), ki *ločeno obravnava medzrnski, razpoklinski in kraški tip vodonosnika. Izpostavljene so posebne značilnosti pretakanja vode v kraških vodonosnikih, zaradi katerih je treba uporabiti drugačne metode za opredelitev vodovarstvenih območij. Našteti so geološki, geomorfološki in hidrogeološki podatki, ki jih je treba določiti: hitrosti in smeri toka podzemne vode, piezometrična gladina podzemne vode, razredčenje dejanskih in morebitnih onesnaževal, velikost in zakraselost napajalnega območja ter*

the protected water areas (1) *and water protection regimes if the water body is intended for the supply of drinking water, and shall supervise the implementation of the prescribed measures.* In the previously valid legislation, the local communities were responsible for these actions. However, many problems occurred in the areas where the protection zones extend to the territory of communes which do not use the drinking water source in question. As a consequence, for many important karst sources with a large extent of the catchment no adequate legal acts for their protection were implemented. Now we are still in a transitional phase, however in the future the conditions should improve due to the transfer of responsibility to the governmental services.

The methods for the designation of water protection zones are defined in the ***Rules on criteria for the designation of a water protection zone*** (*PrKDVO*, 2004). *In the Rules the porous, fissured and karst types of aquifers are treated separately. Special characteristics of water flow in karst aquifer are emphasised owing to which some specific methods for the designation of protection zones should be applied. The following geological,*



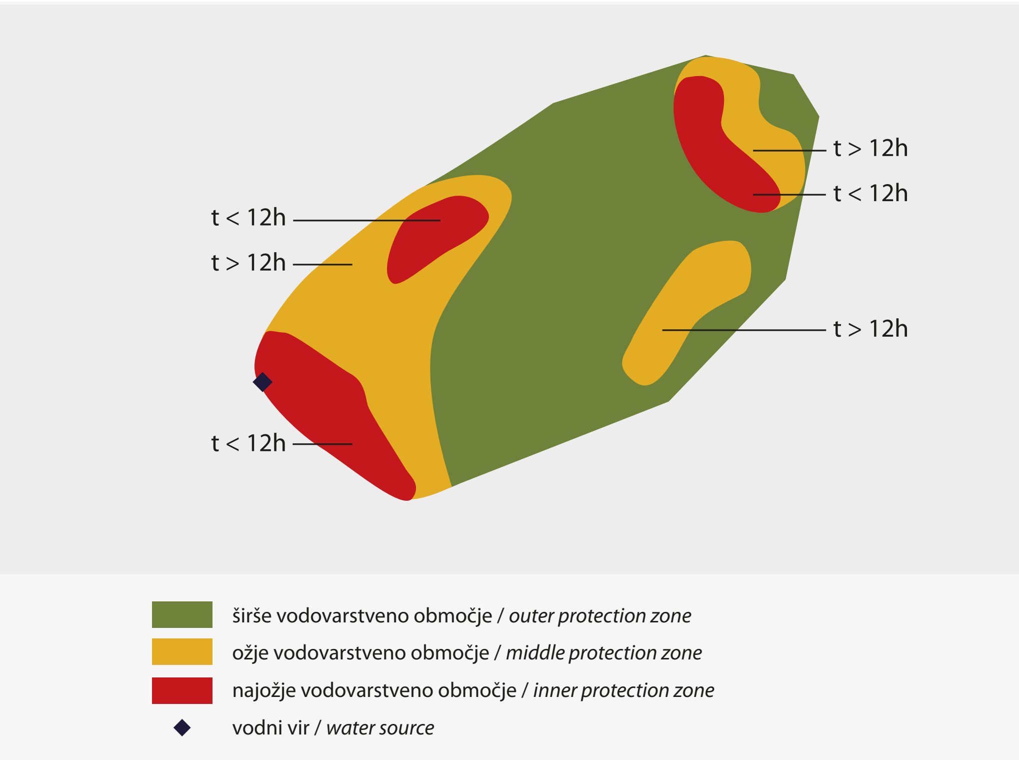
1 Vodovarstvena območja na ozemlju Slovenije po stanju avgusta 2008 (vir *EIONET*).
Water protection zones in Slovenia, situation in August 2008 (source *EIONET*).

geološko-kemijske lastnosti podzemne vode. Poleg tega je navedenih šest raziskovalnih metod, s katerimi naj bi te podatke pridobili. Pravilnik dopušča možnost uporabe samo ene metode, je pa v posebnem odstavku dodano, da je treba v primeru, ko ta ne zagotavlja zanesljive in učinkovite določitve mej, uporabiti rezultate različnih metod. Glede na naše izkušnje je zaradi kompleksne zgradbe in delovanja kraških vodonosnikov uporaba več vzporednih metod nujna in bi jo bilo smiselno predpisati. Poleg osnovnega geološkega, geomorfološkega in hidrogeološkega kartiranja bi bilo treba izpostaviti zlasti sledilne poskuse, ki največ povedo o smereh in značilnostih podzemnega pretakanja vode v krasu.

Za vsak vodni vir so predvideni vsaj trije vodovarstveni pasovi (2). *Meja širšega območja je enaka zunanji meji celotnega naravnega napajalnega območja. Na ožjem območju mora biti zagotovljeno varovanje zajetja z izvedbo interventnih ukrepov v zelo kratkem času (čas dotoka v zajetje večji od 12 ur), na najožjem območju pa zagotovljeno varovanje zajetja pred kakršnimkoli onesnaženjem, ker možnosti izvedbe interventnih ukrepov na tem območju ni (čas dotoka manjši kot 12 ur). Pravilnik navaja tudi značilna kraška območja*

geomorphological, and hydrogeological data have to be defined: the velocities and directions of groundwater flow, piezometric levels, dilution of actual and potential contaminants, extent and karstification of the catchment, and geochemical characteristics of groundwater. Six research methods can be applied to get these data. The use of only one method is allowed, however in a special paragraph the application of several methods is requested in the cases when the limits of protection zones can't be defined reliably and efficiently by the use of only one method. According to our experiences, the parallel use of several methods is essential due to the complex structure and functioning of karst aquifers and should be obligatory. Besides basic geological, geomorphological and hydrogeological mapping, the most useful method for defining the directions and characteristics of groundwater flow in karst are tracer tests.

For each water source at least three protection zones should be designed (2). *The boundary of the outer zone is the same as the catchment boundary. In the middle zone the implementation of intervention measures for protection of the source should be feasible in a very short period (the travel time to the abstraction site more than*



2 Shema omejitve vodovarstvenih pasov v kraških vodonosnikih.
Schematic presentation of water protection zones in karst aquifers.

(zakrasela območja z visokimi hitrostmi pretakanja, ponori in ponikalnice, kraška polja) in jih glede na povezavo z zasičeno cono uvršča v ožji in najožji varstveni pas. Težavo pri upoštevanju tega določila predstavlja dejstvo, da so enake značilnosti za ponore in kraška polja navedene pri obeh pasovih.

Pravilnik v prilogi 1 vključuje nabor prepovedi, omejitev in zaščitnih ukrepov za posege v okolje, v prilogi 2 dopustne vrednosti relativne občutljivosti za izdelavo ocen tveganja, v prilogi 3 pa predpisuje obliko strokovnih podlag za pripravo akta o zavarovanju.

Drugi krovni zakon, ki ureja tudi področje varovanja voda, je ***Zakon o varstvu okolja*** (*ZVO-1*, 2004) oz. predvsem podzakonski akti, ki ga spremljajo. Tako so bile sprejete uredbe o ravnanju z različnimi škodljivimi snovmi in o mejnih vrednostih emisij nevarnih snovi.

V ***Uredbi o emisiji snovi pri odvajanju odpadne vode iz komunalnih čistilnih naprav*** (*UrES*, 2007a) kraški vodonosniki niso bili posebej omenjeni. Nato pa je bila sprejeta ***Uredba o spremembah in dopolnitvah Uredbe o emisiji snovi pri odvajanju odpadne vode iz komunalnih čistilnih naprav*** (*UrsdES*, 2010), ki vsebuje dopolnilo za kraške in razpoklinske vodonosnike. *Za ta območja predpisuje poleg terciarnega čiščenja tudi dodatno obdelavo odpadne vode, če se le-ta odvaja posredno v podzemno vodo na zakraselih območjih. Upravljavec se mora prilagoditi tem zahtevam najpozneje do 22. decembra 2015.*

Podobno je bil dodan člen za kraške in razpoklinske vodonosnike v ***Uredbi o emisiji snovi pri odvajanju odpadne vode iz malih komunalnih čistilnih naprav*** (*UrES*, 2007b). *Pri odvajanju odpadne vode na površje tal ali s ponikanjem v tla mora biti zagotovljeno ponikanje preko objekta za ponikanje vode, katerega prostornina za zadrževanje očiščene komunalne odpadne vode ne sme biti manjša od povprečne dnevne količine, odvedene iz male komunalne čistilne naprave, med dnom objekta za ponikanje in najvišjo gladino podzemne vode pa se mora nahajati plast neomočenih sedimentov ali kamnin ali filtrskega materiala, debeline najmanj 1 m.*

Uredba o emisiji snovi in toplote pri odvajanju odpadnih vod v vode in javno kanalizacijo (*UrES*, 2005b) *določa, da je odpadne vode prepovedano odvajati neposredno (brez precejanja skozi neomočene sedimente ali kamnine, ki so pod površjem tal) v podzemne*

12 hours). In the inner zone no time for the implementation of intervention measures is available, therefore the protection against any kind of pollution should be assured within this area (the travel time less than 12 hours). In the Rules various types of karst are defined (karstified areas with high flow velocities, ponors and sinking streams, karst poljes) and according to their connection to the saturated zone they are classified into the middle or inner protection zone. However, it is not possible to apply this classification unambiguously, because for the two types of protection zones the same characteristics of ponors and karst poljes are defined.

In the Appendix 1 of the Rules the prohibited and controlled activities and protection measures are listed, in the Appendix 2 the allowed values of relative sensitivity for the risk assessment analysis are given, and the Appendix 3 regulates the form of the expert report on which the design of the protection act is based.

The second important act in the field of water protection is the ***Environment Protection Act*** (*ZVO-1*, 2004), which is supplemented with numerous Implementing regulations. These manage the treatment of various harmful substances and define the limit values of their emissions.

In the ***Decree on the emission of substances in waste water discharged from urban waste water treatment plants*** (*UrES*, 2007a) the karst aquifers were not mentioned. However, later the ***Decree on changes and completion of the decree on the emission of substances in waste water discharged from urban waste water treatment plants*** (*UrsdES*, 2010) was approved. It contains the supplement about the karst and fissured aquifers. *Additional to the tertiary purification, an additional treatment of waste waters is needed in the cases of indirect drainage of waste waters into groundwater in karst areas. The managers of the water treatment plants should adapt to this new regulation by 22 December 2015.*

A similar article for karst and fissured aquifers was added to the ***Decree on the emission of substances in the discharge of waste waters from small urban waste water treatment plants*** (*UrES*, 2007b). *In the cases when waste waters are discharged on the soil surface or sink into the ground, the flow must be drained through a sinking facility for the retention of treated communal* *vode. Tudi posredno odvajanje je dovoljeno le v izjemnih primerih, ko te prepovedi niso določene s predpisi, ki urejajo vodovarstveni režim. Pri tem parametri odpadne vode ne smejo presegati za napravo predpisanih mejnih vrednosti za odvajanje neposredno v vode in odvajanje ne sme vplivati na kakovost tal in podzemne vode. Dovoljenje izda ministrstvo v okoljevarstvenem dovoljenju, če iz priložene dokumentacije izhaja, da so izpolnjeni zgoraj navedeni pogoji.* Problem pri tej določbi je v zelo ohlapni definiciji, da *odvajanje ne sme vplivati na kakovost tal in podzemne vode*. Odločitev o tem je prepuščena pripravljavcu strokovnih podlag za izdajo okoljevarstvenega dovoljenja, saj merila še dopustnega vpliva niso postavljena. Smiselna bi bila zato določitev teh meril ob upoštevanju pomembnega vpliva hidroloških razmer.

Uredba o emisiji snovi pri odvajanju padavinske vode z javnih cest (*UrES*, 2005a) *razlikuje med cestami na različnih tipih vodonosnikov in z različno gostoto prometa. Za nekatere izmed tako določenih razredov predpisuje, da je treba za padavinsko vodo, ki odteka s cestišča, zagotoviti zajetje v zadrževalniku padavinske odpadne vode ločeno od zalednih vod, ki nastajajo na območju javne ceste. Pri kraških vodonosnikih je ta meja pri nižji gostoti prometa. Prepovedano je neposredno odvajanje v podzemne vode. Določene so mejne vrednosti parametrov za padavinsko odpadno vodo, in sicer različno, glede na način odvajanja. Pri preseženih mejnih vrednostih je treba zagotoviti dodatno čiščenje. Če gre za vodovarstveno območje, je treba upoštevati predpise, ki urejajo varstveni režim znotraj tega območja.*

V ***Uredbi o emisiji snovi pri odvajanju izcedne vode iz odlagališč odpadkov*** (*UrES*, 2008) in ***Uredbi o mejnih vrednostih vnosa nevarnih snovi in gnojil v tla*** (*UrMVVNS*, 2005) območja krasa niso posebej omenjena.

V ***Pravilniku o obratovalnem monitoringu onesnaževanja podzemne vode*** (*PrOM*, 2006) je postavljenih več posebnih določil za kraške vodonosnike. *Meritve osnovnih in indikativnih parametrov ter drugih onesnaževal, vključenih v obratovalni monitoring, se izvajajo najmanj štirikrat letno na kraških vodonosnikih, če za posamezni vir onesnaževanja v predpisu, ki ureja emisije v okolje iz tega vira, ni drugače določeno.* Glede na naše izkušnje z veliko spremenljivostjo fizikalnih

waste waters. Its volume should not be less than the mean daily amount of water drained out of the small urban waste water treatment plant. The layer of unsaturated sediments or rocks or filter material between the bottom of the sinking facility and the highest level of groundwater should be at least 1 m thick.

