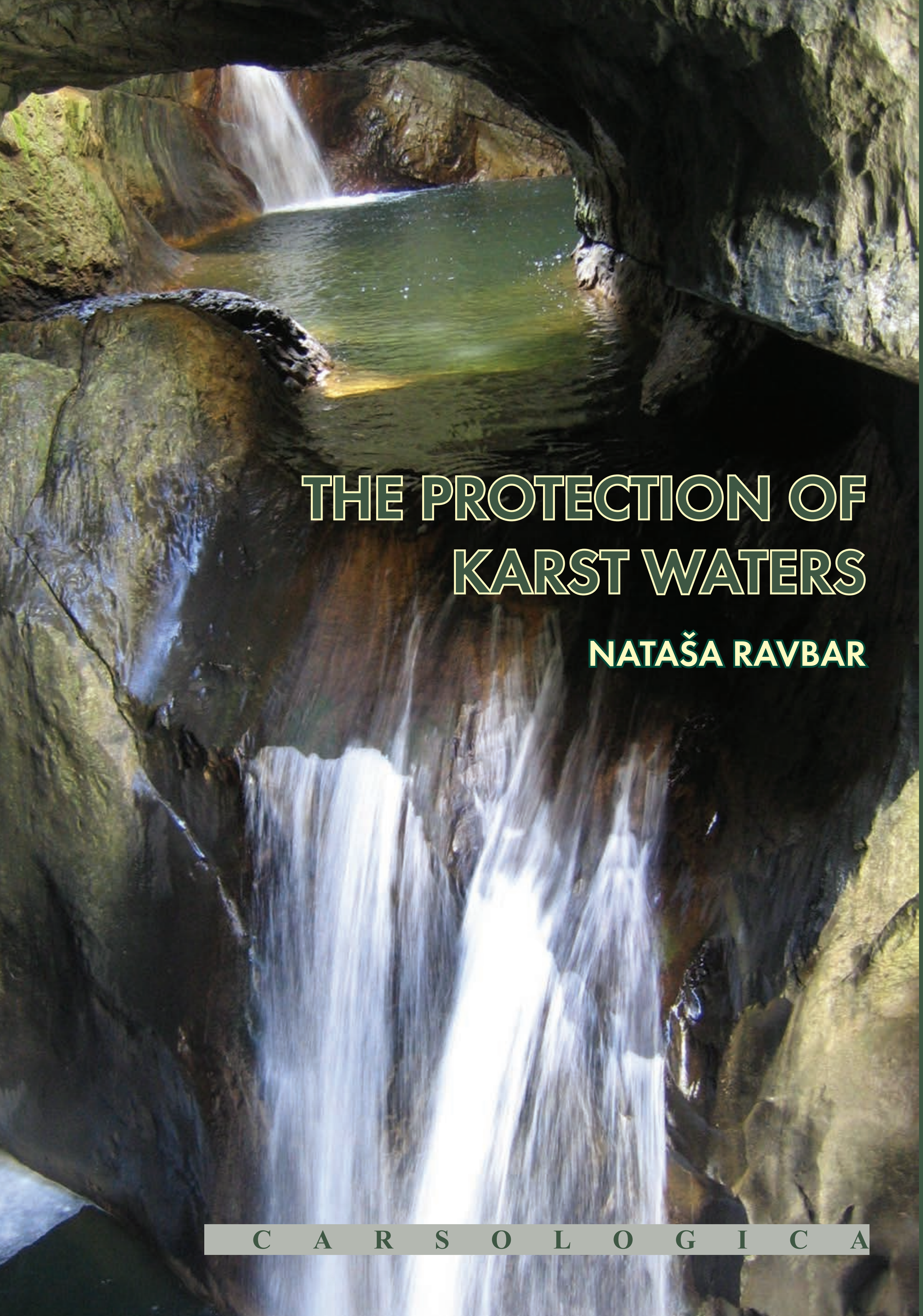

THE PROTECTION OF KARST WATERS

NATAŠA RAVBAR

CARSOLOGICA

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CARSOLOGICA

NATAŠA RAVBAR • THE PROTECTION OF KARST WATERS – A COMPREHENSIVE SLOVENE APPROACH TO VULNERABILITY AND CONTAMINATION RISK MAPPING

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A COMPREHENSIVE SLOVENE APPROACH TO VULNERABILITY AND CONTAMINATION RISK MAPPING

VAROVANJE KRAŠKIH VODA

OBŠIREN SLOVENSKI PRISTOP H KARTIRANJU RANLJIVOSTI IN TVEGANJA ZA ONESNAŽENJE

NATAŠA RAVBAR

POSTOJNA – LJUBLJANA
2007

Don’t spit into a well, you may want to drink out of it.

(Basni, Krylov, Ivan Andrejevič, 1809)

CONTENTS

I – METHODOLOGY

II – APPLICATION

1
INTRODUCTION

1.1 THE BACKGROUND

Abundant sources of both drinking water and water for technological use are becoming more and more valuable. Moreover, water resources are increasingly the subject of conflict and strife as these are becoming less available. Globally, more than a billion people, most of them in developing countries, lack an access to safe drinking water. However, for economical and population growth also some developed countries have been increasingly confronted with a lack of sufficient quantity and quality water resources.

Although carbonate rocks cover only about 12-15% of the world's surface, it has been estimated that already two decades ago a quarter of the global population depended on karst water supplies (Ford and Williams, 1989; Salomon, 2000). However, the experts believe that by the year 2025 almost 80% of drinking water will be derived from the karst aquifers (Forti, 2002). Although these estimations are probably exaggerated, karst water is an important heritage, which will surely play an essential role in the future and thus need to be placed foremost.

In Europe, where carbonate rocks cover 35% of the surface, groundwater from karst aquifers is an especially important water resource. In some countries karst water contributes more than half of the drinking water supply (e.g. in Austria) and in many regions it is the only available source of fresh water (COST Action 65, 1995).

In Slovenia carbonate rocks cover over 44% of the country (Novak, 1993a; Gams, 2003). As in many European regions also in Slovenia, karst aquifers represent important reservoirs of qualitative water resources. Karst sources are already extensively used for drinking water supply, but are not yet completely exploited. At present karst waters cover around half of the country's needs (Brečko Grubar and Plut, 2001).

However, karst aquifer systems are especially vulnerable to contamination in comparison to non-karst ones. Due to rapid recharge of the infiltrating water underground and its fast distribution over large distances, to high flow velocities and short residence time, the self-cleaning capacity of the karst groundwater is very low. Consequently, the remediation and neutralizing of eventual infiltrated contaminant in the karst network would be negligible and the contamination could be, without effective attenuation of its concentration, transported over large distances (Ford and Williams, 1989; Drew and Hötzl, 1999; Zwahlen, 2004).

Therefore the impacts of anthropogenic activities to which karst aquifer systems are exposed could significantly influence groundwater quality. Since karst aquifer systems are very susceptible to contamination and of vital importance, these sources require appropriate and careful managing.

The karst aquifers in Slovenia are mainly in remote areas and are, due to their relief or unfavourable climate conditions, less attractive for intensive settlement, industrial, farming and other activities. Despite relatively favourable conditions for karst water source protection in comparison to some other karst areas worldwide, many of them still remain insufficiently protected. In general, the quality of karst groundwater is still relatively high. Nevertheless, some signs of contamination have already been recorded in some of the springs, showing the shortcomings of drinking water management also in uninhabited alpine karst areas (Kovačič and Ravbar, 2005a).

The reasons for the insufficient protection of karst water sources in Slovenia can be mainly found because of the drawbacks of the previous water protection policy and in the still poor provisions enforced in the existing Slovene legislation. Subsequent reasons are also the conflicting interests in land use and a lack of knowledge about sustainable water management in karst regions.

1.2 GOALS AND OBJECTIVES

In some countries the concept of groundwater vulnerability mapping has been successfully used for protection zoning and land use planning in karst. Several different methodologies for karst groundwater vulnerability mapping have already been proposed. Unfortunately experience of vulnerability mapping of karst aquifers is very modest in Slovenia.

Thus the main purposes of this research are:

- to develop a comprehensive approach for karst water vulnerability and risk mapping and apply it to the test site,
- to apply different intrinsic vulnerability methods to the same test site simultaneously using the same database,
- to compare and describe advantages and disadvantages of each method and evaluate their applicability,
- to validate the results.

However, main stress of our work is to develop and propose a general approach for karst water vulnerability and risk mapping, taking into account the special characteristics of Slovene karst landscapes (Alpine and Dinaric karst). The approach should both suit Slovene environmental legislation and enable comparison across European countries.

On the basis of work accomplished by the European COST Action 620 (Zwahlen, 2004) and previous achievements in vulnerability mapping (Cività, 1993; Vrba and

Zaporozec, 1994; COST Action 65, 1995; Doerfliger and Zwahlen, 1998; Gogu and Dassargues, 2000, 2001; Goldscheider *et al.*, 2000), an additional step has been made within the presented study (Fig. 1.1).

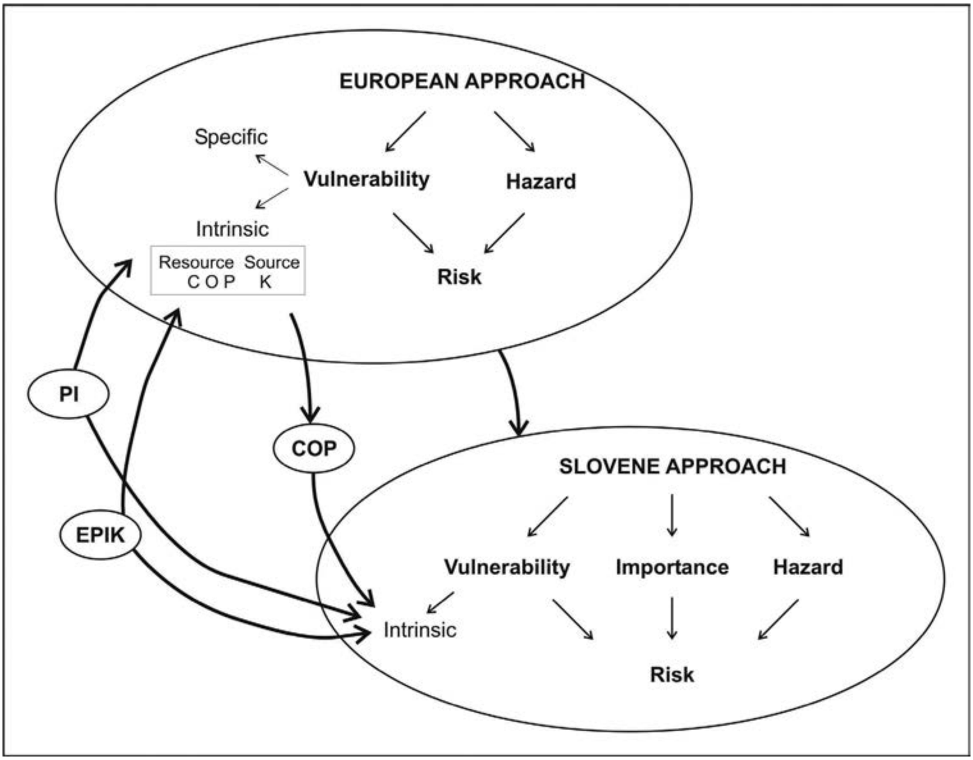


Figure 1.1: Previous achievements of the vulnerability and risk mapping that had a major influence on the Slovene Approach development.

Among the most frequently enforced and many times tested methods we selected the most satisfactory one for application to Slovene karst regions. The selection was based on adequacy of the criteria such as parameter selection, method of parameter weighting and method of final assessment reckoning. Taking the selected COP method (Vías *et al.*, 2002) as a starting-point it was slightly complemented, adapted and made adequate for source vulnerability mapping. The proposed approach offers a new possibility to integrate surface and groundwater protection. Furthermore, temporal hydrological variability has been integrated in the vulnerability mapping concept for the first time.

The so-called Slovene Approach has been tested on a Slovene karst test site in the catchment area of the Podstenjšek springs. In order to evaluate and to compare it to other vulnerability mapping methods some of the most frequently used ones have also been applied to the same test site using the same database. So the following methods for intrinsic vulnerability have been applied: the EPIK method (Doerfliger and Zwahlen, 1998), the PI method (Goldscheider *et al.*, 2000), the COP method (Vías *et al.*, 2002) and the Simplified method (Nguyet and Goldscheider, 2006).

Additionally, to verify how accurate the resulting vulnerability maps correspond to actual situation, different methods of validation (such as tracer tests and statistical methods) have been carried out.

The European COST Action 620 also emphasises that the resources or sources protection requires a sustainable management, which should be based on a comprehensive risk analysis (Daly *et al.*, 2004). In the presented study we therefore proposed a ranking procedure for a comparison between hazards of the same type within the Slovene scale. We also provided importance of a resource or source evaluation.

The topic of water source vulnerability and risk mapping in Slovene karst regions has been studied holistically within this work for the first time, resulting in a general approach for the karst water vulnerability and risk assessment proposal.

I

METHODOLOGY

2

KARST AQUIFER SYSTEMS

2.1 GENERAL PROPERTIES AND VULNERABILITY OF KARST AQUIFERS

Karst aquifers consist of carbonate rocks (limestone, dolomite) which have been exposed to karstification and thus karst conduits of different size could contain relatively large amount of groundwater. From a hydrogeological perspective the most distinctive characteristic of karst aquifer systems that differentiate them from other hydrogeological systems is the high solubility of the rock medium determining the heterogeneity of the infiltration, groundwater flow and outflow of the karst aquifers (White, 1988; Ford and Williams, 1989; Klimchouk and Ford, 2000; Király, 2002; Gunn, 2004).