According to the ***Decree on the emission of substances and heat in the discharge of wastewater into waters and public sewage system*** (*UrES*, 2005b) *it is not allowed to drain waste waters directly (without filtration through a layer of unsaturated sediments or rocks below the surface) into the groundwater. The indirect drainage is permitted only in exceptional cases when no prohibitions are set in the regulations of water protection zones. Additionally, the waste water parameters should not exceed the limit values defined for a direct drainage into waters, and should not reduce the quality of soil and groundwater. The permission is issued in the Environment Protection Licence by the Ministry only if it is evident from the enclosed documentation that the above mentioned conditions are fulfilled.* A weak point of this provision is in a loose definition that *the drainage of waste waters should not reduce the quality of soil and groundwater.* As no exact values of allowed concentrations of possible contaminants in the soil and groundwater are prescribed, only a subjective assessment of the experts preparing the documentation is possible. Therefore the completion of this act is necessary. In its preparation an important influence of hydrological conditions should be taken into account.

In the ***Decree on the emission of substances in the discharge of meteoric water from public roads*** (*UrES*, 2005a) *the roads on various types of aquifers and with different traffic density are classified. The discharge of precipitation water from the roads with higher traffic density has to be directed through a retention pond, separated from the meteoric water within the catchment of the road. The threshold density is lower for karst aquifers. A direct discharge into the groundwater is prohibited. The limit values for the quality parameters of precipitation water from the roads are set. They differ for various types of drainage. An additional treatment is necessary when the limit values are exceeded. For the roads within the water protection zones the protection measures defined for these zones have to be respected.*

in kemičnih parametrov kraških voda s hidrološkimi razmerami lahko rečemo, da so štirje vzorci letno premalo, da bi bili rezultati reprezentativni. V določilu je sicer uporabljena beseda *najmanj*, ki pa ne zagotavlja, da bo dejansko predpisano večje število vzorčenj.

Številna pa so posebna določila za kras v ***Navodilih za izdelavo hidrogeološkega poročila za program obratovalnega monitoringa***, ki so priloga 1 k Pravilniku. *Pri posnetku ničelnega stanja je treba opredeliti najbolj verjetne poti toka podzemne vode. Te smeri so lahko določene na podlagi strukturnega kartiranja, sledilnih poskusov in opazovanja kemijskega stanja podzemne vode ali geofizikalnih raziskav. Na podlagi teh raziskav je treba podati oceno hitrosti in pretoka podzemne vode.*

Vsak obstoječi vir onesnaževanja na krasu se obravnava posebej. Za monitoring se uporabljajo predvsem naravni hidrogeološki objekti. Tam, kjer teh objektov ni ali pa so tako daleč, da lahko na poti od vira onesnaževanja do njih pride do velikega razredčenja onesnaževal in zaradi tega izvajanje obratovalnega monitoringa podzemne vode ni mogoče neposredno, je treba z obratovanjem vira onesnaževanja v najkrajšem možnem času prenehati. Učinke na podzemno vodo se na teh virih onesnaževanja opazuje posredno preko obremenitev in hidrološke bilance padavinskih in izcednih voda ter s preverjanjem hidravličnih značilnosti prekrivnih materialov. Ustreznost prekrivnih materialov se dokaže s hidrološko bilanco. Zvezne meritve pretokov so obvezne na vseh naravnih hidrogeoloških objektih, ki se nahajajo v dolvodni smeri od vira onesnaževanja in so vključeni kot točke za opazovanje kemijskega statusa podzemne vode. Opustitev monitoringa za vire onesnaževanja, ki leže na kraških kamninah, ni dovoljena.

8.3 Ocena pomanjkljivosti in dobrih rešitev

V Zakonu o vodah kraške vode sploh niso omenjene, čeprav bi glede na delež oskrbe iz kraških vodonosnikov v Sloveniji to pričakovali. Dobra rešitev pa je prenos pristojnosti za sprejetje uredbe o varovanju vodnih virov na državne organe, saj so prej na občinskem nivoju pogosto prevladali lokalni interesi in so bili odloki sprejeti le v omejenem obsegu ali pa sploh ne. Žal poteka proces na državni ravni le počasi in je

In the ***Decree on the emission of substances in the discharge of landfill effluent*** (*UrES*, 2008) and in the ***Decree on the limit input concentration values of dangerous substances and fertilizers in soil*** (*UrMVVNS*, 2005) the karst areas are not specially mentioned.

In the ***Rules on the performance of operational monitoring of groundwater pollution*** (*PrOM*, 2006) several particular regulations for karst aquifers are set. *If there is no other specification in the act regulating the emissions from an individual pollution source, the measurements of basic and indicative parameters and other contaminants, which are included in the operational monitoring, should be performed at least four times a year in karst aquifers.* According to our experiences the physical and chemical parameters of karst waters are highly variable at different hydrological conditions. Therefore only four samples per year are not enough to get representative results. Even though in the Rules the term *at least* is used, this is no assurance that a larger number of samples would be requested in the regulations for an individual pollution source.

Numerous particular regulations for karst are defined in the ***Instructions for preparation of the hydrogeological report for the operational monitoring programme*** which are the supplement 1 of the Rules. *In the estimation of the zero conditions, the most probable directions of groundwater flow have to be defined based on the structural mapping, tracer tests, monitoring of the chemical state of groundwater or geophysical researches. The flow velocities and discharges of groundwater have to be assessed.*

Each existent pollution source in karst is treated individually. The natural hydrological objects are usually used as the monitoring points. Any activity at the pollution source should be stopped in a shortest possible time in the areas where no such objects exist or in the cases when they are so remote that a direct monitoring of groundwater is not possible due to a significant dilution of contaminants in the flow between the source and this point. The impacts on groundwater can only be monitored indirectly. The pollution and hydrological balances of precipitation and waste waters have to be assessed. The hydraulic characteristics of the cover materials and their suitability have to be tested by hydrological balance. Continuous discharge measurements zaenkrat za večje kraške vodne vire sprejeta le ***Uredba o vodovarstvenem območju za vodno telo vodonosnikov Rižane*** (*UrVORiž*, 2008).

Še najbolj podrobno so posebnosti krasa opredeljene v Pravilniku o kriterijih za določitev vodovarstvenih območij (*PrKDVO*, 2004). Ta dokaj natančno navaja hidrogeološke parametre, ki jih je treba določiti v strokovnih podlagah za omejitev vodovarstvenih območij, predpisuje pa tudi raziskovalne metode, s katerimi jih je možno določiti. Po našem mnenju je pomanjkljivost v tem, da dopušča uporabo samo posameznih metod, s katerimi dobimo le del potrebne informacije in ne moremo ustrezno pojasniti delovanja kompleksnih kraških vodonosnikov. Izdelovalci strokovnih podlag zato pogosto določijo vodovarstvena območja na podlagi skopih hidroloških in geoloških podatkov, le redko pa so v te namene opravljene raziskave načina napajanja, podzemnega pretakanja in praznjenja kraških vodonosnikov ter izvedeni sledilni poskusi v zaledju vodnih virov. Prav sledilni poskusi so metoda, ki daje najbolj uporabne podatke za razumevanje značilnosti podzemnega pretakanja vode in prenosa snovi v krasu (*Petrič* 2009; *Kogovšek* in *Petrič* 2004). Pogosto tudi ni upoštevana v prostoru zelo spremenljiva ranljivost kraških vodonosnikov (vloga zaščitnih slojev, razvitost kraške mreže, spreminjanje obsega zaledja ob različnih hidroloških razmerah ipd.). V številnih evropskih državah, predvsem tistih z večjim deležem krasa, je že predpisana uporaba koncepta kartiranja ranljivosti in ogroženosti. Več podatkov o teh metodah in o celostno zasnovanem Slovenskem pristopu h kartiranju ranljivosti in ogroženosti (*Ravbar* 2007) je zbranih v poglavju »Alternativna metoda za zaščito kraških vodnih virov« v tej knjigi.

V uredbah o emisiji snovi pri odvajanju odpadne vode iz čistilnih naprav (3) je upoštevana velika ranljivost krasa in so zato od leta 2010 naprej za ta območja postavljene posebne zahteve v smislu dodatnega čiščenja ali zagotavljanja počasnejšega precejanja skozi slabše prepustne plasti. Tudi pri Uredbi o emisiji snovi in toplote pri odvajanju odpadnih vod v vode in javno kanalizacijo (*UrES*, 2005b) so bile ugotovljene težave pri postavljanju pravil za kraške vodonosnike, vendar pa po našem mnenju zaenkrat še niso bile ustrezno rešene. Problem je namreč v razumevanju določila, da *are obligatory at all natural hydrological objects downstream of the pollution source, on which the monitoring of the chemical state of groundwater is organized. It is not allowed to abandon the monitoring in the impact areas of pollution sources in karst.*

8.3 The assessment of deficiencies and good solutions

In the Waters Act the karst is not mentioned, even though this would be expected taking into account that a great portion of drinking water in Slovenia is supplied from karst aquifers. A good solution is the transfer of competences for preparation of the water protection acts to the governmental services. Previously often the local interests prevailed and the water sources were protected only partly or not at all. Unfortunately, the process on the state level is slow and among larger karst water sources only for the Rižana spring the ***Decree on determining the drinking water protection area for the aquifers of Rižana*** (*UrVORiž,* 2008) was implemented.

The most detailed consideration of specific characteristics of karst is given in the Rules on criteria for the designation of a water protection zone (*PrKDVO,* 2004). They contain a detail list of hydrogeological parameters based on which the water protection zones should be designed. The research methods for the assessment of these parameters are suggested. In our opinion the deficiency is in the provision that the use of only one method is allowed. In this way only a part of information needed is obtained and it is not possible to properly explain the complex functioning of karst aquifers. Therefore the water protection zones are often designed on the basis of deficient hydrological and geological data, and only rarely the conditions of recharge, groundwater flow and discharge of karst aquifers are thoroughly studied. In the catchment of water sources the tracer tests are applied very seldom, even though this research method gives the most valuable information for understanding the characteristics of groundwater flow and transport of substances in karst (*Petrič* 2009; *Kogovšek* and *Petrič* 2004). High spatial variability of the vulnerability of karst aquifers (role of protection cover, development of karst network, changes of the catchment

3 Uredba, ki obravnava odvajanje izcednih voda iz komunalnih čistilnih naprav, ima vključena posebna dopolnila za kraške in razpoklinske vodonosnike.
Decree on the discharge of waste waters from the urban waste water treatment plants contains specific regulations for karst and fissured aquifers.

4 Lovilnik olj ob avtocesti Postojna–Vrhnika pri Ravbarkomandi.
The oil collector by the motorway Postojna–Vrhnika near Ravbarkomanda.

5 Prenikanje izcednih voda z neurejenih odlagališč odpadkov ogroža kakovost kraških vodnih virov.
Leachates from unsuitable landfills endanger the quality of karst water resources.

pri posrednem odvajanju v podzemne vode to ne sme vplivati na kakovost tal in podzemne vode. Natančneje merila o mejnih vrednostih za določitev tega vpliva niso opredeljena, zato je odločitev o njih prepuščena pripravljavcu strokovnih podlag. Težava pa je še v tem, da bi bilo treba znanje o prenosu onesnaževal v krasu dopolnjevati tudi na teoretični ravni, da bi ustrezna merila sploh lahko postavili.

Ob gradnji avtocest v Sloveniji pred letom 1991 so bili zgrajeni lovilniki olj (4), ki naj bi zagotovili zadrževanje izlitih naftnih derivatov in olj v primeru prometnih nesreč. Kasneje so bile izdelane nove generacije zadrževalnih in čistilnih objektov, ki naj bi preprečili odtok prve, najbolj onesnažene padavinske odpadne vode s cestnih površin neposredno v kras. Za ureditev iztoka iz teh objektov so za kraška območja predvidena nekoliko strožja merila kot za nekraške terene. Po naših izkušnjah pa predstavljajo nevarnost zlasti težave v zvezi s tehnično izvedbo in vzdrževanjem objektov. Rezultati opravljenih raziskav so bolj podrobno predstavljeni v poglavju pričujoče knjige »Ogroženost kraških vodnih virov zaradi prometa v rednih razmerah«.

V navodilih za izdelavo hidrogeološkega poročila, ki je strokovna osnova za izdelavo programa obratovalnega monitoringa onesnaževanja podzemne vode (5), je postavljenih več posebnih določil za kraške vodonosnike. Glede na naše poznavanje značilnosti prenosa snovi v krasu (*Kogovšek* 2001a, 2010) pa lahko kot pomanjkljivo ocenimo določilo o pogostnosti vzorčenja za monitoring. Z občasnim in skozi celo leto časovno enakomerno razporejenim vzorčenjem zaradi velike spremenljivosti kakovosti kraških voda ne dobimo reprezentativnih vzorcev. Vzorčenje bi bilo treba ustrezno prilagoditi hidrološkim razmeram. Načrt vzorčenja bi moral biti zasnovan na temelju rezultatov sledilnih poskusov, ki ne povedo le, kam, ampak tudi, kako se pretaka voda od vira onesnaženja do kraških izvirov (*Kogovšek* in *Petrič* 2006, 2007, 2010a). Pri tem pa bi ga bilo smiselno ob novih spoznanjih stalno posodabljati. Problem monitoringa kakovosti kraških voda je podrobneje predstavljen v poglavju »Načrtovanje monitoringa podzemne vode v vplivnem območju odlagališč odpadkov na krasu na podlagi rezultatov sledilnih poskusov« v tej knjigi.

extent at different hydrological conditions, etc.) is often neglected, too. In many European countries, mainly in those with a great portion of karst, the use of the vulnerability and risk mapping approach is obligatory. More about these methods and the comprehensively designed Slovene approach to the vulnerability and risk mapping (*Ravbar* 2007) is presented in the chapter »An alternative method for the protection of karst water sources« of this book.

In the decrees on the emission of substances in waste water discharged from waste water treatment plants (3) a high vulnerability of karst aquifers is considered. Therefore some special demands in the sense of additional water treatment or retarded flow through poorly permeable layers have been in force since 2010. In our opinion no adequate solutions for karst aquifers have been found so far in the Decree on the emission of substances and heat in the discharge of wastewater into waters and public sewage system (*UrES*, 2005b). The problem is in the implementation of the regulation that in the case of an indirect discharge the quality of soil and groundwater should not be reduced. As the values of allowed concentrations of quality parameters are not exactly defined, the experts preparing the documentation can only make a subjective assessment. An additional problem is the lack of theoretical knowledge about the transport of contaminants in karst. Further studies are necessary for setting the adequate standards.

During the motorway construction before 1991 the oil collectors (4) were designed to retain the petroleum products and oils in the cases of traffic accidents involving spillages. Later new generations of retention ponds and purification facilities were built to prevent the initial discharge of the most polluted precipitation water from the roads directly into the karst. The regulations regarding the characteristics of outflow from these objects are more strict for karst areas. Nevertheless, according to our experiences the main problems are connected with the technical construction and maintenance of these facilities. The results of our researches are described in the chapter »Threats to karst water sources from traffic in normal conditions« of this book.

In the Instructions for preparation of the hydrogeological report for the programme of operational monitoring of groundwater pollution (5) several special

Sklep

V procesu prilagajanja slovenske zakonodaje evropski so bili na področju varovanja voda sprejeti številni zakoni, uredbe in pravilniki, v njih pa kras kot zelo razširjen, poseben in za Slovenijo značilen tip pokrajine ni bil ustrezno upoštevan. Zaradi tega so se pri izvajanju predpisov v praksi pojavljale številne težave, zelo ranljivi kraški vodonosniki pa niso bili primerno zaščiteni. Postopno so bili tako dodani nekateri novi členi, ki so uvedli posebna določila za kraške sisteme.

S tem je bil storjen pomemben korak k bolj učinkovitemu varovanju izjemno pomembnih kraških vodnih virov. Vendar pa se vsa uveljavljena dopolnila niso pokazala kot dovolj dobre rešitve, zato je treba s prilagajanjem in dopolnjevanjem še nadaljevati. Pri tem je smiselno upoštevati vse dosedanje izsledke o značilnostih pretakanja voda in prenosa snovi v krasu ter jih po potrebi dopolniti z novimi, usmerjenimi raziskavami prenosa kontaminantov v razmerah, ki se pojavljajo v praksi.

regulations for karst aquifers are set. However, based on our understanding of the transport of substances in karst (*Kogovšek* 2001a, 2010) we can assess as inadequate the regulation on the sampling frequency. The quality of karst waters varies significantly dependent on hydrological conditions therefore only occasional sampling in regular time intervals is not representative enough. Our proposal is to adapt the sampling plan to hydrological conditions. Furthermore, the results of tracer tests, which simulate the directions and characteristics of groundwater flow from pollution sources to karst springs (*Kogovšek* and *Petrič* 2006, 2007, 2010a), should be considered. The sampling plan should be regularly updated according to the results of new scientific researches. The chapter »Planning of groundwater monitoring in the impact areas of landfills in karst based on the results of tracer tests« of this book deals with the problems of water quality monitoring in karst areas.

Conclusion

In the process of adjustment of the Slovene water protection legislation to the European legislation many new laws, decrees and rules were adopted. Even though karst is a widely spread, specific and for Slovenia typical environment, no adequate attention was devoted to karst in these acts. This resulted in numerous problems when the new acts were actually implemented in practice. In consequence the karst aquifers were not properly protected. Gradually the acts were supplemented with some new articles introducing special regulations for karst systems.

These adjustments are an important step forward to assure a more efficient protection of extremely important karst water resources. However, not all new regulations are the proper solutions and it is important to continue with the process of adjustments. The existing knowledge about the characteristics of groundwater flow and transport of substances in karst has to be considered and if necessary supplemented with new, targeted researches of the contaminant transport in specific conditions.

9

ALTERNATIVNA METODA ZA ZAŠČITO KRAŠKIH VODNIH VIROV

AN ALTERNATIVE METHOD FOR THE PROTECTION OF KARST WATER SOURCES

NATAŠA RAVBAR

Pri nas je kraška podzemna voda zelo pomemben vir pitne vode, saj skoraj polovico potreb pokrivamo s črpanjem iz kraških vodonosnikov (1). Čeprav so kraški vodni viri v primerjavi z nekraškimi še posebej občutljivi na onesnaženje, pa mnogi še vedno ostajajo neprimerno zaščiteni (*Ravbar* in *Kovačič* 2006).

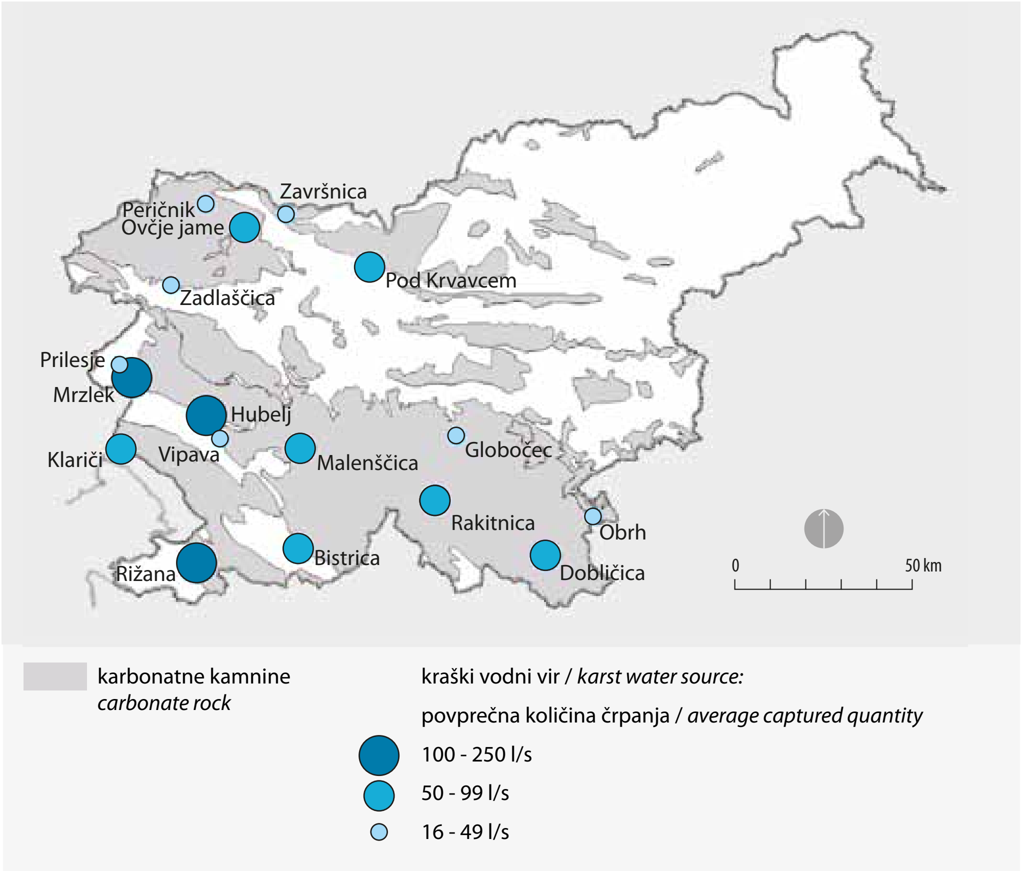
Varovanje vodnih virov (iz izvirov, vrtin) predvideva *Zakon o vodah* (*ZV-1*, 2002) z dopolnitvami, ki v svojih podzakonskih aktih predpisuje merila za določitev vodovarstvenih območij in režimov varovanja (*Pravilnik o kriterijih za določitev vodovarstvenega območja –PrKDVO*, 2004). Kriteriji za zaščito navadno temeljijo na oddaljenosti od vodnega vira oziroma na hitrosti toka podzemske vode do vodnega vira.

Žal v slovenski zakonodaji posebne značilnosti pretakanja voda v krasu niso zadovoljivo upoštevane, kar je podrobneje predstavljeno v poglavju »Prilagajanje slovenske zakonodaje posebnim

Karst groundwater is a very important source of drinking water in Slovenia since almost half the demand is covered by exploiting karst aquifers (1). Although karst water sources are very susceptible to pollution in comparison with non-karst ones, many of them are inadequately protected (*Ravbar* and *Kovačič* 2006).

Protection of water sources (from springs, wells) is provided for by the *Waters Act* (*ZV-1,* 2002) and its supplements. Its implementing regulations prescribe measures for the creation of water protection areas and protection regimes (*Rules on the criteria for the designation of a water protection zone – PrKDVO,* 2004). The criteria for protection are usually based predominantly on the distance from the water source or the groundwater flow velocity.

Unfortunately, Slovene legislation does not sufficiently consider the special characteristics of the groundwater flow in karst which has been in more detail described in chapter »Adjustment of the Slovene



1 Razširjenost karbonatnih kamnin v Sloveniji in pomembnejši kraški vodni viri (po *Ravbar* in *Kovačič* 2006).
Distribution of carbonate rock in Slovenia and major karst water sources (from *Ravbar* and *Kovačič* 2006).

značilnostim kraških vodonosnikov« v tej knjigi. Varovanje kraških vodnih virov pogosto ne vključuje posebnosti pretakanja vode v krasu, kot so heterogenost in kompleksnost napajanja vodonosnikov, spreminjanje hitrosti in smeri pretakanja voda v različnih hidroloških razmerah ipd.

V medzrnskih vodonosnikih so hitrosti pretakanja podzemskih voda zelo nizke, manjše od 10 m na dan. Vodovarstvena območja imajo tako premer le nekaj sto metrov. Na kraških območjih so zadrževalni časi voda v podzemlju kratki (nekaj ur do nekaj dni), kar pomeni omejeno zmožnost razgradnje onesnaževal in odmrtje mikroorganizmov. Obenem pa večja oddaljenost od vodnega vira ne pomeni nujno tudi večje varnosti pred onesnaženjem. Zato zgolj upoštevanje hitrosti ali oddaljenosti nista zadostna kriterija za varovanje kraških vodnih virov, saj bi vodovarstvena območja obsegala več deset do več sto km^2 oziroma celotna zaledja. V različnih hidroloških razmerah se v krasu spreminjajo tudi hitrosti in smeri pretakanja voda. Zato se lahko spreminja obseg prispevnega zaledja, kar je še zlasti pomembno pri določanju vodovarstvenih območij (*Bonacci* 1999; *Ravbar* idr. 2011).

9.1 Ranljivost in tveganje za onesnaženje

Za učinkovito varovanje najbolj občutljivih območij kraških vodonosnikov se v nekaterih evropskih državah pri določanju vodovarstvenih pasov uporablja koncept kartiranja oziroma ocenjevanja ranljivosti, pri načrtovanju rabe prostora pa v ospredje vse bolj stopa ocenjevanje tveganja za onesnaženje (*Vrba* in *Zaporozec* 1994). V ta namen so bile v okviru mednarodnega projekta COST Action 620, pri katerem je sodelovala tudi Slovenija, izdelane smernice za izdelavo tovrstnih ocen (*Daly* idr. 2002).

Na teh osnovah so bile, upoštevajoč razlike med posameznimi kraškimi vodonosnimi sistemi ter razlike v dostopnosti do podatkov in v ekonomskih zmožnostih, izdelane številne metode ocenjevanja in kartiranja občutljivosti kraške podtalnice, ki so bile tudi večkrat uporabljene in preizkušene na

legislation to the special characteristics of karst aquifers« of this book. The protection often fails to include special features of water percolation in karst such as the heterogeneity and complexity of aquifer recharge, changes in velocity and direction of water flow under various hydrological conditions, etc.

Intergranular aquifers display very low groundwater flow velocities, less than 10 m per day. The water protection areas are therefore only several hundred metres in diameter. In karst areas, however, groundwater retention times are short (a few hours to a few days), which means a limited capacity for the degradation of pollutants and the die off of microorganisms. At the same time, a larger distance from the water source does not necessarily mean greater protection from pollution. Therefore, velocity or distance alone do not comprise adequate criteria for the protection of water sources since water protection areas could encompass tens or hundreds of km^2 or even entire catchment areas. The velocities and directions of water percolation also change under different hydrological conditions in karst. The extent of catchment areas can change as a result, which is an important issue in determining water protection areas (*Bonacci* 1999; *Ravbar* et al. 2011).

9.1 Vulnerability and contamination risk

For the effective protection of the most sensitive areas of karst aquifers, a concept of mapping or assessing vulnerability is used in a number of European countries when identifying water protection zones, and land use planning is placing increasing emphasis on the assessment of contamination risk (*Vrba* and *Zaporozec* 1994). To this end, guidelines for making these types of assessments were elaborated (*Daly* et al. 2002) in the framework of the COST Action 620 international project in which Slovenia took an active part.

On this basis and taking differences between individual karst aquifer systems, differences in data accessibility, and the framework of economic capabilities into account, numerous methods of assessing and mapping karst groundwater vulnerability were različnih testnih poligonih po svetu (*Zwahlen* 2004; *Ravbar* 2007; *Goldscheider* 2010 itd.).

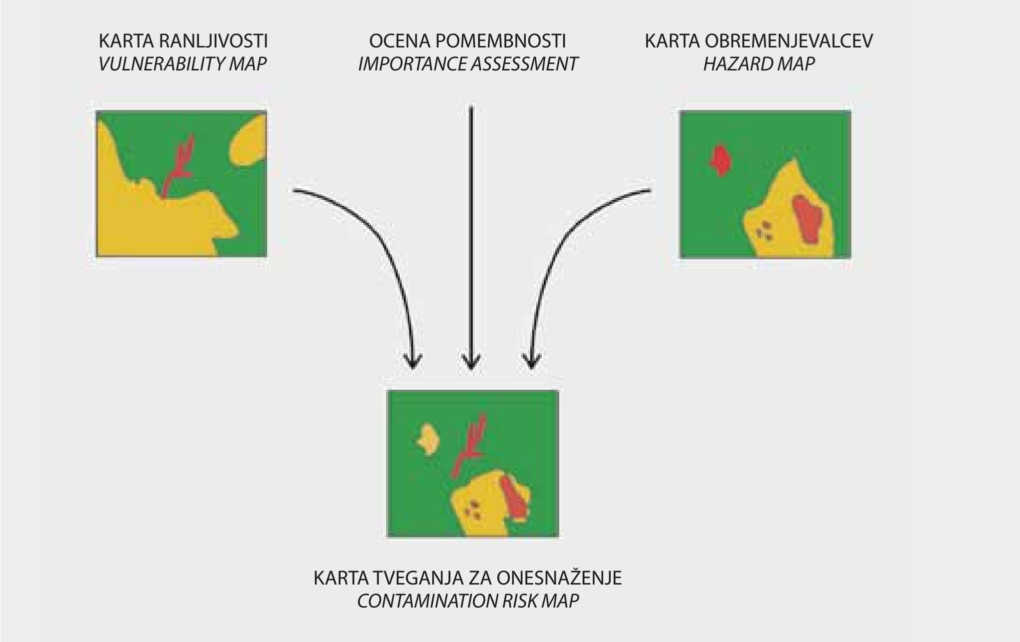
V Sloveniji smo na temelju predlaganih smernic razvili celostno zasnovan Slovenski pristop (*Ravbar* in *Goldscheider* 2007), ki ustreza slovenski okoljski zakonodaji in omogoča primerjavo z razmerami v Evropi. Vključuje ocenjevanje naravne ranljivosti in obremenjevalcev. Ti dve oceni sta podlaga izdelavi ocen tveganja za onesnaženje. Metoda ponuja tudi možnost ocene pomembnosti podzemne vode oziroma vodnega vira, na osnovi katere lahko v primerih onesnaženja predvidimo ekološko in materialno škodo ter izdelamo prednostni seznam saniranja ali preventivnih varovalnih ukrepov (2).