In carbonate (karst) aquifers percolating water dissolves the rocks around the preexisting interconnected fractures, thus enlarging their aperture and the hydraulic conductivity of the flow medium. However, some karst areas are more extensively karstified than others. The amount of dissolved carbonate depends on the chemical composition of the rock, their secondary porosity and the water amount (Ford and Williams, 1989; Gunn, 2004). The relative karstification degree of the various fracture families does not only depend on the geological history of the media, but generally on the direction and the magnitude of the groundwater flow system (Király, 2002). Consequently, the solution processes result in a dynamic evolution of different karst systems.

Particular surface and underground geomorphological features characterise karst aquifers. The most significant characteristics of karst landscapes (if it is exposed) are karrenfields, dolines and swallow holes on the land surface that usually, but not necessarily, develop along the fissured and fractured zones. Such a surface is very permeable and enables immediate infiltration of water into the aquifer (Ford and Williams, 1989).

Water infiltrating from the surface generally moves vertically or sub-vertically towards the groundwater. In the underground the karstification (solutional enlarging of fissures) creates cavities and organizes a flow net between them in a hierarchical manner (Bakalowicz *et al.*, 1994; Gabrovšek, 2000). The underground drainage system is then integrated into efficient, mainly sub-horizontally oriented conduits for the collection, transport and ultimately discharge of recharge waters (Drew, 1999).

Thus unlike porous or fissured aquifers karst ones have a peculiar structure and behaviour that can be schematised by a high permeability, usually unknown channel network of karst conduits, which are immersed in a less permeable limestone volume matrix and well connected to a local discharge area, the karst spring.

The most significant consequence of limestone dissolution associated with karst evolution is increasing hydrogeological heterogeneity in all scales, which is manifested in duality of fundamental hydraulic processes occurring in the aquifer (Király *et al.*, 1995). The most distinctive characteristics reflecting the **duality of karst** concern the aquifer recharge, groundwater flow properties and discharge (Ford and Williams, 1989; Worthington, 1991; Király, 2002).

Duality of the recharge:

- autogenic recharge – from the karst area itself (i.e. the precipitation that enters karst through numerous fissures and voids) or
- allogenic recharge – from adjacent non-karst areas (i.e. the sinking water flow).

The increase of both types of recharge results in a rise of the groundwater level and increase of discharges at the springs.

Duality of the infiltration processes:

- diffuse infiltration through soil and unsaturated zone and
- concentrated infiltration of sinking water bodies (rivers, lakes) that collect water on the surrounding surface and sink underground via swallow holes. Usually these streams continue their way underground through corrosively widened channels.

Allogenic recharge is often point-like, while autogenic recharge is often diffuse. However, diffuse infiltration water that primarily takes place in the fissures of lower permeability can also be enhanced by rapid and concentrated drainage taking place in the epikarst and/or the aquifer itself.

Duality of the groundwater flow processes:

- low flow velocities in the fractured volumes with greater capacity of water storage,
- high flow velocities in the channel network.

Duality of the discharge processes:

- diffuse seepage from the low permeability volumes,
- concentrated discharge from the channel network at the karst springs.

Due to the main characteristics of water flow and storage processes karst aquifer systems are separated into the following sub-systems in the vertical direction (Ford and Williams, 1989; Gunn, 2004):

- **unsaturated zone** (vadose zone) – the dry, upper part of the aquifer where fast drainage through a vertical network of fissures and voids interacts with the slow percolation through low permeability volumes. Upper parts of the unsaturated zone are topsoil, subsoil and epikarst layers.

  Epikarst – the upper part of the unsaturated zone of different thicknesses (a few metres up to several tens or even hundreds of metres). It is a highly permeable and karstified zone below the aquifer surface. Due to its origin by weathering processes it is structurally different from the lower unsaturated zone owing to a larger and more uniform fracturing, which results in a much higher hydraulic conductivity. The epikarst zone hinders the surface runoff by absorbing and temporarily storing rainfall water. Moreover, it rapidly drains infiltrating waters towards enlarged vertical conduits, thus enhancing concentrated infiltration. The remaining stored water constitutes a perched saturated zone, and may contribute to diffuse recharge (Mangin, 1975; Williams, 1983; Klimchouk, 2000),

– **saturated zone** (phreatic zone) – the lower part of the aquifer where flow through the (sub)horizontal conduit network prevails, directly connected to the spring.

The hydraulic functioning of the karst systems is very difficult to predict. It depends on the degree of the fissured or conduit porosity, karst network development or karst type, but varies significantly due to particular hydrological conditions. Each these zones, especially the epikarst zone, play an important role in the behaviour of karst aquifers. An important consequence of the existence of an epikarst layer is the storage and temporal distribution of the karst aquifer recharge.

The epikarst zone is characterised by a network of drainage paths that principally depends on the frequency and pattern of solutionally corroded joints and bedding planes (Gunn, 1981). As jointing density and diffused karstification rapidly diminishes with depth, further recharge is greatly limited. Thus also vertical hydraulic conductivity decreases rapidly with depth (Williams, 1983). Consequently, contrast in permeability between the epikarst zone and underlying less permeable volumes can cause retention of percolation and a water concentration at the base of the epikarst zone. A temporary aquifer can be formed within the epikarst zone. Further downwards in the lower unsaturated zone percolation occurs mainly via major tectonic fissures, which are distant and not uniformly distributed. Water stored in the perched zone flows laterally towards the nearest vertical fissures (Klimchouk, 2000).

Several studies done so far (Mangin, 1975; Gunn, 1981, 1983; Williams, 1983; White, 1988; Ford and Williams, 1989; Király *et al.*, 1995; Király, 2002; Jeannin and Grasso, 1997; Klimchouk, 2000; Petrič, 2002a; Trček, 2003) demonstrate that the epikarst zone highly influences the discharge characteristics of a karst spring (e.g. the shape of a karst spring hydrograph), the base flow component of a spring, the water level oscillation in a karst conduit network and the recharge conditions of low permeability rock blocks. Unfortunately, in many karst landscapes the development of the epikarst is not visible on the land surface. Therefore it is difficult to assess its structure and function – especially the aquifer recharge, storage and discharge processes. The importance of epikarst zone impact on the functioning of the karst system consideration can indirectly be indicated by the recognition of the fast and slow components of water flow within the system.

Hence it follows that karst aquifers are very complex in comparison with non-karst ones (Fig. 2.1) and are, because of their specific structure, particularly susceptible to contamination (Fig. 2.2). Their heterogeneous properties significantly characterise the flow of the groundwater and solute (contaminant) transport mechanisms (Čenčur Curk, 2002). Moreover, groundwater and contaminant flow regime can hardly be predicted and reactions of particular hydrological systems to contamination can be very diverse.

Due to a thin protective soil cover and/or other protective overlaying layers, such

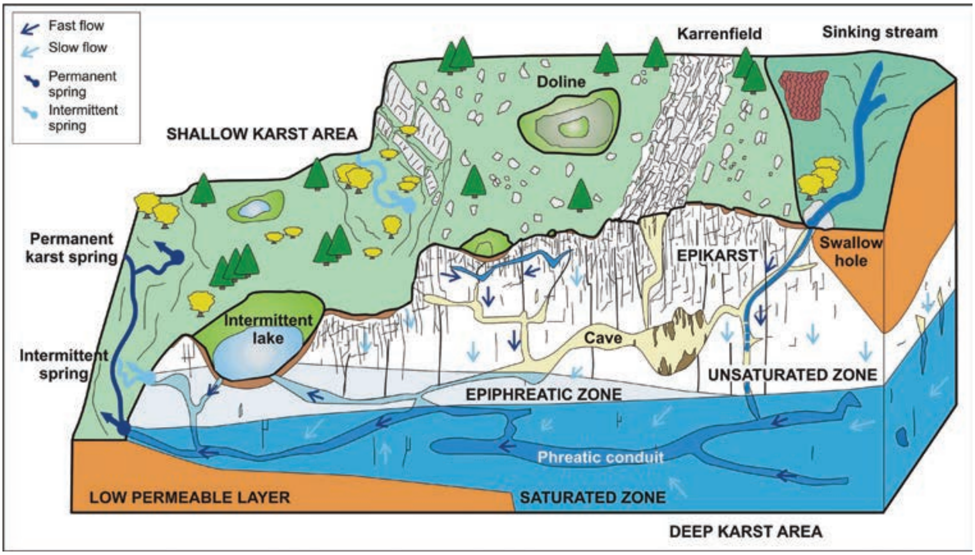


Figure 2.1: Conceptual model of the water flow in a karst aquifer system.

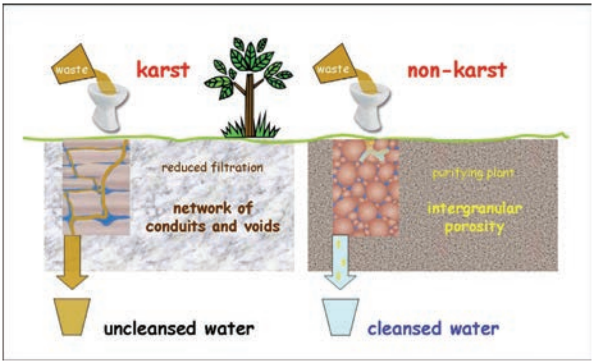


Figure 2.2: The illustration shows the capability of natural self-cleaning capacity of the infiltrating contaminants in karst and non-karst aquifers.

as subsoil and non-karst rocks, rapid infiltration and poor pre-purification of recharged water are prevalent. Natural filtration and attenuation of the possible contaminants before entering the subsurface could thus be limited or significantly reduced.

Moreover, swallow holes, fractures and other open conduits provide routes for the direct entry of water and surface-derived contaminants into the subsurface. Thus poorly filtered concentrated recharge towards the groundwater occurs.

Underground channel systems present the linkage between the recharge and discharge points consisting of an integrated network of preferred rapid flow paths and zones, and a matrix of slow flow through lower permeability volumes. Especially, a channel network makes up the very permeable system of conduit flow characterised by high flow velocities and turbulent flow where the pathways are independent of the surface topography.

Additionally, a net-like structure of interconnected karst conduits with large spatial distribution plays an important role in flow and transport processes over large distances including numerous possible interactions and influences within the three-dimensional formation of the aquifer itself.

Due to rapid recharge of the water infiltrating into the underground, fast distribution of water over large distances, high flow velocities, turbulent flow and short residence time in comparison to most intergranular aquifers, the self-cleaning capacity of karst systems is very low. Consequently, the remediation and neutralizing of the infiltrating contaminants in the karst network is negligible and contamination can be transported over large distances in various directions without effective attenuation of contaminant concentration. Therefore serious contamination problems may result from different human impacts.

Furthermore, in both unsaturated and/or saturated zones, but particularly in the epikarst zone water flow could be retained for few days to several months or even years (Gunn, 1981; Williams, 1983; Klimchouk, 2000; Bricelj and Čenčur Curk, 2005). Contaminants could therefore either easily reach groundwater or could be stored for a very long time in the underground and slowly discharge out of the aquifer causing long-term contamination of the groundwater and spring(s).

2.2 KARST IN SLOVENIA WITH SPECIAL REGARD TO HYDROLOGICAL SYSTEMS

In Slovenia karst regions extend over 44% of the country (Novak, 1993a; Gams, 2003), spreading from the Karavanke range and the plateaux of the Julian and Kamniško-Savinjske Alps at an altitude of 2,500 m on the north, to the Soča river and the shores of the Mediterranean Sea on the west and to the Gorski Kotar massive and Kolpa river on the south. Carbonate rocks are less present in Central Slovenia and are merely absent in the northeastern part of the country. Geotectonically, karst areas belong to the Southern Alps and Dinarids (Placer, 1981).

Large karst massifs and karst plateaux, intersected by shallow karst areas, poljes and valleys, characterize these landscapes. Thick sequences of very pure and deeply karstified Mesozoic limestones and dolomites prevail. The depth of the unsaturated zone can reach several hundreds of metres, in the mountain massifs even 1,500 m and more.

Carbonate rocks are of very high to medium permeability, the groundwater flow velocities ranging between 0.02 and 29.6 cm/s, respectively from 0.72 m/h to about 1,000 m/h (Novak, 1993a).

Less permeable or impermeable deposits traversing karst areas or bordering karst aquifers prevent the underground runoff; so do flysch and less permeable dolomite layers caused by folding and thrusting. However, Slovene karst landscapes are strongly tectonically modified. Fault zones that intersect or border karst areas can act as hydrological barriers as well. Consequently, karst underground water emerges to the surface through numerous efficacious springs at the aquifers' edges.

Catchment areas are often very complex, covering karst and non-karst areas as well. Catchments often extend over several tens or even hundreds of km^2 and are hydraulically connected over long distances. Watersheds often overlap and the flow paths proved by tracer tests often cross each other. Furthermore, it is practically impossible to define the position of individual springs' watersheds precisely due to their high variability in time and strong dependence on the respective hydrological conditions.

Thus, dependent on the respective hydrological conditions in several karst areas, frequent and very high groundwater fluctuations appear (several tens up to a few hundred metres). Consequently variable flow velocities, changing flow directions and surface-underground flow interactions also result.

Karst aquifers in Slovenia mainly consist of deeply karstified carbonate rocks, where groundwater flows in a network of solution conduits is significant. Such aquifers are often without surface water flow (the Kras plateau, the Trnovski Gozd plateau, the Javorniki and the Snežnik mountains, etc.). The autochthonous precipitation water flows through widened fissures and karst channels in different directions towards the springs at the aquifer's margins. Furthermore, sinking water bodies, reappearing on the other side(s) of the aquifer, can additionally recharge individual karst aquifers. In this way several abundant karst springs that are of great national importance for drinking water supply are being recharged.

Very thin or mostly absent protective soil cover and common absence of other protective overlaying layers, such as subsoil and non-karst rocks is significant. Common absence of thicker soil and/or sediment layers and consequently also the scarce vegetation accelerates infiltration of water and contaminants into the underground. Therefore the contaminants lack natural filtration for them to be chemically, biologically or physically cleansed. The average annual precipitation amount in Slovenia is quite high, ranging from 1,000 up to 4,000 mm in the mountainous areas.