Ocenjevanje naravne ranljivosti upošteva geološke, hidrološke in hidrogeološke značilnosti kraškega sistema ter je neodvisno od lastnosti in obnašanja posameznih onesnaževal. Glede na namen sta na voljo dve vrsti ocenjevanja ranljivosti: za podzemno vodo in za vodni vir. Ocenjevanje ranljivosti podzemne vode upošteva parametre, ki nadzorujejo tok infiltrirane vode vse od površja do gladine podzemne vode. Pri tem so pomembni kazalniki prepustnost in debelina prsti in kamnin, ki sestavljajo nezasičeno cono, koncentracija odtoka v podzemlje, na katero vplivata topografija in

elaborated that were applied and tested in a variety of test areas across the world (*Zwahlen* 2004; *Ravbar* 2007; *Goldscheider* 2010, etc.).

Here in Slovenia, the comprehensively designed Slovene approach based on the suggested guidelines was developed (*Ravbar* and *Goldscheider* 2007). This method complies with the Slovene environmental legislation and enables comparison with conditions elsewhere in Europe. It includes assessments of natural vulnerability and contamination hazards. These two assessments form the basis for evaluating contamination risk. The method also offers the possibility of assessing the importance of the water resource or source, on the basis of which it is possible to anticipate ecological and material damage in the event of pollution and formulate a priority list of rehabilitation or preventive protection measures (2).

The assessment of natural vulnerability includes the geological, hydrological, and hydrogeological characteristics of a karst system and is independent of the properties and behaviour of individual contaminants. Relative to the purpose, two types of vulnerability assessment are available: for resources and for sources. Assessment of resource vulnerability includes parameters that control the flow of infiltrated water from the surface all the way to the water table. Here, relevant



2 Shematski prikaz ocenjevanja naravne ranljivosti in tveganja podtalnice ali vodnih virov za onesnaženje.
Schematic presentation of natural vulnerability assessment and water resources or sources contamination risk.

	Kazalnik / *Factor*
Kraška nezasičena cona *Karst unsaturated zone*	Debelina prsti / *Topsoil thickness*
	Struktura prsti / *Topsoil structure*
	Tekstura prsti / *Topsoil texture*
	Prepustnost podtalja / *Subsoil permeability*
	Debelina podtalja / *Subsoil thickness*
	Globina do nezasičene cone / *Depth to the unsaturated zone*
	Razpokanost / *Fracturation*
	Razvoj epikrasa – kraške geomorfološke oblike *Epikarst development – geomorphological features*
	Zaprtost vodonosnika / *Confined situation of the aquifer*
Načini napajanja *Recharge conditions*	Koncentracija toka / *Flow concentration*
	Naklon površja / *Slope gradient*
	Raba tal – vegetacijski pokrov / *Land use – vegetation cover*
	Avtogeno napajanje / *Autogenic recharge*
	Alogeno napajanje / *Alogenic recharge*
	Časovna hidrološka spremenljivost / *Temporal hydrological variability*
Kraška zasičena cona *Karst saturated zone*	Navzočnost mreže aktivnih kraških kanalov *Presence of an active karst network*
	Hidrološke značilnosti izvira / *Hydrological characteristics of a source*
	Interpretacija sledilnih poskusov / *Tracer test interpretation*

Tabela 1 Podatki in kazalniki, ki jih za ocenjevanje naravne ranljivosti upošteva Slovenski pristop.
Table 1 Data and factors included in the Slovene approach to assessing natural vulnerability.

vegetacijski pokrov, ter distribucija in intenziteta padavin. Metoda ponuja možnost upoštevanja časovne hidrološke spremenljivosti ter povezovanja zaščite površinskih in podzemnih voda. Z dodatnim parametrom, ki upošteva značilnosti pretakanja voda v zasičeni coni, je moč oceniti ranljivost vodnega vira (3, tabela 1).

Pri kartiranju obremenjevalcev je za vsakega onesnaževalca predvidena določena vrednost glede na kvalitativno primerjavo potencialne škode (toksičnost substanc, njihova topnost in mobilnost), za primerjavo znotraj ene vrste obremenjevalcev pa se predvideva proces razvrščanja glede na stopnjo strupenosti substanc, čas izpostavljanja obremenjevanju ali glede na količino oziroma velikost onesnaževalca. Upoštevana je še verjetnost onesnaženja, na kar vplivajo tehnični status, stopnja vzdrževanja, varnostne razmere in druge okoliščine. Ocenjevanje

factors include the permeability and thickness of the soil and rock composing the unsaturated (vadose) zone and the concentration of runoff in the underground as influenced by topography, the vegetation cover, and the distribution and intensity of precipitation. The method offers the possibility of considering the temporal variability of hydrological conditions and the linked protection of surface waters and groundwater. The additional parameter, which considers the characteristics of water flow in the saturated (phreatic) zone, makes it possible to assess the vulnerability of a water source (3, table 1).

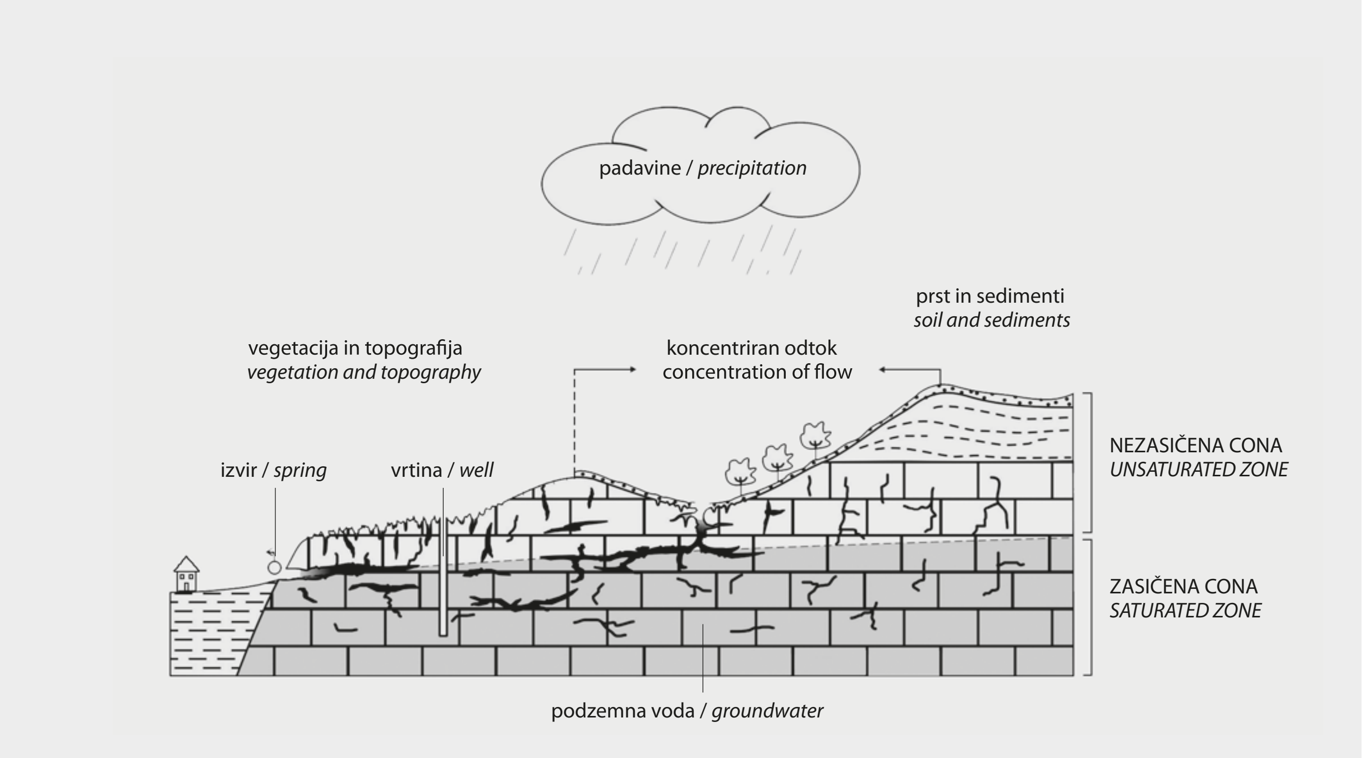
In mapping contamination hazards, a specific value is assigned to each source of pollution relative to the qualitative comparison of potential damage (toxicity of substances, their solubility and mobility); comparison within one type of pollutant, however, requires a classification process relative to the level of toxicity of pomembnosti podzemne vode oziroma vodnega vira združuje socialno, ekonomsko in biološko vrednotenje.

Končni rezultat ocenjevanja naravne ranljivosti je karta, na kateri so različne stopnje ranljivosti kraških voda za onesnaženje prikazane v različnih barvah in jih je mogoče preoblikovati v vodovarstvene pasove. Z identifikacijo najbolj ranljivih območij ponujajo karte naravne ranljivosti optimizacijo vodovarstvenih pasov, primerno in previdno upravljanje vodnih virov ter podlago za načrtovanje monitoringa kakovosti podzemne vode. Na najbolj ranljivih območjih naj bi veljali najstrožji ukrepi varovanja, tako da bi bile najbolj škodljive človekove dejavnosti prepovedane.

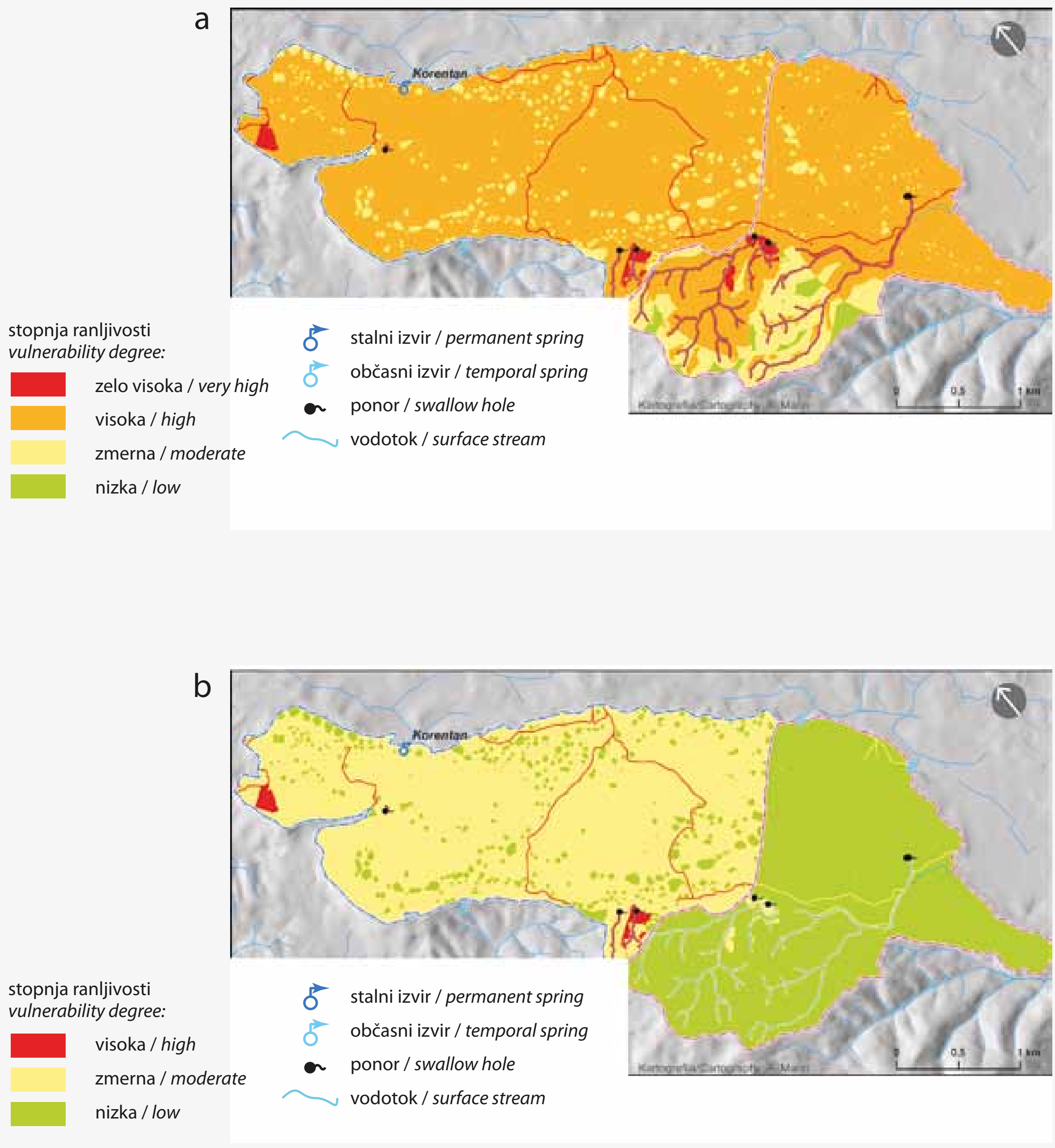
Ko te karte dopolnimo še s tistimi, na katerih prikažemo potencialne in dejanske obremenjevalce, lahko ocenimo tveganje podzemne vode ali vodnih virov za onesnaženje. Tako lahko celostno ovrednotimo

substances and time of exposure to pollution or relative to the quantity or size of the source of pollution. Another factor to consider is probability of pollution as influenced by technical status, maintenance level, safety conditions, and other circumstances. Assessment of the water resource or source importance combines social, economic, and biological factors.