In particular karst areas in Slovenia, some karst phenomena are due to the geological, hydrological and climatic circumstances developed to a different degree. However, the greatest distinction of Slovene karst is a great variety of different karst sub-types in a small area.

Existing karst literature so far (Habič, 1969, 1993; Gams, 1974, 2003; Kunaver, 1983) generally divides Slovene karst landscapes into (Fig. 2.3):
– Alpine karst,
– Dinaric karst and
– Isolated karst.

These karst landscapes do not only differ in origin and consequently in various forms of morphological and water flow characteristics, but also in different degrees of karstification, thickness of soil cover and vegetation density that subsequently influence population density and different land use.

Figure 2.3: Distribution of different karst types in Slovenia.

2.2.1 ALPINE KARST

Karst in the Slovene Alps, named Alpine karst, is characterised by more than 2,000 m high mountain ridges and plateau-like karst massifs cut by deep valleys (Habič, 1969; Kunaver, 1983). The karst plateaux are lower, usually reaching between 1,300 and 1,800 m (the Mežakla, the Jelovica, the Komna, the Pokljuka, the Dleskovška Planota, the Menina, the Velika Planina, etc.).

Tectonically, Slovene Alpine karst belongs to the South Alpine zone, whereas many other alpine karst areas belong to Austro-Alpine and Helvetic zone (Trümpy, 1985), first stretching over the southwestern Austrian Alps and the second one over the French and Swiss Alps, as well as parts of the western Austria.

The Alps in Slovenia consist of numerous nappes, thrusted towards the south. Extensive Upper Triassic and Jurassic limestone and dolomite of several thousands metres thickness are characteristic. Alpine karst mostly extends over the Julian and Kamniško-Savinjske Alps. However, there are smaller karst areas in the Karavanke range, where small patches of Palaeozoic carbonate rocks appear only in places.

In high mountain areas in Slovenia the highest mountain chains are characterised by vast limestone pavements (the Triglavski Podi, the Kaninski Podi, the Kriški Podi, the Rombonski Podi, the Skutini Podi), karrenfields connected with deep shafts excavated by water of melting Pleistocene glaciers and melted snow. Also, other characteristic karst features appear in the Alpine karst, such as snow kettles and solution pans.

The karstification processes in the Alps began in the Lower Pliocene and were interrupted during the Pleistocene period, when the relief was also transformed by the glacial processes (Premru, 1982). Intensive karstification was replaced by strong mechanical weathering. Remains of the glacial processes (glacial deposits and specific rock relief) are found all over the Alps. Several expressive dish-shaped and funnel-shaped dolines, collapse dolines and dry valleys can also be found on the plateaux.

Above the forest-line (1,550 – 1,900 m a.s.l.) the surface is mostly bare rock, where soil cover is very thin or more frequently even absent (Fig. 2.4). In general the soil and vegetation cover is more abundant on the lower-lying karst plateaux (Lovrenčak, 1987).

A predominant part of the abundant precipitation (in places more than 3,000 mm yearly) percolates through the karst aquifer and flows towards the efficacious karst springs in the bottom of the valleys (the Savica, the Boka, the Glijun, the Soča, the Nadiža, etc.). On the less permeable rocks smaller surface streams of torrential character can appear. On the other hand the groundwater supplies several mountain lakes (the Krnsko Jezero, the Sedmera Jezera, the Kriška Jezera, etc.).

In the Alpine karst aquifers, vertical channels and big altitude differences between high plateaux or peaks as recharge areas and springs in valleys prevail (Petrič, 2004). These areas have favourable conditions for deep shaft development, since the unsaturated

Figure 2.4: An example of a bare karst surface on the Kanin high mountain plateau (2,587 m), where the depth of the unsaturated zone exceeds 1,500 m (photo: G. Kovačič).

zone can reach 1,500 m in depth or even more. On the limestone pavements Kaninski and Rombonski Podi and elsewhere shafts even more than 1,000 m deep have been discovered (the Črnelsko Brezno, the Vandima, the Sistem Molička Peč, the Renejevo Brezno, etc.), the deepest in Slovenia being the Čehi II (1,533 m), currently number eight in the list of the world's deepest shafts. Furthermore, not far distant is the Vrtoglavica Cave, the world's deepest single-vertical shaft (643 m).

2.2.2 DINARIC KARST

The Dinaric karst is the largest single karst area in Slovenia, situated in the southern part of the country between the Prealpine mountains and marsh Ljubljansko Barje on the north to the Istria Peninsula on the south; it represents about 2/3 of all karst land in Slovenia (Gams, 2003). To the west it stretches to the Soča (Isonzo) river and the Gulf of Trieste, as well as to the Gorjanci hills on the east. Towards the south Dinaric karst in Slovenia is bordered by political boundary with Croatia.

The Dinaric karst is generally elongated along the strike of the Dinaric mountains, stretching between the Alps and Prokletije mountains in Albania. South of Slovenia it extends over the Dalmatia, southwestern Bosnia, Herzegovina and Montenegro.

The Dinaric karst mainly consists of Mesozoic limestones and dolomites that have been strongly tectonically compressed. Therefore explicit thrusting structure prevails (Placer, 1981). Due to the nappes overthrusting in the southwest direction, thrusts and folds verge in the so-called Dinaric direction (northwest-southeast). Consequently also the majority of the morphological units elongation is dominant in this direction.

The general characteristic of the whole Dinaric karst system, as a karst of expansive karst plateaux, intersected by dense dolines, large collapse dolines and intermediate poljes and karst plains, is valid also for the Slovene Dinaric karst. On high karst plateaux a stony surface prevails, which has in the last few decades been overgrown with forest due to pasture abandoning. The most distinctive morphological features are numerous large dolines of different origin (e.g. the Smrekova and Grda Draga, etc.). The deepest dolines are characterised by vegetation inversion as a consequence of temperature inversion. Significant are also deep shafts (e.g. Brezno Bogumila Brinška, etc.). Some of them still contain ice (e.g. the Velika ledena Jama v Paradani, etc.). In karst plateaux precipitation percolates underground and flows mainly through widened fissures and voids towards the springs at the aquifer's margin.

A chain of poljes (Babno Polje, Loško Polje, Cerkniško Polje, Planinsko Polje, etc.) has been formed along one of the most important tectonic lines in Slovenia, i.e. the neotectonic Idrija strike-slip fault zone. The most impressive forms of poljes appertain to the springs, sinking rivers and intermittent lakes and swallow holes. Various forms of interaction between groundwater and surface water can be observed, particularly at the intermediate poljes, shallow karst areas or in the contact karst areas.

In the western part of the Dinaric karst, many karst features were generated at the contact of the impermeable Eocene flysch with Mesozoic limestone. The flysch was tectonically partially overthrusted by the older sediment cover, forming high karst plateaux (Banjščice, Trnovski Gozd, Nanos, Javorniki, Snežnik, etc.), which extend at altitudes from 700 to 1,700 m. On the lithological contact of karst rocks with impermeable or semi-permeable sediments the so-called contact karst forms, characterised by numerous blind valleys and swallow holes (Mihevc, 1991).

The caves of Škocjanske Jame, known especially for their huge underground river gorge, are included in the UNESCO World Natural Heritage list as the best example of a contact karst cave. Also the longest (20 km) and the best known tourist cave system in Slovenia the cave of Postojnska Jama was formed by the Pivka river sinking underground. However, flysch layers can also act as an important impermeable barrier surrounding the carbonate massifs. Therefore on the contact abundant karst springs appear (Rižana, Hubelj, Vipava, Bistrica, etc.).

Similarly the Triassic dolomite, which predominates on the northeastern rim of the Dinaric karst (the Grosuplje basin, the Stiški Kot, the Temenica river valley, the Mirna basin), is semi-permeable bearing a hilly-valley landscape of fluviokarst. In general dolomite layers are slightly less permeable and, when thicker, may play the role of a

Figure 2.5: Most characteristic for the Dinaric karst are sinking rivers, reappearing several times and flowing superficially on the intermediate poljes or valleys. The figure shows the natural bridge of Veliki naravni most formed by the Rak river – for location see figure 2.6 (photo: N. Ravbar).

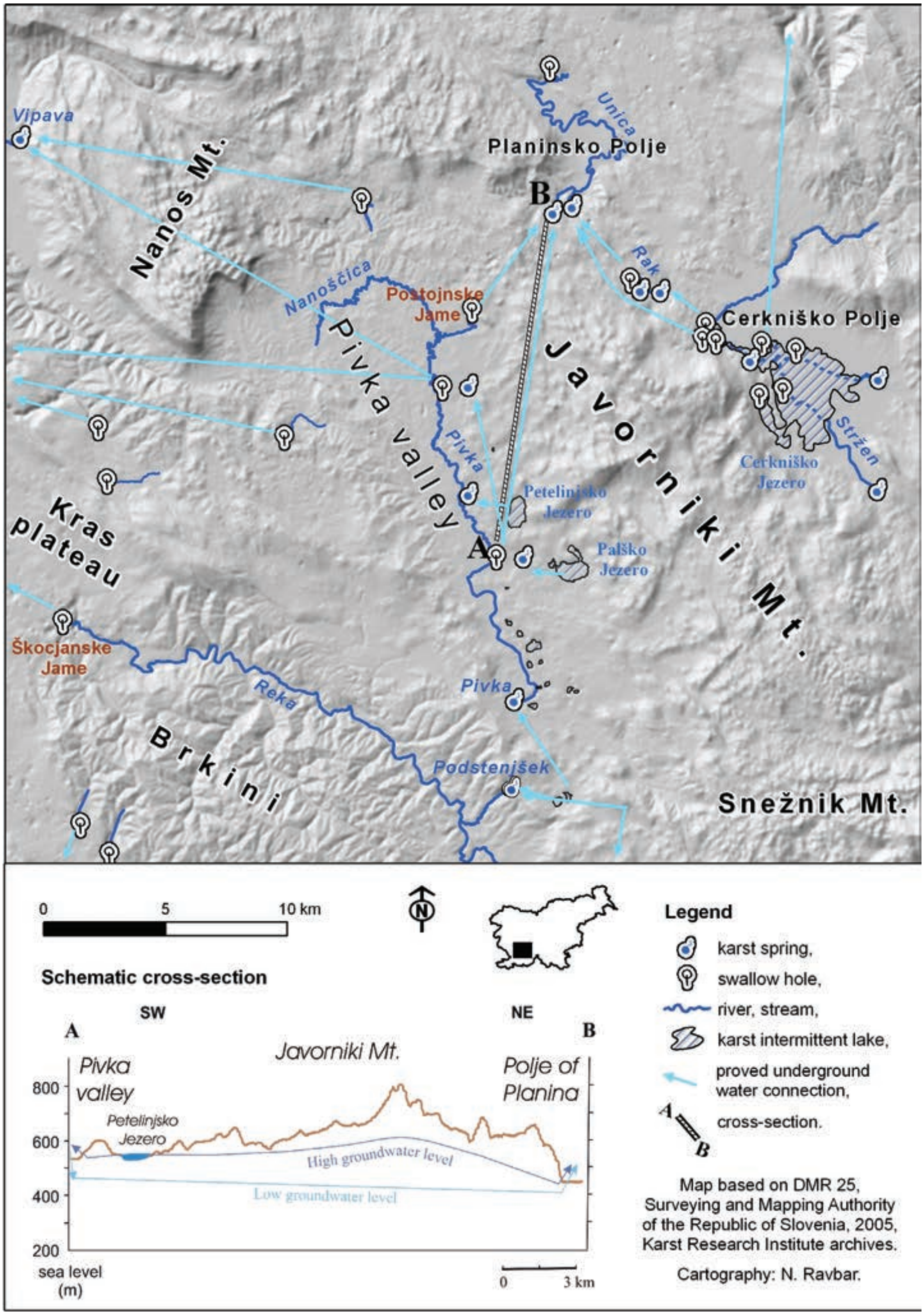


Figure 2.6: Hydrological map of the western Dinaric karst in Slovenia with some underground connections proved by tracer tests, and schematic section of the area during low- and high-water conditions with special emphasis on the Javorniki mountains, Cerkniško and Planinsko Polje and Pivka valley.

relative isolator forcing water to surface flow. Consequently, such areas are predominantly covered by thicker layers of alluvial deposits and soil.

Groundwater level in the southwestern Dinaric karst is inclined from southeast towards northwest and from east towards west (Habič, 1984). In the eastern Dinaric karst the direction of groundwater flow is very diverse, but mainly orientated towards the east. In general, groundwater outflow from the Dinaric karst is mainly controlled by younger, mostly Quaternary tectonic sinking in the border regions. Thus, it is oriented to the lower lying Gulf of Trieste and Friuli plain, as well as to the Soča, Ljubljanica, Krka and Kolpa river basins.

However, Dinaric karst is characterised by several sinking rivers, some of which reappear several times (Fig. 2.5). When flowing superficially they cross poljes, which are often flooded due to groundwater fluctuations. Several intermittent lakes of different size, duration and frequency consequently occur in this region. The largest one is the Cerkniško Jezero, which can extend over 25 km^2 and contains more than 28 million m^3 of water (Kranjc, 2003). Sinking rivers directly connected to springs also formed biggest Slovene cave systems (Postojnska Jama, Planinska Jama, Tkalca Jama, Zelške Jame, Predjama, Križna Jama, etc.).

In these karst systems very high groundwater level fluctuations can be observed. In the famous cave system of Škocjanske Jame water level can rise up to about 70-100 m above the average (Habe, 1966; Gospodarič, 1984). The highest variations, reaching up to 214 m, have been recorded in the nearby Gabranca cave (Margon, 2002).

Furthermore, flow bifurcations can be observed in several Dinaric karst areas, e.g. in Cerkniško Polje and the Pivka valley, which is located on the Adriatic-Black Sea watershed (Habič, 1989). The schematic section in figure 2.6 illustrates the groundwater level fluctuations in this area and consequent flow bifurcation. During low-water conditions, groundwater from the Javorniki mountains and Pivka valley drains towards the Planinsko Polje in the northeast. In wet periods water level rises and a groundwater divide forms below the Javorniki mountains so that a part of the area drains towards the Pivka valley in the southwest.

2.2.3 ISOLATED KARST

In comparison to the Alpine and Dinaric karst, Isolated karst is limited mainly to the isolated Mesozoic limestone and dolomite patches. Individual karst areas of small surfaces appear in the middle of non-karst rocks. Often the carbonate rock outcrops are formed in hills that are isolated on all sides. Also karst features are rare; there are no big underground rivers, caves are short and springs are rather small (Fig. 2.7).

However, even isolated carbonate outcrops are of significant importance for water supply. Many karst springs are captured for local drinking water supply. Nevertheless, their catchment areas are small and therefore particularly susceptible to contamination, especially because they are often situated among urbanized and industrialized areas

Figure 2.7: The Peklenščica river flowing out of the tourist cave Pekel (photo: N. Ravbar).

and/or in the areas of extensive agriculture. Due to the exceptional importance of these water sources for the local supply, these are particularly necessary to protect.

2.3 HUMAN IMPACT ON KARST WATER SOURCE QUALITY – EXAMPLES FROM SLOVENIA

In general, the quality of karst water sources in Slovenia is still relatively high. The wide areas of karst regions are either uninhabited or sparsely populated with almost no agricultural activities or only with traditional ones, which is very favourable for water protection. Therefore, the karst aquifers are often considered as an abundant high-quality drinking water resource.

In the Alps the population is very sparse and human activities are often seasonal, linked particularly with tourism and recreation. Potential and actual threats to the groundwater are predominantly the wastewaters from the mountain huts, ski-resorts, waste disposal dumps and roads. The biggest concentration of these activities is at areas easy of access.

In the Dinaric karst population density is higher on the low karst plateaux, the poljes and in the lowlands. On the contrary, high karst plateaux are generally wide woodlands with very scarce settlement. However, diverse types of hazards, coming from different human activities, threaten the groundwater quality in the Dinaric karst. The greatest contamination mainly derives from urban wastewaters, where sewage is not well regulated or not regulated at all. Some settlements also host most of the industrial activities and small farms. Agriculture is mainly extensive and arable farming is only a supplementary activity to the stockbreeding. Cattle and poultry breeding is characteristic.

Even though the physical environment of a karst aquifer may provide some degree of protection to groundwater with regard to contaminants entering the subsurface, the potential for natural protection is limited and extremely variable (Vrba and Zaporozec, 1994).

Several examples from Slovenia alone show that the response of the karst environment and its constituents to anthropogenic contamination is very specific and characteristically differs from that of other environments. Well-known is the case of the spill in the catchment area of the Rižana karst spring, which supplies the coastal area. In October 1994 there was an accident near Obrov, when 16 m^3 of engine fuel was spilt in the area of the spring's second protection zone, 15 km distant. A few days after heavier rain Rižana and some smaller springs were contaminated (Kogovšek, 1995) and the capture was expelled from the system for three weeks.

A year before, a road accident had happened near Kozina and 18 tons of oil and heating oil had flowed out. The accident happened closer to the spring, 10 km distant from Rižana in similar hydrogeological setting. However, the consequences of the accident were only detected in the nearby caves, but not in any of the springs in the vicinity (Knez *et al.*, 1994).

Another example was when there was an efflux of oil derivatives near Žužemberk. In a longer period in 1991, 30 m^3 of heating oil leaked out from a factory of chemical condensers. At first the contamination did not affect a nearby spring 200 m away. The leaked heating oil was detected in a karst channel near the factory and was floating on water. Afterwards the oil slowly flowed away, but the accident caused permanent contamination of the nearby spring (Kogovšek, 1996).

In October 1998 drinking water supply from the Globočec water source was cut off for a month because an unknown quantity of engine fuel flowed out. The dangerous substances flowed into the Tržiščica sinking river near Ortnek in the spring's catchment area (Fig. 2.8). Eight days (199 hours) after the accident and three days after abundant rains, increased concentration of engine fuel was detected in the spring (Kogovšek and Petrič, 2002).

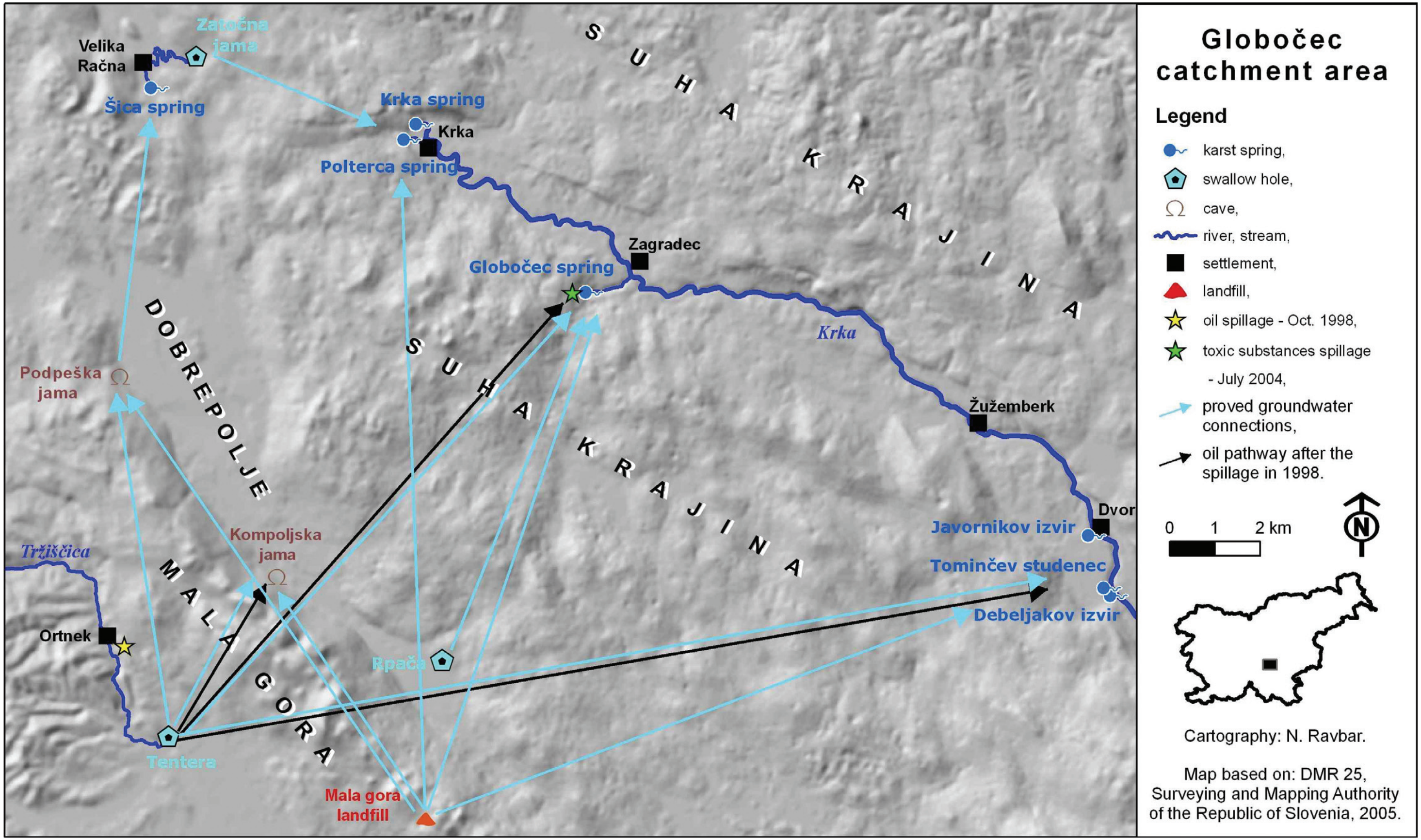


Figure 2.8: Sketch of the proved groundwater connections in the Globočec catchment area and places of the contamination events (after Novak, 1987; Kogovšek and Petrič, 2002; Kogovšek et al., 2005).

Figure 2.9: On the Velika Planina plateau pasturing has a certain impact on the karst water. Many of the pastoral houses have their own manure heaps that are unsecured and present serious hazards to the springs at the aquifer's margin (photo: N. Ravbar).

On the other hand in summer 2004 a group of individuals caused spillage of 4,000 litres of sulphuric acid and bark-liquor in the immediate vicinity of the Globočec spring. The place of spillage was 1,100 m horizontally and about 150 m of height difference distant from the spring. It was placed on the edge of a doline and heavy rains followed the event. Unfortunately the monitoring of the water quality began as late as two days after the spillage when the contamination might have already been drained out. Nevertheless, in the monitoring period no worsening of the water quality was detected (Ravbar, 2005a).

In the case of the Krupa spring, permanent contamination with PCBs has been detected since 1985 due to illegal dumping in the catchment (Polič *et al.*, 2000). This spring that represents the most important potential source of drinking water for whole Bela Krajina region is useless now.

Some serious potential hazards to the quality of karst groundwater can be found even in sparsely inhabited areas, as in the case of the Velika Planina (Fig. 2.9), Snežnik and Kanin karst plateaux where some signs of contamination have already been recorded in some of the springs, deriving mostly from sports, tourist, farming and construction activities (Komac, 2001; Kovačič and Ravbar, 2005b).

Any kind of contamination is a problem and should therefore be avoided. How-

Figure 2.10: Different human activities if unsecured pose a threat to karst groundwater – junk yard near Postojna in the immediate vicinity of the Malenščica water source (photo: N. Ravbar).

ever, especial effort in this direction should be made when a drinking water source is in question.

A better explanation of groundwater and contaminant movement, and the behaviour and reaction of karst to contamination could be achieved by understanding the flow of water through individual conduits. Indeed, karst systems are highly heterogeneous and anisotropic. Furthermore, each karst system has its individual characteristics.

Time, duration and intensity of contamination in case of deliberate or unintentional chemical or biological contamination in the catchment area can successfully be predicted only if we have a good knowledge of the geological and hydrological characteristics of the affected area. Thus detailed hydrogeological investigation and observations for individual water sources are necessary.

Transfer of contaminants does not depend on the characteristics of the aquifer alone but also on the characteristics of the contaminant. Some contaminants can behave differently from water; they react with the protective cover of soil, sediment or vegetation (if these are present) and with the rock through which it flows. It depends also on whether the substance is lighter or heavier than water and if it is soluble in water (Sinreich, 2004).

Since cleansing of contamination in karst is almost impossible or is only exceptionally effective, comprehension of the flow and transport processes of a certain contaminant at different hydrological conditions are also necessary.

Much more important and cheaper is prevention, which should include appropriate and careful management, as well as strict implementation of the restrictions. Unfortunately, the influences of anthropogenic activities on nature and human dependence on preservation of clean nature are often not clear to people. Therefore it is necessary to make them acquainted with the importance of sustainable management of the karst water sources (Fig. 2.10). Education of people and control over the implementation of regulations in water protection areas is therefore of exceptional importance.

3
KARST WATER SOURCES IN SLOVENIA

3.1 IMPORTANCE OF KARST WATER SOURCES

The present drinking water supply in Slovenia is based on capture of permanent and abundant springs or on pumping of groundwater. Each source supplies several tens of thousand inhabitants and the waterwork networks are, due to sparse settlement, usually several hundred kilometres long. On the other hand, sources of small water quantities are gradually losing their importance since the authorities are tending to abandon local catchments and to connect users to a regional water supply network (Ravbar, 2006).

In Slovenia large amount of water resource can be found as groundwater in the intergranular aquifers. Nevertheless, in some areas contamination of groundwater is

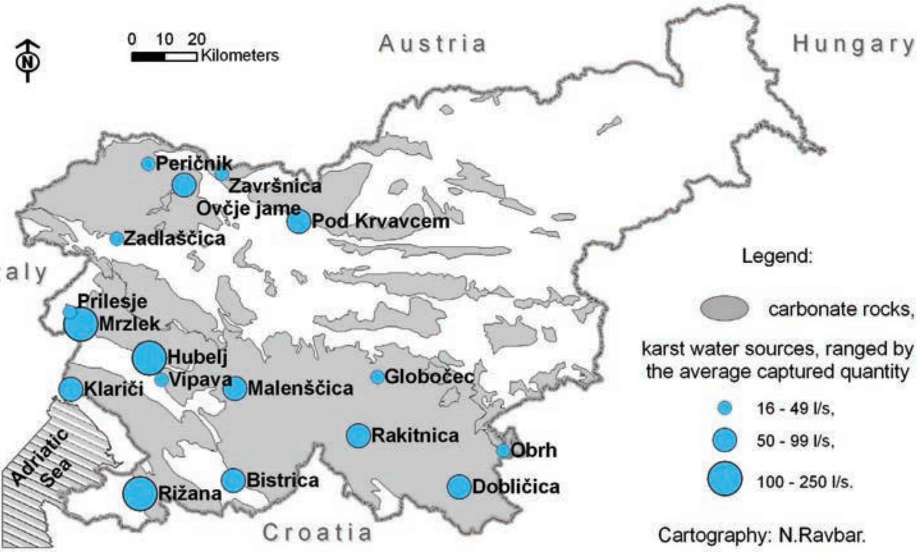


Figure 3.1: Schematic map showing the extent of carbonate rocks outcrops and some of the most important karst water sources.

very high and water levels are progressively falling. As an alternative, karst aquifers are becoming more and more important for regional and local drinking water supply.

Half of the country's needs are already covered by the capturing of karst water sources, but in the dry period of the year this amount reaches about two thirds of the total consumption (Brečko Grubar and Plut, 2001). Extensive areas on the western, southwestern, southern and southeastern parts of the country are almost entirely dependent on karst water sources (Fig. 3.1). Therefore in Slovenia karst aquifers are of special economic importance.