The final result of the natural vulnerability assessment is a map showing various levels of vulnerability to pollution of karst waters in different colours that can possibly be converted into water protection zones. By identifying the most vulnerable areas, natural vulnerability maps offer the optimization of water protection zones, proper and careful management of water sources, and a basis for planning the monitoring of groundwater quality. The strictest protection measures should apply to the most vulnerable areas, and the most harmful human activities should be prohibited.



3 Konceptualni model kraškega vodonosnika in parametri, ki vplivajo na ranljivost podzemne vode ali vodnega vira (po *Andreo* idr. 2006).
Conceptual model of karst aquifer and parameters influencing the vulnerability of water resources or sources (from *Andreo* et al. 2006).



4 Naravna ranljivost a) Orehovškega vodonosnika in b) izvira Korentan, ocenjena z uporabo Slovenskega pristopa (po *Marin* idr. 2011).
Natural vulnerability of a) the Orehek aquifer and b) the Korentan spring assessed using the Slovene approach (from *Marin* et al. 2011).

dosedanje človekove vplive in identifikacijo območij z neustreznim upravljanjem, nakažemo reorganizacijo rabe prostora in boljšo prakso v prihodnjem načrtovanju, izdelamo podlago za različne presoje vplivov na okolje ter lažje predvidimo posledice in škodo (ekološko in materialno) ob različnih onesnaženjih. Stopnjo tveganja za onesnaženje dosežemo z upoštevanjem ocen ranljivosti, obremenjevanja in pomembnosti.

9.2 Aplikacija nove metode in preverjanje rezultatov

Doslej je bil Slovenski pristop v okviru različnih projektov apliciran na treh različnih kraških vodonosnikih pri nas. Uporabljen je bil za ocenjevanje naravne ranljivosti Orehovškega kraškega vodonosnika in v preteklosti opuščenega vodnega vira Korentan pri Postojni (4; *Marin* idr. 2011). Zaradi pomanjkanja raziskav in podatkov je bila na območju Krvavca z uporabo Slovenskega pristopa napravljena le analiza naravne ranljivosti podzemne vode (*Juvan* in *Čenčur Curk* 2008).

Najbolj celostna študija kartiranja ranljivosti in tveganja, skupaj s preskusom veljavnosti dobljenih rezultatov, je bila opravljena v zaledju manjšega kraškega izvira Podstenjšek v jugozahodni Sloveniji, ki je zajet za lokalno vodooskrbo (*Ravbar* 2007). Hidrografsko zaledje sestavljajo zakraseli apnenci in dolomiti, ki so narinjeni na neprepustne eocenske flišne plasti. Spodaj ležeče flišne kamnine vplivajo na obstoj plitvega kraškega vodonosnika, kar ob izjemno visokih vodah omogoča dvig kraške podzemne vode na površje in pojavljanje dveh presihajočih jezer, Šembijskega jezera in Narič. Na območju presihajočih jezer prekrivajo apnence različno debeli kvartarni aluvialni nanosi, v suhi dolini, na vzhodnih obronkih zaledja, pa se ponekod pojavljajo pleistocenski periglacialni sedimenti.

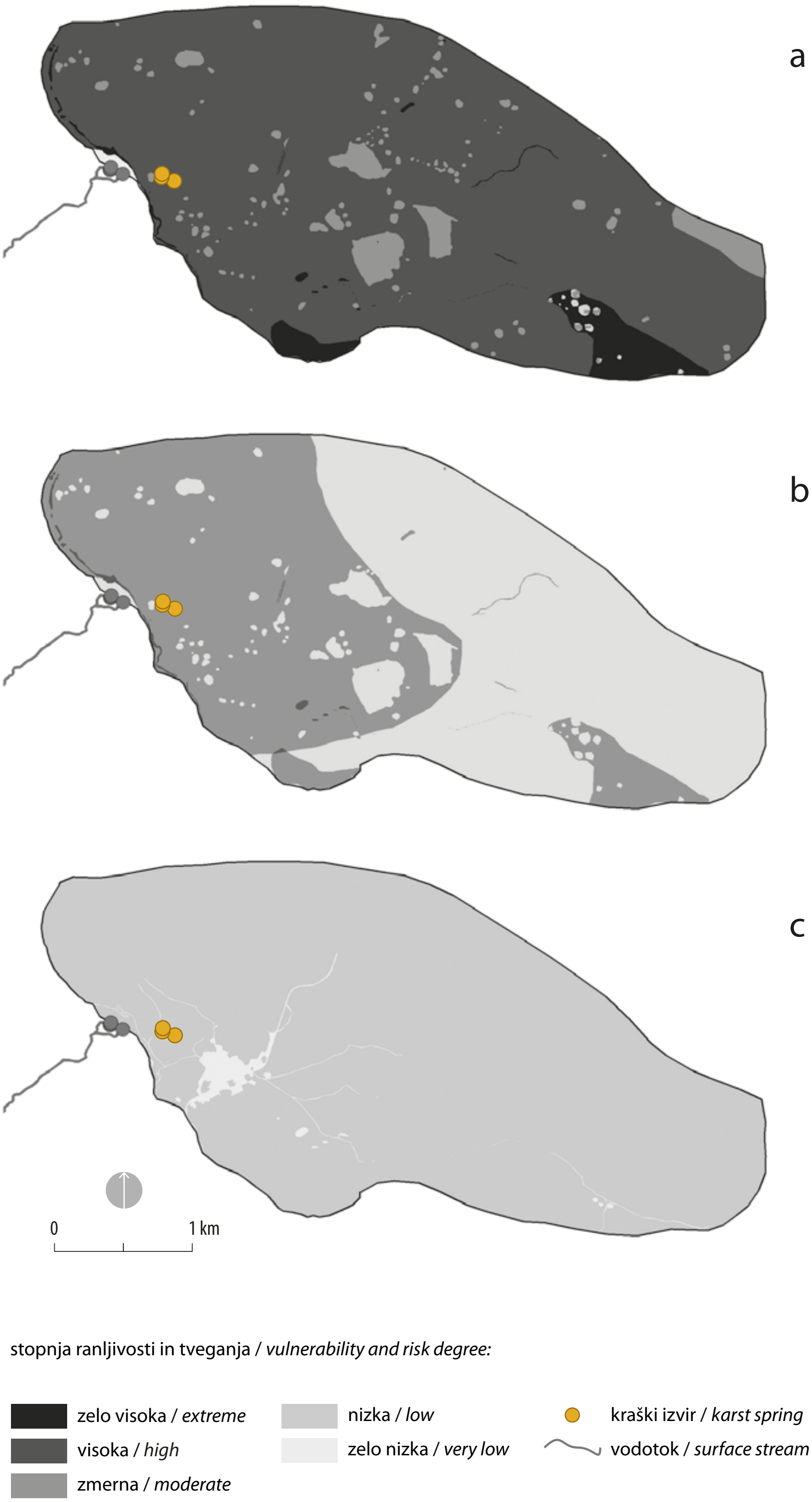
V zaledju vodnega vira Podstenjšek ni resnejših dejanskih in potencialnih virov onesnaženja. Večji del zaledja je neposeljen, poraščen z gozdom ali pa se uporablja za ekstenzivne pašnike in travnike. Strnjena poselitev je le na območju spalnega naselja Šembije, v katerem živi okrog 200 prebivalcev.

When these maps are complemented by those showing potential and actual sources of pollution, it is possible to assess the water resources or sources risk of contamination. Thus it is possible to make a comprehensive assessment of existing human impacts and identify areas with inadequate management, reorganize land use and apply better practice in future planning, create a foundation for a variety of environmental impact assessments, and facilitate the predictions of consequences and damage (ecological and material) of a variety of pollution events. The level of contamination risk can be determined by taking the vulnerability assessment, hazard assessment, and importance assessment into account.

9.2 Application of the new method and verification of results

Up to date the Slovene approach was applied in the framework of various projects to three different Slovene karst aquifers. It has been used to assess the natural vulnerability of the Orehek karst aquifer and of the no longer exploited Korentan spring near Postojna (4; *Marin* et al. 2011). Due to lack of research and data was in the area of Krvavec using the Slovene approach made only the analysis of resource natural vulnerability (*Juvan* and *Čenčur Curk* 2008).

The most comprehensive study mapping vulnerability and risk including a test of validity of the results was conducted in the catchment area of the Podstenjšek spring, a smaller karst spring in southwestern Slovenia exploited for the local water supply (*Ravbar* 2007). The hydrographical catchment area is composed of karstified limestone and dolomite thrust over impermeable Eocene flysch. The underlying flysch rock caused the formation of a shallow karst aquifer that allows the rising of karst groundwater to the surface during extreme high water conditions and the appearance of two intermittent lakes, Šembijsko jezero and Nariče. In the area of these intermittent lakes, the limestone is covered by variously thick Quaternary alluvial deposits while Pleistocene periglacial sediments are found in some places in a dry valley at the eastern edge of the catchment area.



5 Primer aplikacije Slovenskega pristopa na obronkih snežniškega vodonosnika: karti naravne ranljivosti a) podzemne vode, b) kraškega izvira Podstenjšek in c) karta tveganja Podstenjška za onesnaženje (po *Ravbar* 2007).
Example of application of the Slovene approach at the edge of the Snežnik aquifer: maps of natural vulnerability of a) groundwater, b) of the Podstenjšek karst spring and c) a contamination risk map of the Podstenjšek spring (from *Ravbar* 2007).

Naselje ima urejeno kanalizacijsko omrežje, odpadne vode pa so speljane v manjšo čistilno napravo zunaj napajalnega zaledja izvirov.

Vodni vir ogroža regionalna cesta, ki nima urejenih obcestnih kanalov za odvajanje izcednih voda, razen skozi naselje. Kakovost vodnega vira obremenjuje pokopališče, ležeče neposredno nad izviri, in sedem manjših divjih odlagališč odpadkov v zaledju.

Rezultate ocenjevanja ranljivosti smo preverili s pomočjo dveh kombiniranih sledilnih poskusov, ki sta skupno zajemala šest injicirnih točk. Preverjanje je potrdilo ocenjeno naravno ranljivost reprezentativnih točk, izbranih za injiciranje sledila, in obenem to, da je metoda verodostojna. Končne karte tako omogočajo izpopolnjeno razmejitev vodovarstvenih pasov, označujejo območja neprimernega ravnanja in dajejo podlago za boljše rešitve v prihodnjem načrtovanju rabe prostora (5).

9.3 Uporabnost Slovenskega pristopa

Koncept ocenjevanja ranljivosti in tveganja ponuja ravnotežje med varovanjem na eni ter prostorskim načrtovanjem in ekonomskimi interesi na drugi strani. Preprečuje postavitev potencialnih onesnaževalcev na območjih, kjer obremenjevanje že dosega ali celo presega naravne samočistilne sposobnosti, in hkrati opozarja na območja z najvišjo stopnjo tveganja, ki terjajo takojšnje ukrepanje in sanacijo.

Uporabna vrednost takšnih kart je zelo velika, saj lahko odgovorni za odločanje o izrabi prostora z njihovo pomočjo ugotovijo, katera območja znotraj zaledja posameznega vodnega vira so primerna za določene človekove dejavnosti ter katera in do kakšne mere so potrebna zaščite, kar pa lahko pomeni tudi prepoved opravljanja kakšne dejavnosti. Predvidimo lahko tudi sanacijske ukrepe dejanskih onesnaževalcev in skladno s tveganjem določimo terminski plan njihove izvedbe. Karte ranljivosti in tveganja za onesnaženje podzemne vode so tako za državne in krajevne organe, odgovorne za načrtovanje in odločanje o rabi prostora, koristna osnova pri njihovih odločitvah.

There are no major actual or potential hazards in the catchment area of the Podstenjšek spring. The greater part of the catchment is unpopulated, covered with forest, or used for extensive pastures and meadows. Denser settlement is only found in the area of the Šembije suburban town which has about 200 inhabitants. The settlement has a regulated sewage system, and waste waters are channeled to a small sewage treatment plant outside the spring's catchment area.

However, the water source is threatened by a regional road that has no gutters for controlling runoff. The quality of the water source is also threatened by the cemetery located directly above the springs and seven small illegal dumps in the catchment.

The results of the vulnerability assessment were verified by two multi-tracer tests that together included six injection points. The verification confirmed the assessed natural vulnerability of the representative points selected for injection of the tracer and the credibility of the method. The final maps thus allowed an improved demarcation of water protection zones, identified areas of inadequate management, and provided a foundation for better solutions in future land use planning (5).

9.3 Applicability of the Slovene approach

The concept of assessing vulnerability and risk offers a balance between protection on the one hand and spatial planning and economic interests on the other. It prevents adding potential sources of pollution in areas where pollution already reaches or even exceeds natural self-cleansing capacities and at the same time shows areas of the highest risk level that call for immediate action and rehabilitation.

The maps produced by the Slovene approach are extremely useful since those responsible for making decisions about land use can employ them to identify areas inside individual catchment areas suitable for certain human activities, areas in need of protection, and the level of their protection, which can result in banning certain activities. It is also possible to envisage rehabilitation measures for actual sources of pollution and determine a schedule for their implementation

Slovenski pristop spada med izredno sofisticirane metode, saj je za aplikacijo treba ogromno podatkov, časa, finančnih in tehničnih virov. Vendar je preskus veljavnosti dobljenih rezultatov pokazal, da je uporaba takšnih metod v primerjavi s preprostejšimi bolj upravičena, saj prinaša zanesljivejše in manj subjektivne rezultate (*Ravbar* in *Goldscheider* 2009).

Ker je Slovenski pristop zasnovan celostno in kot edina izmed obstoječih metod za ocenjevanje ranljivosti in tveganja kraške vode za onesnaženje upošteva posebnosti slovenskega krasa in pretakanje voda v različnih hidroloških razmerah, bi bil lahko kot dopolnilo vključen v obstoječo slovensko zakonodajo na področju varovanja kraških vodnih virov in načrtovanja rabe prostora na krasu.

relative to the level of risk. Maps of natural vulnerability and the pollution risk to groundwater therefore provide a useful decision-making basis for national and local authorities responsible for spatial planning and land use.