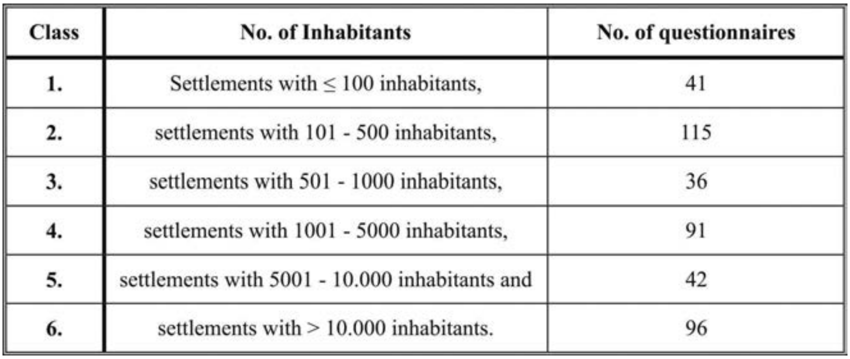
3.2 CONTEMPORARY DRINKING WATER CONSUMPTION - IN SOUTHWESTERN SLOVENIA

3.2.1 INTRODUCTORY REMARKS

One of the most important aspects of the sustainable management of the existing water resources in the long-term is thrifty consumption of water. To find out the common characteristics in water consumption, individuals' habits and attitude towards drinking water, we carried out a research in the frame of the international AQUADAPT project (2003) financed by the European Union. The aim of the project was to research and develop the knowledge for further strategic planning and management of water resources. The results of the research have been compared between different European regions in Spain, Great Britain, France and Slovenia. Here only the most relevant results on drinking water consumption in households are presented.

In Slovenia the southwestern part of the country, where karst sources contribute

Table 3.1: Settlement size classification and number of questionnaires completed in each class.



Class	No. of Inhabitants	No. of questionnaires
1.	Settlements with ≤ 100 inhabitants,	41
2.	settlements with 101 - 500 inhabitants,	115
3.	settlements with 501 - 1000 inhabitants,	36
4.	settlements with 1001 - 5000 inhabitants,	91
5.	settlements with 5001 - 10.000 inhabitants and	42
6.	settlements with > 10.000 inhabitants.	96

more than 95% of the total drinking water, has been chosen. In 2003 a detailed inquiry of 421 households was made.

The total number of questionnaires was primarily divided according to the number of inhabitants in an individual region of the existent regional typology (Gams, 1983). Afterwards altogether 64 settlements were selected according to their size and connection to public, local or individual water supply (Tab. 3.1). Within each class, settlements were randomly chosen (Fig. 3.2). The answers were entered into a computer database and were processed with MS Excel, MTI@SHS Pragma 5.07 and SPSS.

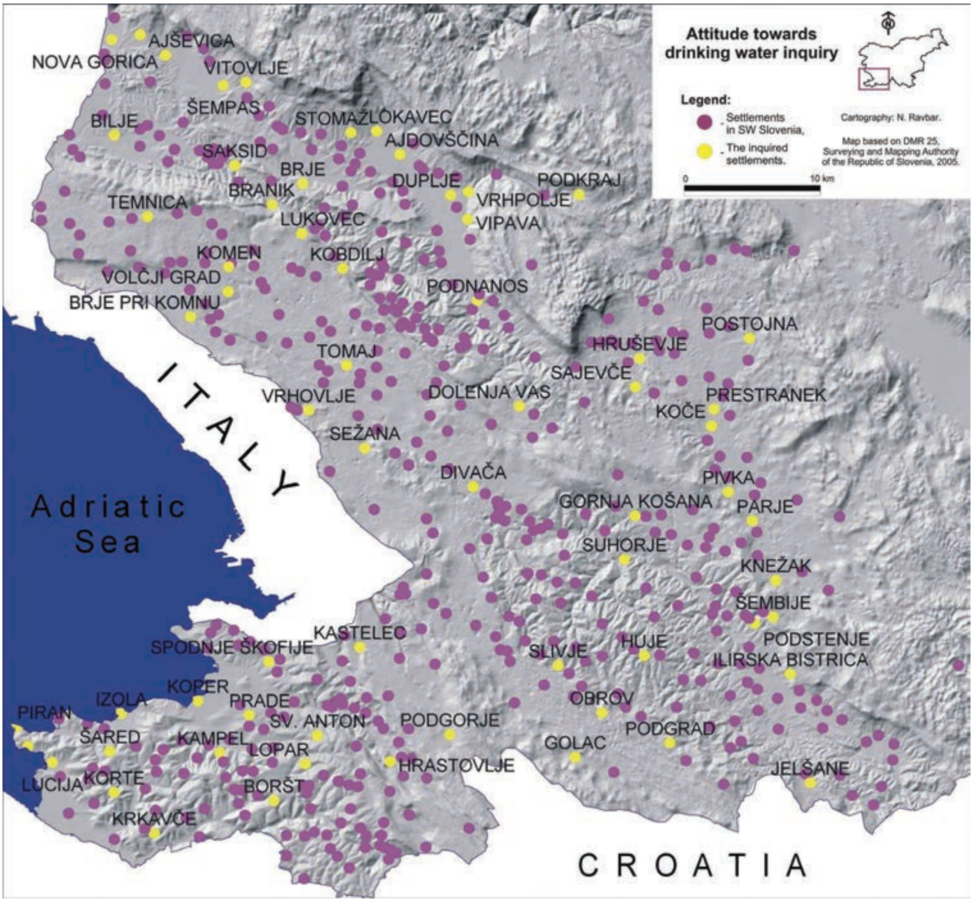


Figure 3.2: Settlements where the inquiry was carried out.

3.2.2 ATTITUDE TOWARDS DRINKING WATER

In Slovenia in terms of spatial planning the evaluation of natural heritage is not a priority especially regarding areas of great market value. The concern about nature becomes of the utmost anxiety only in case of conflicts between different land users and naturalists supported by media or in the case of a bigger ecological catastrophe.

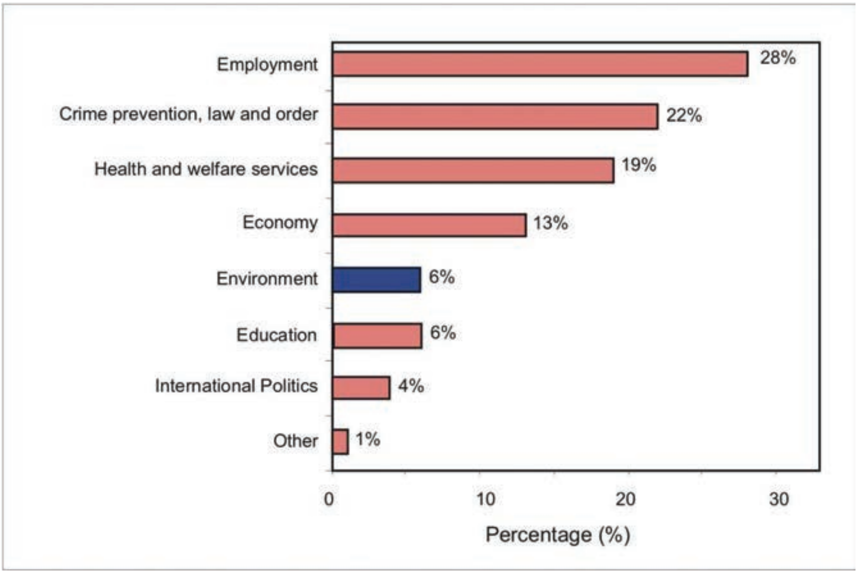


Figure 3.3: Environmental protection issue listed among some other socio-economic problems in the state.

The statement has been confirmed by the inquiry when the environmental protection issue has been considered as less alarming in comparison to some other socio-economic problems in the state. It has been listed in the fifth place together with education problems (Fig. 3.3). However, the problems connected to unemployment, crime, health and social protection have been ranked higher (Veljanovski and Ravbar, 2005).

The reasons for careless comprehension of the environmental value can mainly be found in the country's large areas of preserved nature and individuals' poor comprehension of the extensiveness and interaction of human influence on nature. However in Slovenia preserved nature and richness of ecosystems are self-evident. It is also believed that water in our country is abundant despite its spatial and temporal distribution.

People believe that numerous efficient karst springs present an inexhaustible source of quality drinking water, but a great portion of these have already been exploited, at least partly. Nevertheless, these sources could soon become useless due to careless conservation and negligent management as in the example of the Krupa river.

Answers to a question, 'how seriously the problems related to water are considered in comparison to other global issues', showed that most Slovene consumers are not aware

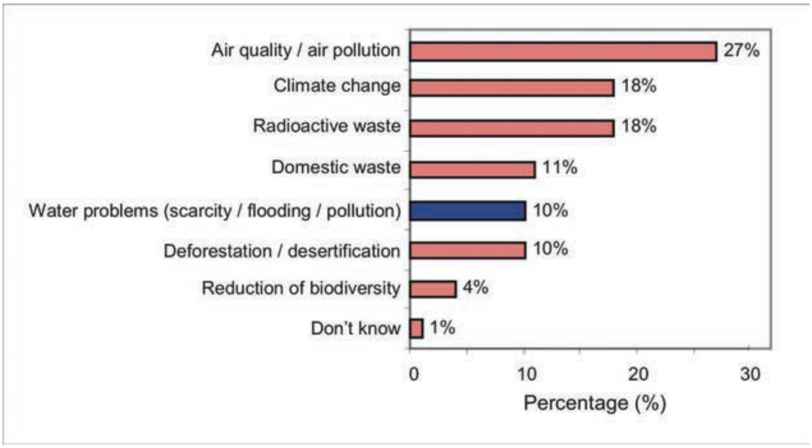


Figure 3.4: Problems concerning water ranged in comparison to other global issues.

of the importance of water resources and their management. Most of those asked considered that climate change and inadequate control over radioactive waste dumping raised the highest concerns (Veljanovski and Ravbar, 2005). They considered that problems connected with water (pollution, shortage, flooding) as well as cutting forests were less alarming despite that the research was done in extremely hot and dry summer time when the drought and leakage of drinking water were topical subjects (Fig. 3.4). Greatest concern for the environment can be found among the higher educated population and in urban societies.

Reflections of the underestimate of drinking water importance are the extremely negligent and unthrifty consumption. According to the household drinking water consumption research the average Slovene uses 130 to 150 l of water per day (Veljanovski

Table 3.2: The frequency assessment of performing the chosen activities that relate to the use of water in households.

Activity	Time period	Average number of activities
Washing the car at home	monthly	1
Use of washing machine	weekly	4
Use of dishwasher	weekly	5
Washing up dishes by hand	weekly	3
Showering	weekly	20
Bathing	weekly	4

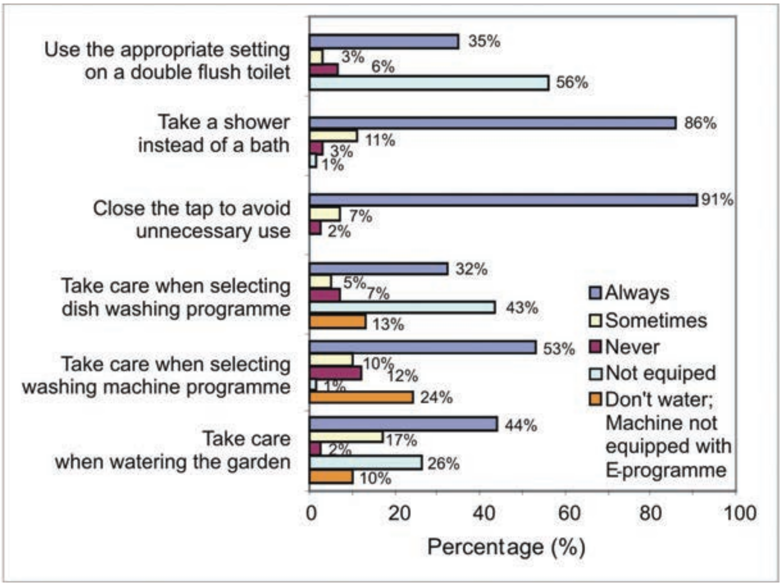


Figure 3.5: The actual deeds of individuals in order to save water (Veljanovski and Ravbar, 2005).

and Ravbar, 2005). The biggest quantities are used for flushing households' and toilets' waste. It has been estimated that for such purposes an individual uses 1.4 m^3 of water per month. Each day a person uses about 50 l of drinking water for flushing the toilets, which is one of the most inexpedient uses of drinking water.

The households use most of the water with the use of the washing machine. Nearly every household (98% of households) owns one that is on average used four times a week (Tab. 3.2). The dishwasher is used even more frequently, but only 56% of all households own one. A household uses 2.2 m^3 of water per month for washing. Furthermore, drinking water is additionally used for car washing and garden watering (Veljanovski and Ravbar, 2005).

In comparison with some other countries, the biggest consumption of water in households is in Spain – 265 litres per person per day. It is followed by Norway (224 l/person/day), the Netherlands (218 l/person/day) and France (164 l/person/day). The least consumption of drinking water is in Belgium (115 l/person/day), Estonia (100 l/person/day) and Lithuania (85 l/person/day) (The AQUADAPT project, 2003; Kazalci okolja 2003, 2004).

The actual deeds of individuals in order to save water in some aspects show care for drinking water, but in other aspects they are wholly contemptuous (Fig. 3.5). Namely, nine of ten asked always turn off the tap to avoid unnecessary use. Just as many also take a shower instead of a bath. Half of those asked always choose the economical programme for washing clothes, but only a third use the economical programme for washing the dishes.

Less than a half of the asked has installed double flushing system in a toilet, however only 35% also uses the advantages of this system in practice. In addition, 40% of the asked uses tap water for garden irrigation. Generally the most concerned are also the most active in water-saving behaviours (Veljanovski and Ravbar, 2005; Aledo *et al.*, 2006).