While the Slovene approach is a very sophisticated method that requires vast amounts of data, time, and financial and technical resources, the validity of the results acquired demonstrates that the use of such methods is justified in comparison with simpler methods because it achieves more reliable and less subjective results (*Ravbar* and *Goldscheider* 2009).

Because the Slovene approach is comprehensive and is the only existing method for assessing the vulnerability of and contamination risk to karst waters that considers the special features of Slovenian karst and the flow of groundwater under various hydrological conditions, it could be included in the upgrading current Slovene legislation in the field of protecting karst water sources and planning land use in karst areas.

10

PRILAGODITVE POPLAVAM NA KRASU

ADAPTING TO FLOODING ON KARST

GREGOR KOVAČIČ, NATAŠA RAVBAR

Poplave na kraških poljih, območjih plitvega in kontaktnega krasa, so reden pojav, saj lahko nastopajo večkrat letno. Med katastrofalne dogodke uvrščamo deset-, petdeset- ali stoletne poplave, ki ogrožajo okrog 68 km^2 v kraških pokrajinah, od tega je slab odstotek urbanih površin (*Anzeljc* idr. 1995). Večja poplavna območja na krasu so ob Pivki in spodnjem toku Reke, na Cerkniškem, Planinskem, Ribniško–Kočevskem in Radenskem polju ter v Dobrepolju.

Tovrstne poplave so povezane z višino vode v kraškem podzemlju oziroma s presežkom dotekajoče vode nad zmogljivostjo odtočnih kanalov. Na različen vodostaj vplivajo hidrogeološki (velikost in geometrija vodonosnika, efektivna poroznost, velikost in povezanost kraških kanalov) in meteorološki dejavniki (tip, količina, intenzivnost in razporeditev padavin ter intenzivnost taljenja snega).

V kraških pokrajinah ločimo dve vrsti poplav: zajezitvene in prelivne (*Kranjc* 1981). Zajezitvene poplave so značilne za območja ponikalnic, kjer vode vtekajo v podzemlje z nekraškega obrobja. Zaradi premajhne požiralne zmogljivosti podzemskih kanalov, ki niso sposobni prevajati dotekajočega presežka vode, se vodostaj viša gorvodno in preplavi bližnji okoliški svet. Za takšna območja so značilna pogosta in velika nihanja vode, ki se lahko spreminjajo za več deset, ob nenadnih zajezitvah odtočnih kanalov celo več kot sto metrov v zelo kratkem času, kot je primer zajezitvene poplave leta 1965 v Škocjanskih jamah. Takrat je nivo vode v podzemeljskem kanjonu Reke naraščal s povprečno hitrostjo 5 m/h, s približno enako intenziteto se je poplavna voda tudi umaknila (*Habe* 1966).

Prelivne poplave nastanejo zaradi dviga piezometra v kraškem vodonosniku. Ko se podzemlje napolni z vodo, se aktivirajo občasni izviri in estavele. Voda se razlije po uravnanem svetu, dnu kraških kotanj. Zaradi kraškega zadržka se poplave pojavijo z zamikom in se obdržijo različno dolgo, več dni ali več tednov. Zaradi majhnega strmca voda nima velike transportne moči in odlaga malo gradiva, navadno le mulj ali droben pesek. Poplave na kraških poljih so lahko obenem obojega tipa, zajezitvene in prelivne. Ojezeritev večine večjih kraških polj v Sloveniji je posledica razlike v količini dotekajoče in odtekajoče

Karst poljes, areas of shallow karst and contact karst, experience regular flooding that can occur several times a year. Catastrophic events such as ten-, fifty-, or hundred-year floods threaten around 68 km^2 in Slovenian karst regions, about one percent of which is in urban areas (*Anzeljc* et al. 1995). Major flood areas on karst are found along the Pivka river and the lower reach of the Reka river, on the Cerkniško, Planinsko, Ribniško-Kočevsko, and Radensko poljes, and in Dobrepolje.

These floods are linked to the water level in the karst underground or a surplus of inflowing water above the swallow capacity of runoff channels. The water level is influenced by hydrogeological factors (size and geometry of the aquifer, effective porosity, size and linkage of karst channels) and meteorological factors (type, quantity, intensity, and distribution of precipitation and factors affecting the intensity of snow melting).

Two types of floods can be distinguished in karst regions: sinkhole floods and overflow floods (*Kranjc* 1981). Sinkhole floods are characteristic of sinkhole areas where waters flow into the underground from the surrounding non-karst areas. Due to the insufficient swallow capacities of underground channels that are not able to carry surpluses of inflowing water, the water level rises upstream and floods the surrounding areas. The frequent and large oscillations of water characteristic of such areas can display changes of tens of metres or even more than a hundred metres in a very short time when runoff channels experience sudden blockages as, for example, the 1965 sinkhole flood in the Škocjan caves/Škocjanske jame. During this flood, the water in the underground canyon of the Reka river rose at an average speed of 5 m/h; the floodwater also receded at approximately the same velocity (*Habe* 1966).

Overflow floods occur due to the rising water table in karst aquifers. Once the underground is filled with water, periodic springs and estavelles are activated. The water overflows leveled areas at the bottom of karst depressions. Due to the retention of water in karst aquifers, the flooding occurs after a time lag and remains for various periods ranging from several days to many weeks. Due to the small inclination, the water does not have major transporting power and deposits only small amounts of material, usually just mud or fine sand. Both vode. Kraška polja so naravni zadrževalniki pretočnih viškov in pomembni regulatorji vodnih razmer rek v spodnjih delih porečij.

10.1 Pregled večjih poplav in njihove škode

Celovitega zgodovinskega pregleda poplav na kraških območjih Slovenije ni, v literaturi razpolagamo le z nekaterimi podatki. Med večje poplave uvrščamo poplavo na Kočevskem polju septembra 1973, ko je bilo v 8 vaseh zalitih 24 hiš in še precej več kleti. Nekatere hiše so bile poplavljene do 1,5 m visoko. Največja škoda je bila na obdelovalnih zemljiščih, saj pridelki še niso bili pobrani. Poplavljena je bila glavna prometnica Ljubljana–Kočevje. Zalitih je bilo več gospodarskih obratov, kjer so bili poškodovani izdelki in naprave. Prišlo je tudi do izpada proizvodnje (*Kranjc* in *Lovrenčak* 1981). Veliko škode je bilo tudi v Dobrepolju, kjer so poplave pogostejše v njegovem južnem delu (Struge). Katastrofalne poplave so območje Strug prizadele že leta 1933, 1939 in 1948 (*Kranjc* 1981; *Meze* 1983).

Na Cerkniškem polju je bil nivo vode povečan nad običajnega spomladi 1985. Škoda, nastala na infrastrukturi in v kmetijstvu, je bila ocenjena na približno 514.400 evrov (*Kranjc* 1986). Ob novembrskih poplavah 1990 je bila povzročena škoda ob Reki 1,61 milijona evrov (*Kranjc* in *Mihevc* 1991), vendar gre v večini za škodo v nekraškem delu njenega porečja. Takrat je bilo popolnoma ojezerjeno tudi Planinsko polje. Preplavljenih je bilo približno 9 km^2 zemljišč, neprevozne so bile vse ceste, ki prečkajo polje, večje škode pa visoke vode niso povzročile (*Bat* 1992).

V preteklih letih so bile izjemno visoke vode, tako po obsegu, najvišjem vodostaju kakor trajanju, zabeležene novembra 2000. V polnem obsegu so bila poplavljena kraška polja Notranjske in Dolenjske. Voda je na Loškem, Cerkniškem in Planinskem polju ter v Rakovem Škocjanu poplavila ceste in izpostavljene stanovanjske objekte. Gladina Cerkniškega jezera na vodomerni postaji Dolenje Jezero je 29. novembra dosegla rekorden vodostaj v opazovanem obdobju 1995–2011 in je bila podobno rekordna kakor leta 1926 (*Kogovšek* 2001b). Vodostaj je bil na nadmorski višini 552,096 m, površina jezera 26 km^2, prostornina vode v

types of flooding, sinkhole and overflow, can occur on karst poljes at the same time. In Slovenia, the formation of lakes on the majority of larger karst poljes is the consequence of the difference in the volumes of inflowing and outflowing water. Karst poljes are natural retainers of discharge surpluses and important regulators of water conditions in rivers in the lower parts of river basins.

10.1 A survey of major floods and flood damage

There is no comprehensive historical survey of floods in the karst areas of Slovenia and only minimal data is available in the literature. One major flood occurred in September 1973 on the Kočevsko polje when 24 houses and many more basements in 8 villages were flooded. The water rose up to 1.5 m high in several houses. Cultivated land suffered the greatest damage because the crops were still unharvested. The main Ljubljana–Kočevje road was also flooded. The flood affected a number of industrial facilities and damaged stocks, inventory, and equipment. In some places production stopped (*Kranjc* and *Lovrenčak* 1981). There was also considerable damage in Dobrepolje, where floods most frequently occur in its southern part (Struge). The Struge area had previously been struck by catastrophic floods in 1933, 1939, and 1948 (*Kranjc* 1981; *Meze* 1983).

The water level increased above its usual highs on the Cerkniško polje in the spring of 1985, and the damage to infrastructure and agriculture was estimated at around 514,400 euros (*Kranjc* 1986). The November 1990 flood caused 1.61 million euros of damage in the area along the Reka river (*Kranjc* and *Mihevc* 1991) but most of the damage occurred in the non-karst part of the river basin. At the same time, the Planinsko polje was completely flooded and turned into a lake. About 9 km^2 of land was flooded, the roads crossing the polje were impassable, but the high waters caused no major damage (*Bat* 1992).

More recently, the highest waters were recorded in November 2000 according to their extent, level, and duration. Karst poljes in the Notranjska and Dolenjska regions were flooded to their full extent. On the Loško, Cerkniško and Planinsko poljes, and in Rakov Škocjan, roads and residences were exposed to flooding. On 29 November, Cerknica lake reached a record-breaking jezeru pa je znašala nekaj več kot 82 milijonov m^3 (*Kovačič* 2010b). Na Zgornji Pivki so bila poleg poplav ob strugi Pivke ojezerjena vsa presihajoča Pivška jezera, poplavljena pa tudi območja, kjer poplave še niso bile zabeležene (*Kovačič* 2005). Na kraškem polju med Bačem, Knežakom in Koritnicami je izjemen porast gladine kraške podtalnice (20–35 m) povzročil ojezeritev na skupni površini 0,6 km^2, oživela je tudi suha struga nekdanje Pivke, ki je tekla po cesti skozi naselje Bač. Največ škode je bilo povzročene na cestah in v kmetijstvu. Poplava je prizadela 23 stanovanjskih in 7 drugih objektov, tako da je bilo skupno prizadetih 15 % vseh stavb s stanovanji v omenjenem naselju. Poplava je poškodovala tudi manjši proizvodni obrat in povzročila izpad proizvodnje. Ocenjena skupna škoda je znašala približno 248.200 evrov (*Kovačič* 2005, 2010a).

10.2 Visoke vode septembra 2010

Izredno visoke vode septembra 2010 so najhuje prizadele južni del Dobrepolja pri Strugah (1). Voda je na polje bruhala iz jam in izvirov ob vznožju Male gore, s severa pa se je pridružila poplavna voda Rašice, ki ni mogla ponikniti v ponorih pri Ponikvah. Na območju Struške doline je bilo poplavljenih 60 hiš, gladina vode je ponekod segala tudi do 4 m visoko. Od sveta je bilo odrezanih okrog 300 prebivalcev iz treh vasi, na oceno škode pa bo treba še počakati. Vzroka septembrskih poplav v Strugah v letih 1933 in 2010 sta bila enaka: součinkovanje prekomernega dotoka iz kraških izvirov in poplavne vode površinske Rašice.

Nižje ležeči deli cestišč so bili neprevozni tudi na Babnem, Loškem, Cerkniškem, Planinskem, Ribniško–Kočevskem in Radenskem polju ter v Rakovem Škocjanu, poplavljenih je bilo nekaj hiš. Ker so bila polja Notranjske pred obilnim deževjem med 17. in 19. septembrom – takrat je v njihovem zaledju padlo okrog 300 mm dežja – suha, vodostaji poplave niso bili rekordni, so pa dosegli višino pogostih velikih poplav. Zalito je bilo tudi rekordno obsežno območje pred Postojnsko jamo (do nadmorske višine 520 m), narasla Pivka pa je terjala smrtno žrtev. Na Zgornji Pivki so bile poplave v obsegu rednih visokih poplav in niso dosegle rekordnih vodostajev iz leta 2000.

water level at the Dolenje Jezero water gauging station for the 1995–2011 monitoring period and matched the similar record of 1926 (*Kogovšek* 2001b). The water level reached 552.096 m a.s.l., the surface of the lake covered 26 km^2, and the volume of the lake water was just above 82 million m^3 (*Kovačič* 2010b). The Upper Pivka area experienced flooding along the course of the Pivka river, all the intermittent Pivka lakes were full, and even areas that had never recorded flooding were under water (*Kovačič* 2005). The exceptionally high rise of the water table level (20–35 m) in the karst polje between Bač, Knežak, and Koritnice resulted in a lake that covered 0.6 km^2 and a revival of a dry river bed of the former Pivka river that ran down the road through the settlement of Bač. Roads and agriculture suffered the most damage, but the flooding also affected 23 residential and 7 other buildings, a total of 15 % of all buildings in the settlement. The flooding also affected a smaller industrial facility and caused production to stop. The total estimated damage was about 248,200 euros (*Kovačič* 2005, 2010a).