Those asked were also inquired about their willingness for alternatives to reduce drinking water consumption. Contemporary technology enables us to use filtered water from bathtubs and washbasins (so-called grey water) to flush the toilets. Even in cases when the water expenses in the households would not be lowered 71% of all asked would accept usage of lower quality water for flushing toilets. Mainly the costs of the installation and maintenance of the grey water system would prevent them deciding for filtered water usage (Veljanovski and Ravbar, 2005). Most who were willing to introduce technological changes in their households were from the Vipava valley, the Coastal region and from the Kras plateau.

Nevertheless, the results of the research show that the prices of water do not significantly influence the attitude of individuals' behaviour towards drinking water. If the water supply companies would introduce a system of double prices for water, which is already practised with electrical energy, half of the respondents would switch on household devices during the cheap periods. For each fifth household this would not be possible due to everyday circumstances, while one fourth of the households would not change their habits due to the double prices only. Even if the prices of water would increase for one quarter, 66% of those asked would still not change their habits (Veljanovski and Ravbar, 2005).

In general, the individuals of the southwestern part of Slovenia claim that they are willing to change their water consumption habits. However, the present drinking water price is in comparison to other living costs far too low, so that the consumers would considerably save by consuming less water.

3.2.3 WATER SOURCE MANAGEMENT AND ITS QUALITY

The development of the public water supply in Slovenia has in the past few decades had precedence over the other developmental goals. Therefore fewer and fewer people are dependent on capturing of rainwater or other local water sources. Even to some remote settlements with a small number of inhabitants a quality drinking water supply is being ensured. Even though it is not expressed in their attitude towards water, some, especially elder people still have a concern about the water deficiency.

A great part of the asked in Slovenia knows the origin of water supply in their homes, comparing to those in Spain, Great Britain and France. Nine out of ten know where the drinking water that runs from their taps come from and where the wastewater from their households runs to (Fig. 3.6). As many are also of the opinion that the management of water resources in their vicinity should be set as a priority in contrast to their general low interest for the environmental protection issue (Aledo *et al.*, 2006).

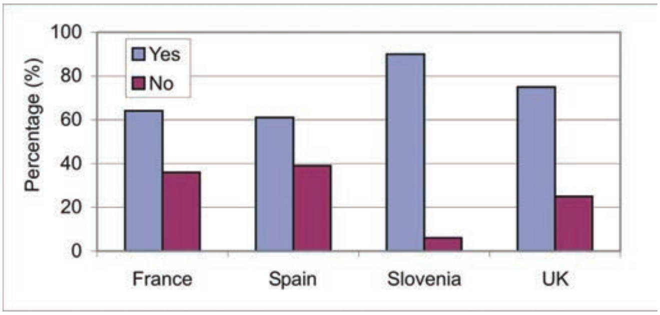


Figure 3.6: Percentage of the asked that know where their water is extracted. Comparison among the countries.

Nine of ten Slovenes questioned were of the opinion that in the future global pollution, climate change and local pollution (inadequate waste deposits, inadequate treatment of wastewater) will have the biggest negative affect upon the quality of the water resource in their region. They attribute considerably smaller danger to intensive industry and traffic or farming (Fig. 3.7). Nevertheless, this belief could only be the consequences of the media interest, which does not reflect the adequate understanding of the negative consequences of human careless treatment with drinking water resources. Additionally, half of those asked claimed that the water quality of their region had significantly deteriorated in the past ten years, while only one third stated that they did not notice any change (Veljanovski and Ravbar, 2005).

The fact is that in the future spatial planning in general and thus planning of water supply will have to consider the wishes, demands and solutions of the local users and not merely the solutions offered by professionals. However, only one third of all asked showed willingness to participate actively in public discussions regarding the management of water sources and the planning of the drinking water supply.

Most of the individuals asked (80%) trust their daily supplies of tap water and also drink it when they are at home. Only 9% consider tap water is of low quality giving the

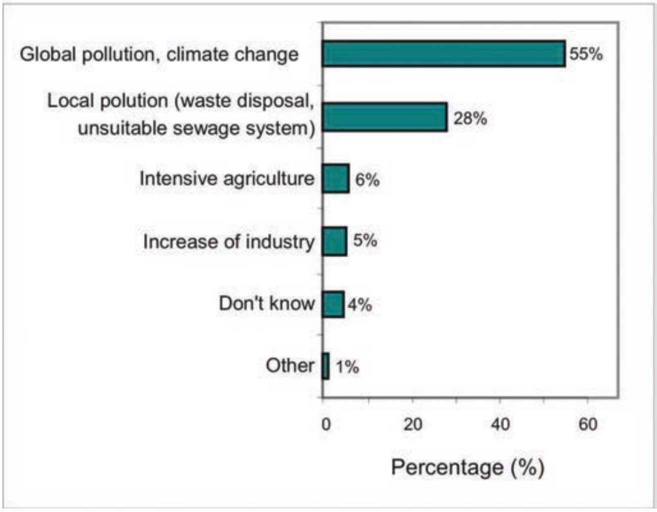


Figure 3.7: Opinion of the asked, which among the activities will most negatively influence drinking water resources in their region in the coming decades.

reasons that water is hard, has a bad taste, an unpleasant smell or that it is coloured. On the other hand, they were less concerned by the fact that tap water could be contaminated with nitrates, fertilisers, heavy metals and faeces. The most highly satisfied with the quality of tap water are those in the Vipava valley and in the Brkini hills and the least satisfied of all are on the Kras plateau.

In comparison to other studied areas, more than 80% of the British, 60% of French and only 36% of Spanish trust the quality of their daily supplies of tap water, which is characterized by significant water problems. The Spanish also think that they are very poorly informed of the quality of drinking water. In general, those most concerned and those who trust the quality of their daily supplies also drink water from the pipe. Tap water is drunk by 70% of British, 57% French and only 23% Spanish, according to those asked (Aledo *et al.*, 2006).

3.2 CONCLUSIONS

The droughts of the past years have been a warning that the state should have a reasonable strategy of capturing and usage of drinking water. Since the public supply of drinking water has been expanding, its consumption is constantly increasing. Even though the amounts of water used in households are lower in comparison to the amount in industry and agriculture, the quantities are not negligible. Therefore the results of the analysis can represent an additional basis for future water sources management. Making a detailed research of the water consumption in households, we obtained an insight into the individuals' habits and attitudes towards drinking water.

An economical and ecological solution for the assurance of adequate quality and quantity of drinking water (in the drought periods also) is in the first place based on economical consumption, which in the case of Slovene households is not satisfactory. With the inquiry we ascertained that most of the people support the protection of the environment and especially water sources; however, when forced to change habits or with restrictions interfering their everyday life, their enthusiasm decreases. Later also Smrekar (2006) made a very similar research in the city of Ljubljana and its vicinity and came to analogous conclusions.

In planning the future water supply, numerous other local water sources linked to traditional ways of water supply need to be considered. Eventual rainwater usage for garden irrigation or car washing, and purified wastewater usage for communal activity (street washing) or for the needs of farming and industry (as technological water) should not be excluded (Ravbar, 2005b).

4
PROTECTION OF WATER SOURCES

4.1 PRELIMINARY NOTE

Slovene karst sources are of great national importance for drinking water supply. Since karst aquifer systems are very susceptible to contamination, these sources require appropriate and careful managing. Nowadays the situation in the field of karst water protection management in Slovenia is, unfortunately, more or less a reflection of an old legislation. Despite relatively favourable conditions for karst water sources protection in Slovenia compared to some other karst areas elsewhere, many of them still remain insufficiently protected.

The reasons mainly originate in the disorder in the previous water protection policy. Furthermore, the existing Slovene legislation still has drawbacks in terms of consideration of special characteristics of water flow within karst regions. Subsequent reasons are also the conflicting interests in land use and a lack of knowledge about sustainable water management in karst regions.

4.2 SLOVENE LEGISLATION ON WATER SOURCE PROTECTION

Until recently, environmental acts for the protection of water sources and groundwater have been very general. However, with the independence of the country and its integration into European Union great progress in the environmental legislation has been made. Concerning drinking water sources only individual source protection has been enforced in Slovene legislation, but as in some other European countries no general resource protection policy has been provided so far.

Elaboration of the water protection zones and their regimes used to be provided by the old *Waters Act*, enacted in 1981 and its amendments. According to this *Act* (Ur.l. SRS 35/1981) local administrative agencies have been competent for water protection zones determination. This led to confusion in water sources protection for various reasons.

In the *Act* there was no legal basis set up for establishing a uniform methodology for the determination of water protection areas and regimes (Kovačič and Ravbar, 2005a).

Thus until recently several different methodologies have been enforced (Breznik, 1976; Janež, 1986, 1988, 1989, 1995; Rismal, 1993; Petauer and Veselič, 1997, 2000).

General characteristics of proposed methodologies for water source protection zones determination are the transfer time delineation criteria, which define different water protection zones, and the division of hydrological background. However, they differ markedly in their method for the determining the extent of individual protection zone, using different parameters. Due to the lack of sufficient data, the individual water protection zones were often not established on a solid hydrogeological basis, and were thus based only on available information on the geological structure. Nevertheless, for proper protection sufficient studies on source recharge, tracer tests in their catchments and other hydrological surveys are needed, especially in karst environments. Thus such protection zones could often be insufficient and may be ineffective (Ravbar and Kovačič, 2006a).

Catchment areas of individual captured springs or wells have consequently been protected on the basis of various approaches. As a result, non-comparable water protection zones and regimes exist. Thus while planning particular land use that extends over several different protected areas (e.g. roads, industry, etc.) difficulties can appear. Provisions of different sources protection areas are not unified and could for particular anthropogenic activity have diverse demands that would not be compatible (Prestor, 2002).

Protection zones often extend over several administrative areas. However, administrative borders between these communities hinder adequate protection. Due to the conflicts of interest between land users and/or in land use planning between neighbouring municipalities, protection zones of water sources where catchment areas spread into neighbouring municipalities and/or countries are not valid and therefore ineffective.

In the case of the Rižana karst spring (Fig. 4.1), which is tapped for the water supply of the Slovene coastal region, most of the second water protection zone extends over the neighbouring municipalities and even into the neighbouring country (Croatia) and hence the spring is not protected.

As with the Rižana karst spring, for the same reasons many other springs like the Malenščica, Bistrica and the Globečec springs are not suitably protected either. The Malenščica spring is the only source of drinking water supplying 20,000 inhabitants and the economy of the Postojna and Pivka municipalities. Even though the water protection zones have been delineated and the necessary provisions defined two decades ago (Habič, 1987), the required decrees have not been accepted due to the conflicting interests in land use.

The Globočec spring is a regionally significant water source, but is only protected in the administrative area of one municipality even though more than half of its influential area extends also to the neighbouring administrative areas (Ravbar, 2005a).

Nevertheless, even where the protection zones and regimes have been established, control over the implementation of the provisions has often been ineffective and the control over the contaminators has been relatively weak.

The example of the Bistrica karst spring illustrates some problems of water management in the area of an uninhabited Snežnik karst plateau, where sufficient protection zones have not yet been set up and water protection regulations have not been implemented properly (Kovačič, 2003a; Ravbar and Kovačič, 2006a).

Unfortunately, Slovene legislation on protection of water sources is in practice mostly only passive protective regulation requiring certain restrictions of the urbanization and other human development activities in the catchment area of a source. Suitable sewage drainage, clean industry development and temperate usage of fertilizers and other means used in agriculture are also prescribed (Prestor, 2002). Commonly three water protection zones are foreseen and are delineated by the contour lines. Only exceptionally a fourth zone is provided. In protection areas of lower degree stricter restrictions for the actual and potential activities are prescribed.

Recently water source protection has been based on the protection zones enacted by the new *Waters Act* (Ur.l. RS 67/2002) and by the derived *Rules on criteria for the designation of a water protection zone* (Ur.l. RS 64/2004). According to the new legislation that has been prepared in order to standardize the methodological approach and rules for defining the water protection zones the government and its institutions are responsible for establishment of protection areas and for ensuring the implementation of the provisions in each protection zone (Kovačič and Ravbar, 2005a). The present water protection policy has been in force for only a relatively short period of time, thus the majority of the karst source protection zones are based on the old legislation.

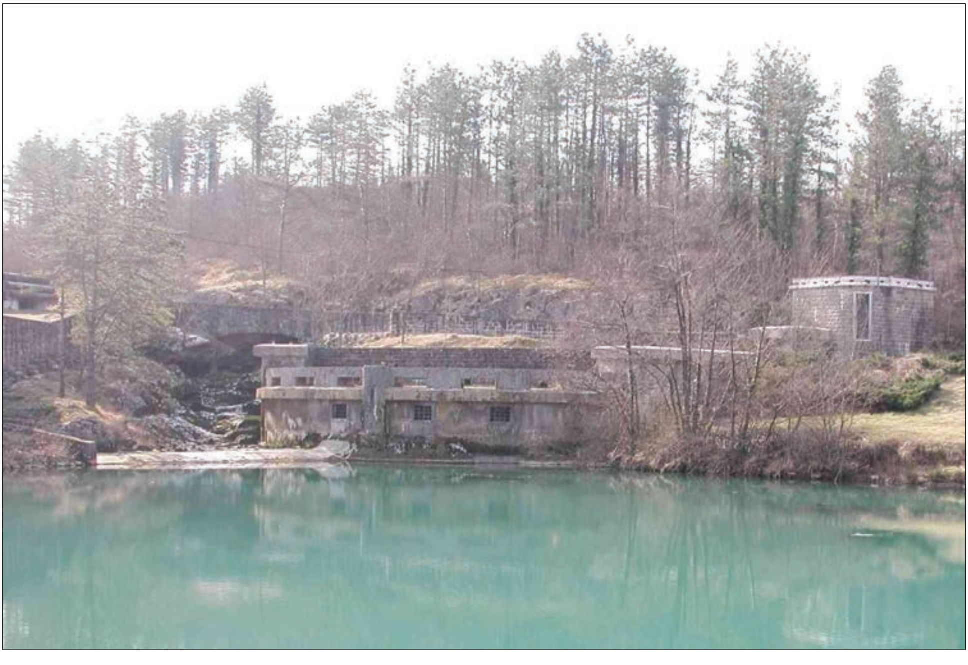


Figure 4.1: A part of the Rižana karst spring catchment area extends over neighbouring municipalities and even into the neighbouring country where, due to the conflicting interests in land use planning, the existing water protection zones are not valid (photo: N. Ravbar).

4.3 THE LEGISLATIVE RESPONSE TO THE KARST ENVIRONMENT

In Slovenia karst aquifers are mostly remote and densely wooded areas. Due to the relief and sometimes also due to unfavourable climatic conditions, karst areas are unpleasant for settlement and for the development of industry, traffic, agriculture or other activities. Despite relatively favourable circumstances for protection in comparison to conditions on karst areas worldwide, many of the karst water sources are still insufficiently protected. Furthermore, their protection is often neglected in land-use management.

Since not many previously established water protection zones have been adapted to the new legislation, some inadequately designated water protection zones are still valid. In the methodologies existing up to now, water protection areas have usually been very poorly defined. Particular protection zone delineation has been determined according to the available time for intervention respectively on the bases of travel time from the injection point towards the source. However, not all of the methodologies have provided tools for karst source protection though they have been commonly used for that purpose.

Also in the present Slovene legislation not enough attention has been devoted to the criteria for determination of karst water source protection. According to the regulations, the concept of karst water protection is still based only on the transfer time from the point of infiltration to the point of outflow (spring or well). Thus, crucial criteria for karst sources protection zones delineation include the flow velocities in the unsaturated zone and groundwater. The Outer Protection Zone coincides with the boundaries of the entire catchment area, while for the Inner Protection Zone delineation travel time of 12 hours has been used as main criteria (Ur.l. RS 64/2004).

However, evaluation of different flow velocities (contamination transport times) in a sense of water protection and spatial distribution of different values of flow velocities within the background of an outflow is rather challenging. The characterization of flow and solute (contaminant) transport mechanisms in heterogeneous karst aquifers (e.g. different values for diffuse and point recharge) could meet several problems as well (White, 2002; Perrin *et al.*, 2004).

Furthermore, where groundwater flow velocities are high, protection zones would cover large areas, often the entire catchment due to the groundwater flow velocities as the main criteria for the protection zoning. However, it is impossible to require a high protection for large areas. Such spatial planning would be unreasonable and not practical. Above all, in areas with great market value of the land, rigorous land use restrictions would be controversial (Ravbar, 2006).

Regarding the abovementioned *Rules* (Ur.l. RS 64/2004), the boundaries of water protection zones of karst aquifers should not only be determined on the basis of data on the velocities of karst groundwater, but also on information about the directions of groundwater flow, the depth of water table, the attenuation of actual and potential pollutants, the chemical characteristics of karst groundwater and the extent and karstification degree of the hydrological background.

The *Rules* (Ur.l. RS 64/2004) recommend several different methodologies for gathering these data. Carrying out a tracer test in the catchment area of a specific spring is not an obligatory one, though it is our opinion that it is one of the most appropriate hydrological methods providing results on the underground flow paths, hydraulic properties of the aquifer and a helpful tool to delineate the catchment area of the particular water source. Such a configuration of legislation, unfortunately, allows the possibility of less accurate delineation of particular water protection zones (Ravbar and Kovačič, 2006a).

Furthermore, groundwater velocities are not the only crucial aspects to determine higher/lower susceptibility of karst groundwater to contamination. Some other factors affecting the natural attenuation capacity of karst aquifers (function of protective cover, concentration of flow, karstification rate) are of at least the same importance (Brouyère *et al.*, 2001; Goldscheider and Popescu, 2004), but are still not properly included in the karst water protection legislation in Slovenia. However, for proper protection studies on source recharge, there is a need for tracer tests in their catchments and other hydrological research.

Particular susceptibility of karst systems to contamination that depends on the role of the protective cover, karst network development, alteration of hydrological boundaries of catchment areas at different hydrological conditions is not considered either. The present ineffectiveness and insufficiency of the karst water source protection result above all from the lack of knowledge about specific characteristics of particular karst aquifer behaviour.

One of the most unfavourable consequences of unregulated conditions in the field of water protection legislation is that there is still practically no control over potential and actual polluters of groundwater (Ravbar and Kovačič, 2006a).

4.4 VULNERABILITY AND RISK MAPPING AS AN ALTERNATIVE

The concept of groundwater vulnerability and risk mapping could be an alternative approach for successful protection zoning delineation and land use planning in karst (Daly *et al.*, 2002). Some experiences have already proved this concept to be a useful conceptual framework, which could be the basis for the establishment of water protection zones and regimes. In some countries respective vulnerability mapping approaches have also been integrated in the states' legislation. Nevertheless, the concept of intrinsic vulnerability assessment and mapping is not directly included in the methodology described in the *Rules* (Ur.l. RS 64/2004).

Furthermore, the intrinsic vulnerability only considers natural characteristic of an aquifer or catchment area, while the extent and degree of the human activities are not included. However, when planning particular land use and spatial development in future, it is essential to know if and where the degree of the anthropogenic impacts has already reached or even exceeded the natural self-cleaning capacity of karst aquifers/sources (De Ketelaere *et al.*, 2004).

It is important to consider the existing human activities in order not to lose important information, since the response of the karst environment to the certain future human intervention could depend to a great extent on the existing contamination. Therefore risk mapping should be applied, describing both the natural characteristics and the actual and/or potential hazards to the groundwater or water source (Hötzl, 2004; Neukum and Hötzl, 2007).

5

VULNERABILITY ASSESSMENT AND MAPPING

5.1 TERMINOLOGY

The term **vulnerability of groundwater to contamination** was introduced in the late 1960s, but no general definition and methodology for the construction of vulnerability maps has been agreed. COST Action 65 (1995) shows considerable variation in the definitions that had been proposed by then and in the usage of the vulnerability concept. Some researchers limited the definition to the intrinsic geological and hydrogeological characteristics of an area and others claimed that land use and management practices could also be included. Still others found that vulnerability depends on the properties of individual contaminants or group of contaminants, but is independent of specific land use (Gogu and Dassargues, 2001; COST Action 65, 1995).

Recently the most used definitions that have consequently been proposed by the COST Action 620 (Goldscheider, 2004) are the following (since this study mostly takes the achievements of the COST Action 620 project as a basis, it accepts the same definitions and concepts):

The term **vulnerability** of groundwater indicates the liability of a hydrological system to contamination respectively its neutralizing capacities against the contamination. It is used in the opposite sense to the natural protection of a hydrological system against the contamination.

As Zaporozec and Vrba (1994) previously suggested distinguishing between intrinsic and specific vulnerability, COST Action 620 (Goldscheider, 2004) uses the same division, but with a slightly different definition.

The term **intrinsic vulnerability** of groundwater to contaminants is the intrinsic characteristic of an environment, which determines its ability to reduce negative influences of contamination and to re-establish the equilibrium of the environment. It takes into account the geological, hydrological and hydrogeological characteristics of the area, but is independent of the nature of the contaminant and the contaminant scenario (Zaporozec and Vrba, 1994; Daly *et al.*, 2002; Goldscheider, 2004).

Travel and residence time of contaminants in the aquifer and their attenuation capacity are dependant upon the properties of each individual contaminant. Therefore the term **specific vulnerability** is used to define the vulnerability of groundwater to a particular contaminant. It takes into account the properties of a particular contaminant or group of contaminants and its interaction with the hydrogeological system (Sinreich *et al.*, 2004). COST Action 620 proposes specific vulnerability to be an additional weighting factor based on the intrinsic assessment and should be used in addition to intrinsic assessment.

Zaporozec and Vrba (1994) suggest the specific vulnerability should take into account the properties of the contaminant and the land use practices in addition to intrinsic properties. In contrast, according to COST Action 620 the specific vulnerability is independent of the land use practices. It is rather suggested to show the aspects of land use on separate hazard and risk maps (discussed in chapter 8).

According to COST Action 620 there are two general approaches in water protection: **resource** protection aims to protect the whole aquifer and **source** protection that aims to protect a particular spring or well (Goldscheider and Popescu, 2004).

5.2 THE CONCEPT OF VULNERABILITY

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide a certain degree of protection to groundwater. Vrba and Zaporozec (1994) emphasise that vulnerability is a relative, non-measurable and dimensionless property that is often considered as a qualitative notion.

However, according to the concept, proposed by the COST Action 620 (Brouyère, 2004; Daly *et al.*, 2004) the applied definition of vulnerability should provide end users information on (Fig. 5.1):

- the transit time of a contaminant to reach the target (most important),
- the contaminant concentration (important) and
- the duration of the contamination at the target (less important, optional aspect for specific purposes).

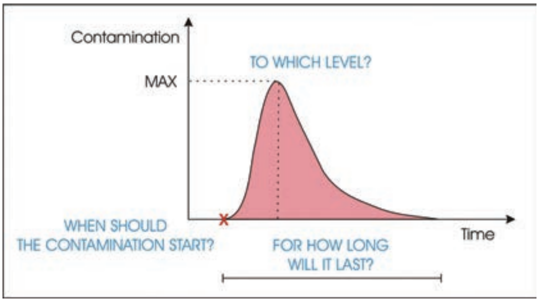


Figure 5.1: The three basic questions that have been initiated into the groundwater vulnerability mapping concept (Brouyère, 2004).

The fundamental idea is to show that the protection provided by the natural environment varies at different locations and thus subdivides the whole area into several units that have different degrees of vulnerability. Results of vulnerability assessment are portrayed on a map, using different colours to symbolize different degrees of vulnerability (Vrba and Zaporozec, 1994; Gogu and Dassargues, 2000).

Hence, the concept of groundwater vulnerability is relatively young. The first vulnerability mapping was made by Margat (1968) and Albinet and Margat (1970). On the basis of lithology they made a vulnerability map at a scale 1:1,000,000 for the territory of France. Vierhuff *et al.* (1981) made a vulnerability map of the same scale for the territory of Western Germany.

Since then several different methodologies have been developed regarding the differences between particular karst aquifer systems, data availability and economic resources. In addition, these methods have been many times tested and implemented in different test sites worldwide. Overviews of some of the most commonly used ones have been prepared by Cività (1993), Zaporozec and Vrba (1994), COST Action 65 (1995), Gogu and Dassargues (2000), Magiera (2000), Goldscheider (2002) and Zwahlen (2004).

The examination of scientific literature shows considerable variations among the methodologies with regard to purpose, reason and objectives of vulnerability mapping usage (Goldscheider, 2002). These differ for various criteria, such as scale (local, regional, national), purpose (land use planning, protection zoning) and objectives (intrinsic/specific vulnerability, source/resource vulnerability).

Vrba and Cività (1994) differentiate three major groups of vulnerability methods:
- hydrogeological complex and setting methods (partially DRASTIC),
- parametric system methods (e.g. GOD, DRASTIC, EPIK),
- analogical relations and numerical models (e.g. AVI).

Instead of the latter group Goldscheider (2002) distinguishes index models and analogical relations and in addition adds two supplementary groups:
- mathematical models (e.g. VULK) and
- statistical methods.

Regarding the differences in water flow characteristics within particular aquifer systems different methods can be differentiated:
- methods exclusively adequate to intergranular aquifers (e.g. DRASTIC),
- methods adequate to all types of aquifers but providing methodological tools for karst aquifers (e.g. PI) and
- methods taking into account specific properties of karst aquifer systems (e.g. EPIK).

Hence, the concept of groundwater vulnerability mapping is not restricted to karst. However, since karst aquifers need special protection for the previously mentioned reasons, this concept is most relevant when applied to karst landscapes. Due to heterogeneity of carbonate aquifer systems it is also most complicated when applied to karst (Goldscheider, 2005). Although the concept of groundwater vulnerability is applicable for all types of aquifers it is, due to the special properties of karst aquifers, essential to include characteristics of water flow within karst hydrological systems into the concept.

Groundwater and/or source vulnerability maps are thus practical tools for land use management and protection zoning since the main purpose of vulnerability mapping is to identify the most vulnerable areas and to prioritise those (Vrba and Zaporozec, 1994). In some of the countries, the concept of groundwater vulnerability mapping has been successfully used for protection zone delineation and land use planning. However, in some of the countries respective vulnerability mapping approaches have been integrated in the state legislation e.g. the Irish method in Ireland (Groundwater Protection Schemes, 1999), the SINTACS method in Italy (Cività and De Maio, 1997). The EPIK method (Doerfliger and Zwahlen, 1998) has been integrated in Swiss legislation only for karst sources. The GLA method (Hölting *et al.*, 1995) is a supplement to the German groundwater protection schemes.

5.3 OVERVIEW OF SOME BASIC METHODS

Nowadays various methodologies are in use to assess either vulnerability of groundwater in general or vulnerability of the respective wells and karst springs tapped for the water supply. So far most frequently used methods are DRASTIC (Aller *et al.*, 1987), GOD (Foster, 1987), EPIK (Doerfliger and Zwahlen, 1998), SINTACS (Cività and De Maio, 1997), PI (Goldscheider *et al.*, 2000), VULK (Jeannin *et al.*, 2001), the European Approach (Daly *et al.*, 2002) and others.

The first existing method with special consideration to karst aquifers was the EPIK method (Doerfliger and Zwahlen, 1998), which strongly influenced the later ones. Soon afterwards the PI method was proposed (Goldscheider *et al.*, 2000), the method that could be applied to non-karst aquifers but including tools for karst aquifers vulnerability assessment as well.

Due to the European Framework Directive demanding member states to develop and implement the aquatic environment, the European Commission set up the COST Action 620 programme (COST stands for Cooperation in Science and Technology) entitled *Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers*. Within the programme, 51 specialists from 15 European countries were brought together to consider holistically the specific behaviour of carbonate aquifers and their particular sensitivity to anthropogenic impacts. Different working groups were tasked with the development of an improved and consistent approach for the protection of karst groundwater called the European Approach (Zwahlen, 2004) even though some previous attempts trending to the same goal had already been made.