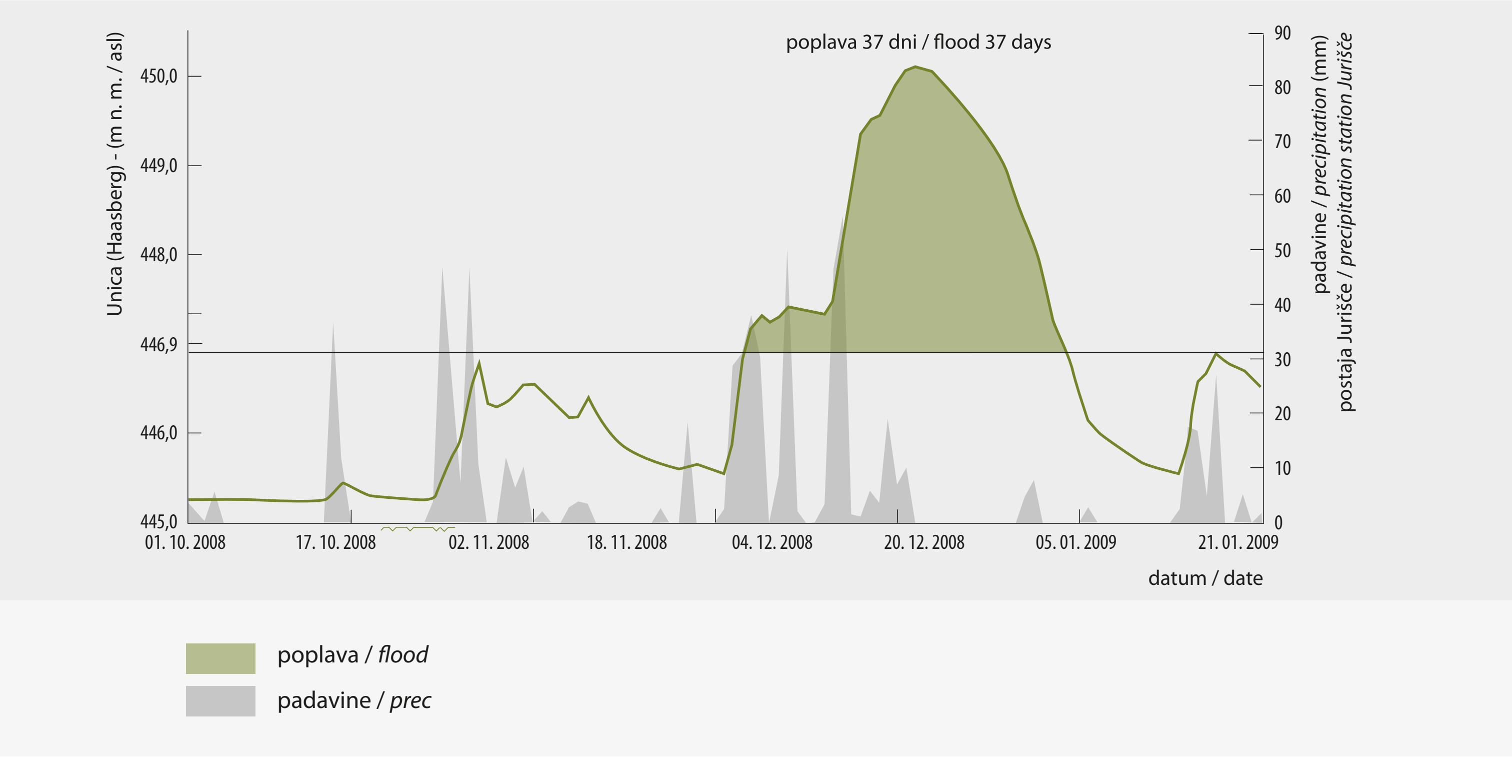
10.2 The high waters of September 2010

The exceptionally high waters of September 2010 hit the southern part of Dobrepolje near Struge worst (1) as water erupted onto the polje from the caves and springs at the foot of the Mala gora ridge. It was joined from the north by floodwater from the Rašica river that was unable to sink in the ponors near Ponikve. There were 60 houses in the Struge valley flooded, the water level reached up to 4 m high in places, and about 300 residents from three villages were cut off from the world. The damage has not yet been fully calculated. The causes of the September flooding of the Struge area in 1933 and 2010 were the same: the coincidence of excess discharge from karst springs and the flooding of the surface Rašica river.

Sections of lower-lying roads were also impassable in the Babno, Loško, Cerkniško, Planinsko, Ribniško-Kočevsko and Radensko poljes, and in Rakov Škocjan, and several houses were flooded. Prior to the abundant precipitation event between 17 and 19 September when around 300 mm of rain fell in their catchment areas, the poljes in the Notranjska region were dry, so flood water levels did not reach record heights although they did

1 Poplavljena hiša v Dobrepolju 21. septembra 2010.
A flooded house in Dobrepolje on 21 September 2010.

2 Poplavljena hiša v naselju Log pri Hotedršici v Hotenjskem podolju 18. septembra 2010 (foto *Arhiv Prostovoljnega gasilskega društva Hotedršica*).
A flooded house in Log near Hotedršica in the Hotenjsko valley system on 18 September 2010 (photo *Archive of the Volunteer firemen society Hotedršica*).



3 Dinamika poplavljanja Planinskega polja decembra 2009 (vir *Kovačič* in *Ravbar* 2011).
Dynamics of the Planinsko polje flooding in December 2009 (source *Kovačič* and *Ravbar* 2011).

Škodo so povzročali tudi ekstremno visoki pretoki na kraških izvirih, še posebej Hubelj, ki je spodjedel cesto tik pod izvirom in poplavljal dolvodno. V njegovem zaledju, na območju Trnovskega gozda, je med 16. in 20. septembrom padlo več kot 500 mm dežja in izvir je dosegel rekorden pretok (59 m^3/s). Izjemne 4-dnevne septembrske padavine na območju Trnovskega gozda so povzročile poplavo Zadloškega polja in Zadlog odrezale od cestne povezave čez Črni vrh, škode na objektih ni bilo. V tem obdobju je v Hotenjskem podolju v Hotedršici poplavljala Hotenjka, na ravniku med Godovičem in Grčarevcem so se napolnile suhe struge in pojavili so se površinski vodotoki, voda je zalila številne vrtače in ogrožala stanovanjske objekte (2). Zaprti sta bili cesti Godovič–Kalce pri Hotedršici in Kalce–Col pri Kalcah. Poplavljeni so bili tudi najnižji deli Logaškega polja, kjer je Logaščica pred ponorom Jačka poplavila številne stanovanjske objekte.

Visoki so bili tudi pretoki Vipave (poplave v spodnjem delu porečja) in Kolpe. Veliko škode je povzročila Rižana, ki je poplavljala stanovanjske objekte, onemogočala promet po regionalni in lokalnih cestah ter železniški progi in iz ribogojnice odplavila za 150 ton rib. Ljubljanica in Krka, ki imata večinoma kraško zaledje, sta zaradi zadrževalne zmogljivosti njunih zaledij izkazali sekundarni poplavni val, ki je povzročil upočasnjen odtok voda z že poplavljenih območij.

10.3 Dinamika poplavljanja kraških polj

Meritve vodostajev (pretokov) oziroma analiza dinamike naraščanja in upadanja vodostajev so temeljno orodje za preučevanje ekstremnih hidroloških dogodkov in njihovih posledic. Ilustrativen je primer dinamike poplavljanja Planinskega polja, tipičnega kraškega polja. Poplavni val decembra 2009 so povzročile tritedenske intenzivne padavine, katerih količina je za dvakrat presegla povprečne vrednosti iz obdobja 1975–2004. Vodostaj Unice (Haasberg) je naraščal 3–4 cm/h in dosegel višek na nadmorski višini 450,12 m, kar lahko označimo kot veliko, a običajno poplavo. Površina poplave je obsegala 9,84 km^2, prostornina vode pa je bila 40,6 milijonov m^3. Najnižji predeli polja so bili do 8 m pod vodo, poplava pa je trajala 37 dni (3).

reach the level of frequent major flooding. The flooded area in front of the Postojna cave reached a record height (up to 520 m a.s.l.), and the swollen Pivka river claimed one life. In the Upper Pivka area the floods were within the limits of regular high levels and did not reach the record levels of the year 2000. Damage was also caused by extremely high discharges at karst springs, particularly Hubelj, which undermined the road just below the spring and flooded downstream. More than 500 mm of rain fell between 16 and 20 September in its Trnovski gozd catchment area, and the spring achieved a record discharge of 59 m^3/s. The exceptional 4-day September precipitation in the Trnovski gozd area also caused the flooding of the Zadloško polje and cut off Zadlog's road link to Črni vrh but caused no damage to buildings. In the same period, the Hotenjka river flooded at Hotedršica in the Hotenjsko river system, dry riverbeds filled on the plain between Godovič and Grčarevec, surface streams appeared, and water flooded numerous dolines and threatened residential buildings (2). The Godovič–Kalce road near Hotedršica and the Kalce–Col road near Kalce were closed to traffic. The lowest parts of the Logaško polje, where the Logaščica river flooded numerous residential buildings above the Jačka ponor, were flooded as well.

The Vipava (on the lower reach of the river) and Kolpa rivers were high as well, and the Rižana river caused considerable damage by flooding residential buildings, disabling traffic on local and regional roads and the railway, and washing 150 tons of fish from a fish farm. The Ljubljanica and Krka rivers, which have predominantly karst catchment areas with high retention capacities, experienced secondary flood waves that slowed the runoff from already flooded areas.

10.3 Dynamics of karst polje flooding

Measurements of water levels and discharges and analyses of the dynamics of the rise and fall of water levels are basic tools for studying extreme hydrological events and their consequences. An illustrative study of the flood dynamics of the Planinsko polje, a typical karst polje, considered a large flood wave that occurred in December 2009. The flooding was caused by three

Študija je pokazala, da je po izjemno intenzivnih padavinah reakcija kompleksnega kraškega sistema z avtogenim in alogenim napajanjem ravno tako hitra kot reakcija površinskih voda in da so zadrževalne zmogljivosti krasa v takšnih situacijah zanemarljive (*Kovačič* in *Ravbar* 2011).

10.4 Človek in poplave na krasu

Za poplave na kraških poljih je značilna umirjenost, pojavljanje na istih mestih in do približno enake višine. V preteklosti so se domačini poplavam prilagodili s primerno rabo tal, gradnjo naselij pa so pomaknili na višja obrobja (4). Poplave zato niso posebej nevarne in ne povzročajo večje škode, razen ob izjemno visokih vodah, ki so navadno sezonske, vezane na poznojesenski padavinski višek, zimska deževja in taljenje snega. Škoda nastaja zgolj v kmetijstvu in na infrastrukturi, redkeje na bivalnih in gospodarskih objektih. Žal pa se sodobna gradnja tudi na krasu vse pogosteje usmerja v potencialno poplavna območja, zlasti tam, kjer poplave niso vsakoleten pojav in so potrebe po novih zazidalnih površinah velike (npr. Logaško polje).

weeks of intense precipitation when the amount was twice the average values of the 1975–2004 period. The water level of the Unica river (Haasberg) rose by 3–4 cm/h and reached its peak at an altitude of 450.12 m a.s.l., which can be considered major but still normal flooding. The flooded area covered 9.84 km^2 and the water volume was 40.6 million m^3. The lowest parts of the polje were 8 m below the high water level and the flood lasted for 37 days (3).

These measurements and the subsequent analysis showed that after exceptionally intense precipitation, the reaction of this complex karst system with its autogenous and allogenous recharging is just as rapid as the reaction of its surface waters and that the retention capacity of the karst in such situations is negligible (*Kovačič* and *Ravbar* 2011).

10.4 Man and flooding on karst

Calm floods occurring in the same places and reaching approximately the same levels are characteristic of karst areas. In the past, local populations adapted to the flooding by adopting suitable land use and building their settlements on the higher margins of poljes (4). Floods

4 Na Planinskem polju so hiše postavljene nad nivo najvišje poplave; stanje 25. decembra 2010 pri vodostaju jezera na nadmorski višini 449,66 m.
Houses on the Planinsko polje are located above the level of the highest recorded flood; situation on 25 December 2010 at the water level of 449.66 m a.s.l.

Lep primer prilagojene rabe zemljišč na poplavnih območjih na krasu so kraška polja Notranjskega podolja. Prikazan je primer Planinskega polja. Raven običajne poplave je na nadmorski višini 448,2 m. Takrat voda sega preko mostu čez Unico na cesti Planina–Laze. Raven velike poplave je 449,5 m, ko voda delno že zalije most čez Unico pri Haasbergu in je cesta Unec–Planina neprevozna. Kot izredno poplavo lahko označimo vodostaj 450,2 m, ko je poplavljen most v Malne (*Kovačič* in *Ravbar* 2011). Tudi izredne poplave na Planinskem polju, ko prostornina jezera, ki doseže obseg 9,86 km^2, znaša po izračunih približno 41,5 milijona m^3, ne povzročajo škode in otežujejo zgolj promet po lokalnih cestah, razen če se pojavijo v času, ko kmetijski pridelki še niso pospravljeni. Zaradi hitrejšega odtekanja vode so pod cestami na polju zgrajeni številni prepusti, ponori so opremljeni z železnimi rešetkami, mostovi čez reke in ceste so dvignjeni nekoliko nad okoliški svet (5).

Kartografski sloji območij poplavljanja v Sloveniji, ki so dostopni na spletnem portalu Agencije RS za okolje (ARSO), opredeljujejo Planinsko polje kot območje katastrofalnih poplav, čeprav se te redno pojavljajo. V tem oziru je treba natančno določiti poplavne kote rednih in izrednih poplav ter kartografske prikaze temu primerno popraviti.

Primerov neustrezne rabe prostora na poplavnih območjih na krasu je veliko. Logaško polje oziroma območje ob ponoru Jačka, kjer ponika Logaščica, je eno izmed bolj znanih. Občina in država sta na poplavnem območju, ki je ustrezno označeno tudi na kartografskih prikazih poplav ARSO, dovolili gradnjo stanovanjskih blokov in hiš (*Trček* 2010). Omenjeno območje je bilo v zadnjem času poplavljeno decembra 2009, spomladi 2010, septembra 2010 pa so narasle vode Logaščice ponovno poplavile v večjem obsegu in poškodovanih je bilo 46 stanovanjskih objektov. Realna škoda posledic septembrske poplave v občini Logatec znaša 2,5 milijona evrov (*Barut* 2011), vendar je tu zajeta škoda, ki je nastala tudi na drugih poplavnih območjih v občini (npr. Hotenjsko podolje). Po poplavah decembra 2009 je občina naročila poplavno študijo za naselje Logatec, ki predvideva ohranjanje neposeljenih poplavnih površin na Logaškem polju in gradnjo na stavbnih zemljiščih izključno pod posebnimi pogoji (*Žagar* 2011).

therefore do not present any particular danger and do not cause significant damage except during seasonal high waters associated with the late fall precipitation peak, winter rains, and the melting of snow. The damage is limited mainly to agriculture and infrastructure and rarely affects residential and industrial buildings. Regrettably, modern construction in karst areas is increasingly oriented towards potential flood areas, especially where floods are not an annual occurrence and where there is major demand for new built-up areas (e.g. Logaško polje).

The poljes of the Notranjska region are a fine example of properly adapted land use in karst flood areas. On the Planinsko polje, for example, the level of regular floods reaches 448.2 m a.s.l., and the water typically overflows the bridge across the Unica river on the Planina–Laze road. The major flood level is 449.5 m a.s.l. when the water floods the bridge across Unica near Haasberg and the Unec–Planina road becomes impassable. A water level of 450.2 m a.s.l. marks an extraordinary flood when the bridge to Malni is flooded (*Kovačič* and *Ravbar* 2011). However, even major floods on the Planinsko polje, when the lake stretches to cover 9.86 km^2 and according to calculations its volume reaches 41.5 million m^3, do not usually cause any serious damage. They merely affect the traffic on local roads, unless they occur when the crops are still in the fields. To facilitate more rapid runoff, numerous culverts have been installed under the roads on the polje, ponors are furnished with iron gratings to avoid blockages, there are bridges across the river and stream beds, and the roads are raised somewhat above the surroundings (5).

The maps of flood areas in Slovenia available on the web site of the Environmental Agency of the Republic of Slovenia (EARS) identify the Planinsko polje as a 'catastrophic' flood area, even though floods occur regularly. In this context it is necessary to define precisely the flood heights of regular and extraordinary floods and correct the cartographic presentations accordingly.

There are many examples of inappropriate land use on karst flood areas. The Logaško polje, the area by the Jačka ponor where the Logaščica river sinks, is one well-known example. The municipality and the state allowed the construction of apartment buildings and houses on the flood area, even though it is appropriately marked on EARS maps (*Trček* 2010). In recent times, this

5 Poplavljena cesta v Malne (Planinsko polje) dne 25. decembra 2010, kjer so vidni prepusti pod cesto za hitrejše odtekanje poplavne vode.
The flooded road to Malni (Planinsko polje) on 25 December 2010 showing culverts for faster runoff of floodwater.

6 Poplavno območje v okolici Bača (vir *Kovačič* 2010a).
The flood area in the vicinity of Bač (source *Kovačič* 2010a).

Manj znano območje neprilagoditve poplavam na krasu je Zgornja Pivka pri naselju Bač. Študija visokih voda novembra 2000 je pokazala, da se obstoječa stavbna zemljišča in stavbna zemljišča dolgoročnega občinskega načrta prekrivajo z območji izrednih poplav v Baču in okolici (6). Za doseganje poplavne varnosti bi morali izdelati karte poplavnih območij v okolici Knežaka, Bača in Koritnic, na katerih bi označili ogrožena območja, kjer bi morali gradnjo novih objektov omejiti, četudi je povratna doba izrednih poplav zelo dolga (*Kovačič* 2010a).

Pregled kartografskih prikazov območij pogostih in katastrofalnih poplav ARSO v kraških pokrajinah Slovenije odkrije vrsto pomanjkljivosti in nedoslednosti. Poplavna območja na kraških poljih Notranjske so označena kot območja katastrofalnih poplav, četudi so redno poplavljena in poplave na njih večje škode ne povzročajo. Enako so kot območja katastrofalnih poplav označene poplavne površine v Pivškem podolju, čeprav so poplave ob Pivki v zgornjem in spodnjem toku (pred ponorom) redne. Kotanje presihajočih Pivških jezer so tudi označene kot območja katastrofalnih poplav, kljub temu da se večina kotanj napolni vsaj enkrat letno, med poplavna območja pa denimo niso uvrščeni Šembijsko jezero in Nariče (7) pri Šembijah, Bačko in Laneno jezero pri Baču ter poplavno obmo-

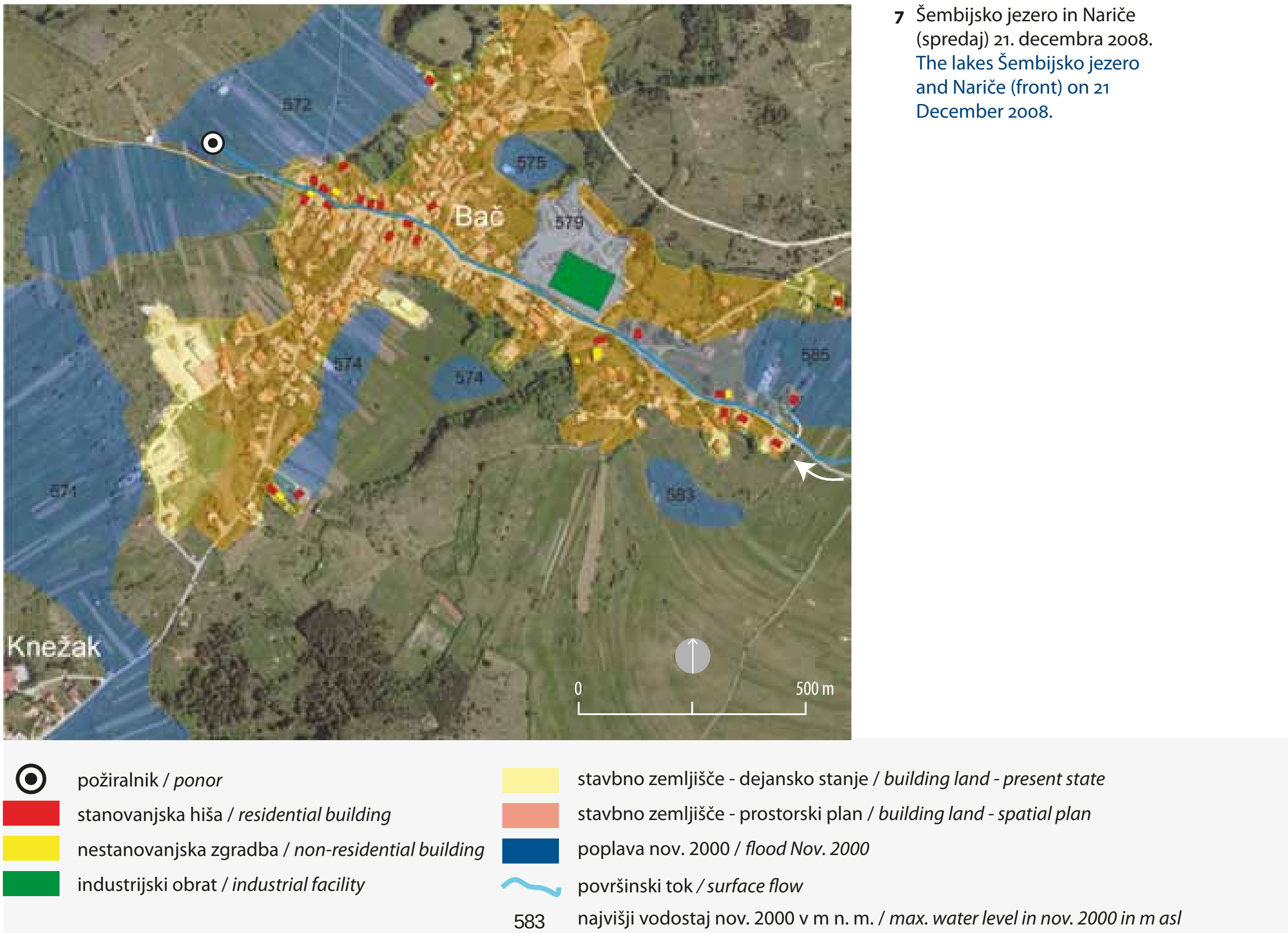
area was flooded in December 2009 and the spring of 2010, and in September 2010 the swollen waters of the Logaščica river flooded a large area and damaged 46 residential buildings. The total damage resulting from the September flooding in the Municipality of Logatec amounted to 2.5 million euros (*Barut* 2011), but this figure includes damage that occurred in other flooded areas in the municipality as well (e.g. Hotenjsko valley system). After the December 2009 flood, the Municipality of Logatec commissioned a flood study for the town of Logatec that envisages the preservation of unsettled flood areas on the Logaško polje and construction on building land exclusively under special conditions (*Žagar* 2011).

The Upper Pivka area near the settlement of Bač is a less well-known area of inadequate adaptation to floods on karst. A study of high waters in November 2000 showed that the existing building land and the projected building land of the long-term municipal plan overlap with areas of extraordinary flooding in Bač and the surroundings (6). To achieve flood safety, flood maps of the areas around Knežak, Bač, and Koritnice should be elaborated that designate risk areas where construction of new buildings should be limited even though the return period of extraordinary floods is very long (*Kovačič* 2010a).

čje na kraškem polju med Koritnicami, Knežakom in Bačem. V Notranjskem podolju niti Rakov Škocjan niti Hotenjsko podolje na zemljevidih ARSO nista označena kot poplavni območji, enako pa velja tudi za Zadloško polje na Črnovrški planoti.

Podobnih primerov je v Sloveniji še več, kar kaže potrebo po natančni preučitvi obsega, pogostosti pojavljanja in višin poplav na poplavnih območjih na krasu. S poglobljeno študijo zgodovinskih virov, natančnih kartografskih prikazov, digitalnega modela višin, satelitskih posnetkov poplav septembra 2010 in poplav v bližnji preteklosti ter z uporabo GIS-ov bi morali na državni ravni v dovolj natančnem merilu (parcele) določiti površine in višine rednih in izrednih poplav za vsako območje poplav na krasu posebej ter v seznam poplavnih območij uvrstiti tudi tista, ki na obstoječih zemljevidih niso opredeljena kot poplavna. Za razlikovanje med redno in izredno poplavo se zdi

A survey of EARS maps of catastrophic flood areas in the Slovene karst regions reveals a number of shortcomings and inconsistencies. Flood areas on karst poljes of the Notranjska region are marked as areas of catastrophic floods even though they experience regular flooding that causes no major damage. Similarly, flood areas in the Pivka valley system are marked as catastrophic flood areas even though floods along the upper and lower (before the ponor) courses of the Pivka river occur regularly. The basins of the intermittent Pivka lakes are also marked as catastrophic flood areas, even though the majority of the basins are filled at least once a year. On the other hand, flood areas such as the lakes Šembijsko jezero and Nariče (7) near Šembije, the lakes Bačko jezero and Laneno jezero near Bač, and the flood area on the karst polje between Koritnice, Knežak, and Bač are not identified. Rakov Škocjan and Hotenjsko valley system in the Notranjska region are not marked as



7 Šembijsko jezero in Nariče (spredaj) 21. decembra 2008.
The lakes Šembijsko jezero and Nariče (front) on 21 December 2008.

bolj smiselno uporabiti kriterij višine poplave in ne pogostost pojavljanja. Tovrstni poplavni zemljevidi bi služili kot podlaga za načrtovanje rabe prostora na poplavnih območjih na krasu, s čimer bi se lahko izognili neprimernim posegom na teh območjih, še posebno gradnji objektov.

Sklep

Vodne ujme uvrščamo med najbolj pogoste naravne nesreče na krasu, ki povzročajo predvsem gospodarsko škodo, terjajo pa tudi človeška življenja. Kraška polja in druge kraške pokrajine so sicer naravni zadrževalniki pretočnih viškov in dobri regulatorji poplav v spodnjih delih porečij (npr. na Ljubljanskem barju, v dolini Krke), lahko pa povzročijo tudi sekundarne poplavne viške v dolinah rek, ki jih napajajo kraški izviri.

Zato je ne le za kraške pokrajine ključno dobro poznavanje pretakanja voda v krasu, zadrževalne kapacitete vodonosnikov in reakcije izvirov na napajanje. Tako lahko predvidimo izpostavljenost določenega območja vodnim ujmam, ki je ključni del prostorskega načrtovanja in nam je lahko v bodoče v pomoč pri boljšem preventivnem delovanju in zaščiti.

Žal pa še vedno ostajamo brez ustreznih meritev dinamike naraščanja in upadanja vodostajev na kraških območjih. Hidrološke opazovalnice so redke. Za morebitno predvidevanje visokih voda v prihodnosti bi bilo zato nujno treba obnoviti v preteklosti opuščene vodomerne postaje oziroma vzpostaviti sistematični dolgotrajni monitoring na kraških vodotokih in dostopnih mestih do kraške podtalnice.

flood areas on the EARS maps, nor is the Zadloško polje on the Črni Vrh plateau.

Numerous similar cases exist in Slovenia, pointing to the need for a detailed study of the extent, frequency, and height of floods in flood areas on karst. An in-depth study of historical sources, precise cartographic presentations, a digital elevation model, satellite shots of the September 2010 floods and floods in the recent past, and the use of geographical information systems should be employed at the national level to identify the areas and heights of regular and extraordinary floods at a precise enough scale (plots) for each flood area on karst. Furthermore, the list of flood areas should include all those areas not identified as flood areas on the existing maps. To distinguish between regular and extraordinary floods, flood height seems to be a more appropriate criterion than frequency. This type of the flood map would serve as a basis for land use planning on flood areas on karst in order to avoid inappropriate encroachments on these areas, particularly the construction of buildings.

Conclusion

Floods rank among the most frequent natural disasters in karst regions, causing primarily economic damage but occasionally claiming lives. Karst poljes and other karst areas are natural reservoirs for discharge surpluses and good flood regulators in the lower parts of the river basins (e.g., the marsh Ljubljansko barje, the valley of the Krka river), but they can also cause secondary flood peaks in the valleys of rivers fed by karst springs.

A good understanding of water flow in karst areas, the retention capacity of aquifers, and the reactions of springs to recharging is therefore of key importance, and not just for karst regions. With this knowledge, it is possible to anticipate the exposure of certain areas to flooding, which is an essential part of spatial planning that can help us improve prevention and protection measures in the future.

Unfortunately, there are still no appropriate measurements of rising and falling water levels in karst areas at our disposal and only a few hydrological observation points. The possible prediction of floods in the future requires the urgent restoration of abandoned water gauging stations or the implementation of systematic long-term monitoring of karst aquifers and access points to karst groundwater.

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