Hence it followed that individual groups and individuals within the COST Action 620 have taken this approach as the basis for the particular methodology development. Consequently several usable methods appropriate to the particular karst terrain such as LEA, COP method, the Time-Input method and VULK have been developed (Zwahlen, 2004).

Within this research the methods applied to the test site and the methods that influenced the proposed Slovene Approach to a greater extent are described in more detail: the EPIK method, the PI method, the SINTACS method, the Irish method, the European Approach, the COP method and the Simplified method.

5.3.1 THE EPIK METHOD

The EPIK method is a multiparameter method for intrinsic vulnerability mapping with special respect to hydrological characteristics in karst aquifers (Doerfliger, 1996; Doerfliger and Zwahlen, 1998; Doerfliger *et al.*, 1999). So far it is one of rare existing methods developed for karst source vulnerability assessment (except for the VULK and the VURAAS methods). Four parameters are taken into account: development of the epikarst (E), effectiveness of the protective cover (P), infiltration conditions (I) and development of karst network (K).

Each parameter is given a ranking index and a weighting coefficient is then attributed to each of the indexed parameters according to their degree of protection. By adding the protection values of each parameter a protection index (F) is calculated (Fig. 5.2). The final values are subdivided into four classes of vulnerability and can be used to establish protection zones.

The EPIK method has been tested in many test sites and applied in many karst types all over the world. Moreover, it has been introduced into the Swiss environmental legislation for the source protection zones delineation.

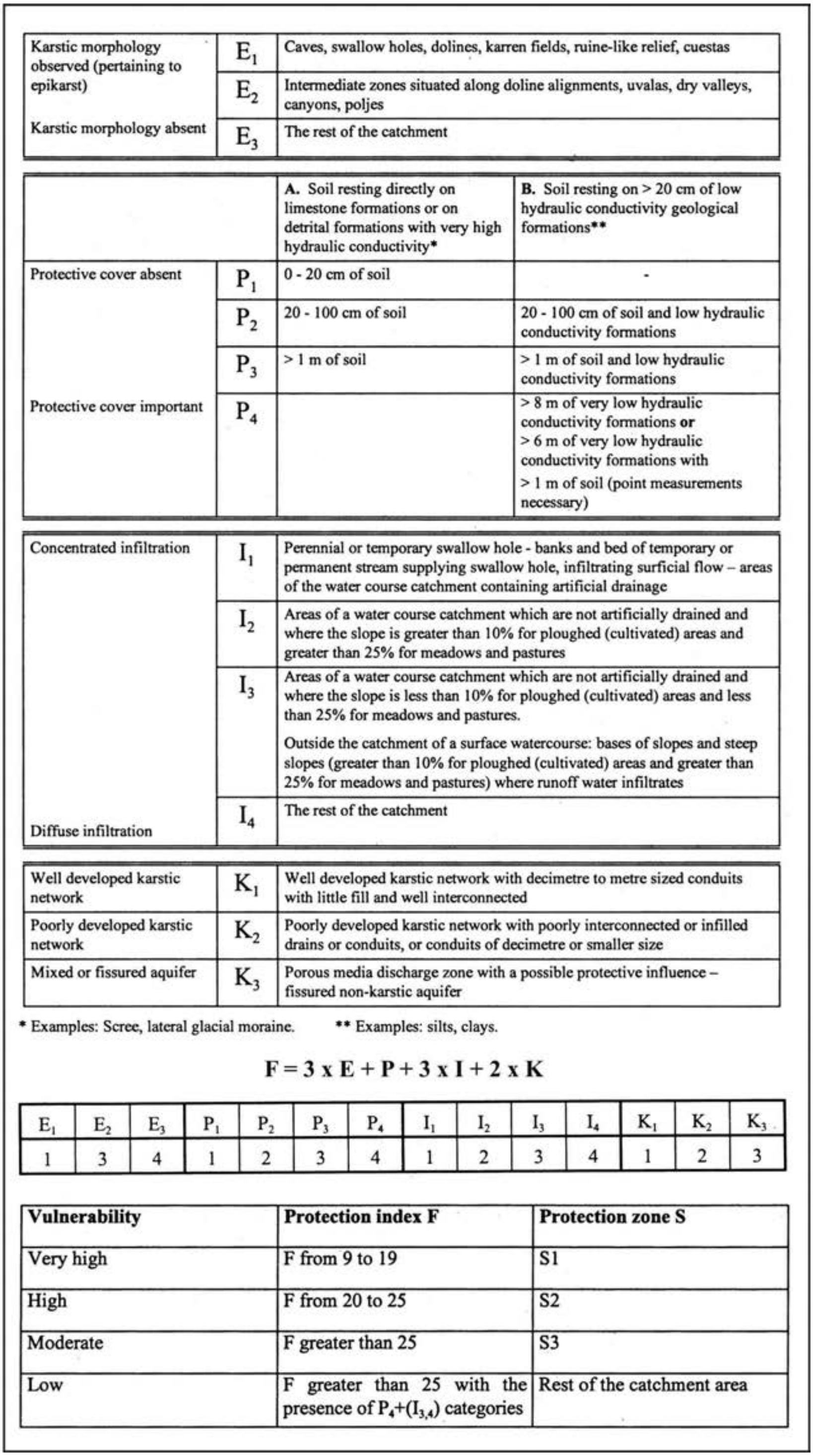
The evaluation of the E parameter is mainly based on the karst morphology observation and is subdivided into three categories indicating decreasing vulnerability. The most vulnerable areas are assigned to swallow holes, dolines and other depressions, karrenfields and fractured outcrops, as well as quarries and outcrops along the roads or railways. The medium vulnerability indicates the intermediate zones along these features and the lowest vulnerability indicates the rest of the catchment.

The EPIK method requires relatively simple information on the protective cover, which is including both soil cover and other geological formations. Only the protective cover thickness is considered. In order to classify the P parameter two cases are proposed according to whether or not low hydraulic conductivity geological formations occur below the soil. The thicker the protective cover the lower is vulnerability.

The evaluation of infiltration conditions is based on the identification of zones of concentrated infiltration (permanent or temporary swallow holes and sinking streams) and diffuse infiltration areas. Areas with diffuse infiltration are considered to be less vulnerable than areas of concentrated infiltration. The areas of diffuse infiltration are then differentiated by the slope gradients and land use. However, the method only distinguishes between arable areas and meadows/pastures, but does not provide instructions how to consider areas like forested areas, urban areas, etc.

The presence or absence of karst network and the degree of network development is evaluated in terms of several different direct and indirect indicators: speleological and geomorphological characteristics, tracer test interpretation, spring hydrograph and water quality variability analyses.

The EPIK method is quite easy to apply and also user friendly. Nevertheless it is only applicable for small catchments and only for source vulnerability mapping. Moreover, there is a question if the gained results are correct. Goldscheider (2002) already



Karstic morphology observed (pertaining to epikarst)	E_1	Caves, swallow holes, dolines, karren fields, ruine-like relief, cuestas
	E_2	Intermediate zones situated along doline alignments, uvalas, dry valleys, canyons, poljes
Karstic morphology absent	E_3	The rest of the catchment

		A. Soil resting directly on limestone formations or on detrital formations with very high hydraulic conductivity*	**B.** Soil resting on > 20 cm of low hydraulic conductivity geological formations**
Protective cover absent	P_1	0 - 20 cm of soil	-
	P_2	20 - 100 cm of soil	20 - 100 cm of soil and low hydraulic conductivity formations
	P_3	> 1 m of soil	> 1 m of soil and low hydraulic conductivity formations
Protective cover important	P_4		> 8 m of very low hydraulic conductivity formations **or** > 6 m of very low hydraulic conductivity formations with > 1 m of soil (point measurements necessary)

Concentrated infiltration	I_1	Perennial or temporary swallow hole - banks and bed of temporary or permanent stream supplying swallow hole, infiltrating surficial flow – areas of the water course catchment containing artificial drainage
	I_2	Areas of a water course catchment which are not artificially drained and where the slope is greater than 10% for ploughed (cultivated) areas and greater than 25% for meadows and pastures
	I_3	Areas of a water course catchment which are not artificially drained and where the slope is less than 10% for ploughed (cultivated) areas and less than 25% for meadows and pastures. Outside the catchment of a surface watercourse: bases of slopes and steep slopes (greater than 10% for ploughed (cultivated) areas and greater than 25% for meadows and pastures) where runoff water infiltrates
Diffuse infiltration	I_4	The rest of the catchment

Well developed karstic network	K_1	Well developed karstic network with decimetre to metre sized conduits with little fill and well interconnected
Poorly developed karstic network	K_2	Poorly developed karstic network with poorly interconnected or infilled drains or conduits, or conduits of decimetre or smaller size
Mixed or fissured aquifer	K_3	Porous media discharge zone with a possible protective influence – fissured non-karstic aquifer

* Examples: Scree, lateral glacial moraine. ** Examples: silts, clays.

$$F = 3 \times E + P + 3 \times I + 2 \times K$$

E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

Vulnerability	**Protection index F**	**Protection zone S**
Very high	F from 9 to 19	S1
High	F from 20 to 25	S2
Moderate	F greater than 25	S3
Low	F greater than 25 with the presence of $P_4+(I_{3,4})$ categories	Rest of the catchment area

Figure 5.2: Evaluation of the four EPIK parameters, calculation of the protection index and its transformation into the protection zones (Doerfliger and Zwahlen, 1998).

exposed some weaknesses concerning methods inconsistencies. The critical remarks refer to incomplete evaluation of the E factor, since epikarst existence is not always easily recognizable only by the surface karst features. Furthermore, the consideration of different recharge conditions and the thickness of the unsaturated zone are missing. There are also some discrepancies concerning contradictory attributes values and weighting system, so that the results could lead to inconsistent results.

5.3.2 THE PI METHOD

The PI method was developed before the European Approach and uses the same conceptual model and factors as it, but slightly different nomenclature (Goldscheider *et al.*, 2000; Goldscheider, 2002). The method is grounded on the GLA, the Irish and the EPIK methods. It is based on the assessment of the protective function of the layers above the saturated zone (P) and the infiltration conditions (I) in order to produce the final protection factor (Fig. 5.3). These two factors correspond to the O and C factors of the European Approach.

The effectiveness of the protective cover is based on the slightly modified version of the GLA method. It takes into account the lithological properties of the unsaturated zone and the degree of fracturing, as well as epikarst development and confined situation of the aquifer in order to describe its influence on groundwater vulnerability. In contrast to some other methods, the PI method does not require individual karst feature mapping (e.g. karren, caves, dry valleys), asserting that the epikarst zone can be highly developed also without any visible karst features as well.

A greater importance is assigned to the subsoil and topsoil characteristics. The annual recharge amount is considered as well. The topsoil parameter is quantified taking into account the effective field capacity eFC down to a depth of 1 m. The subsoil parameter is quantified taking into account the grain size distribution of the subsoil horizon multiplied by the depth of each horizon.

The parameter indicating the infiltration conditions shows the degree to which the protective cover is bypassed. The determination of the infiltration conditions requires the dominant flow processes assessment, the vegetation cover and the slope gradient, as well as mapping of swallow holes, sinking streams and their catchments. The dominant flow process is assessed on the basis of the topsoil permeability and presence of low permeability layers.

Both parameters are combined in order to yield a vulnerability map. The protection factor is calculated by multiplying the P and I factors. The final values are subdivided in five classes of natural protection and vulnerability respectively.

The PI method is applicable to all types of aquifers and provides special methodological tools for karst. It considers the groundwater as a target, therefore it is appropriate for resource vulnerability mapping. The PI vulnerability map combined with an aquifer map can be used for source protection as the Irish method does (Goldscheider, 2002).

Topsoil - T

eFC [mm] up to 1 m depth	T
> 250	750
> 200-250	500
> 140-200	250
> 90-140	125
> 50-90	50
< 50	0

Recharge - R

Recharge [mm/y]	R
0-100	1.75
>100-200	1.50
>200-300	1.25
>300-400	1.00
>400	0.75

Subsoil - S

Type of subsoil (grain size distribution)	S
clay	500
loamy clay, slightly silty clay	400
slightly sandy clay	350
silty clay, clayey silty loam	320
clayey loam	300
very silty clay, sandy clay	270
very loamy silt	250
slightly clayey loam, clayey silty loam	240
very clayey silt, silty loam	220
very sandy clay, sandy silty loam, slightly sandy loam, loamy silt, clayey silt	200
sandy loam, slightly loamy silt	180
slightly clayey silt, sandy loamy silt, silt, very sandy loam	160

Type of subsoil (grain size distribution)	S
very clayey sand, clayey sand, loamy silty sand	140
sandy silt, very loamy sand	120
loamy sand, very silty sand	90
slightly clayey sand, silty sand, sandy clayey gravel	75
slightly loamy sand, sandy silty gravel	60
slightly silty sand, slightly silty sand with gravel	50
sand	25
sand with gravel, sandy gravel	10
gravel, gravel with breccia	5
non-lithified volcanic material (pyroklastica)	200
peat	400
sapropel	300

Lithology - L

Lithology	L
claystone, slate, marl, siltstone	20
sandstone, quarzite, volcanic rock plutonite, metamorphite	15
porous sandstone, porous volcanic rock (e.g. tuff)	10
conglomerate, breccia, limestone, dolomitic rock, gypsum rock	5

Fracturing - F

Fracturing	F
non-jointed	25.0
slightly jointed	4.0
moderately jointed, slightly karstified or karst features completely sealed	1.0
moderately karstic or karst features mostly sealed	0.5
strongly fractured or strongly karstified and not sealed	0.3
Epikarst strongly developed, not sealed	0.0
not known	1.0

Thickness of each stratum in [m] - M

Bedrock - B
$B = L \cdot F$

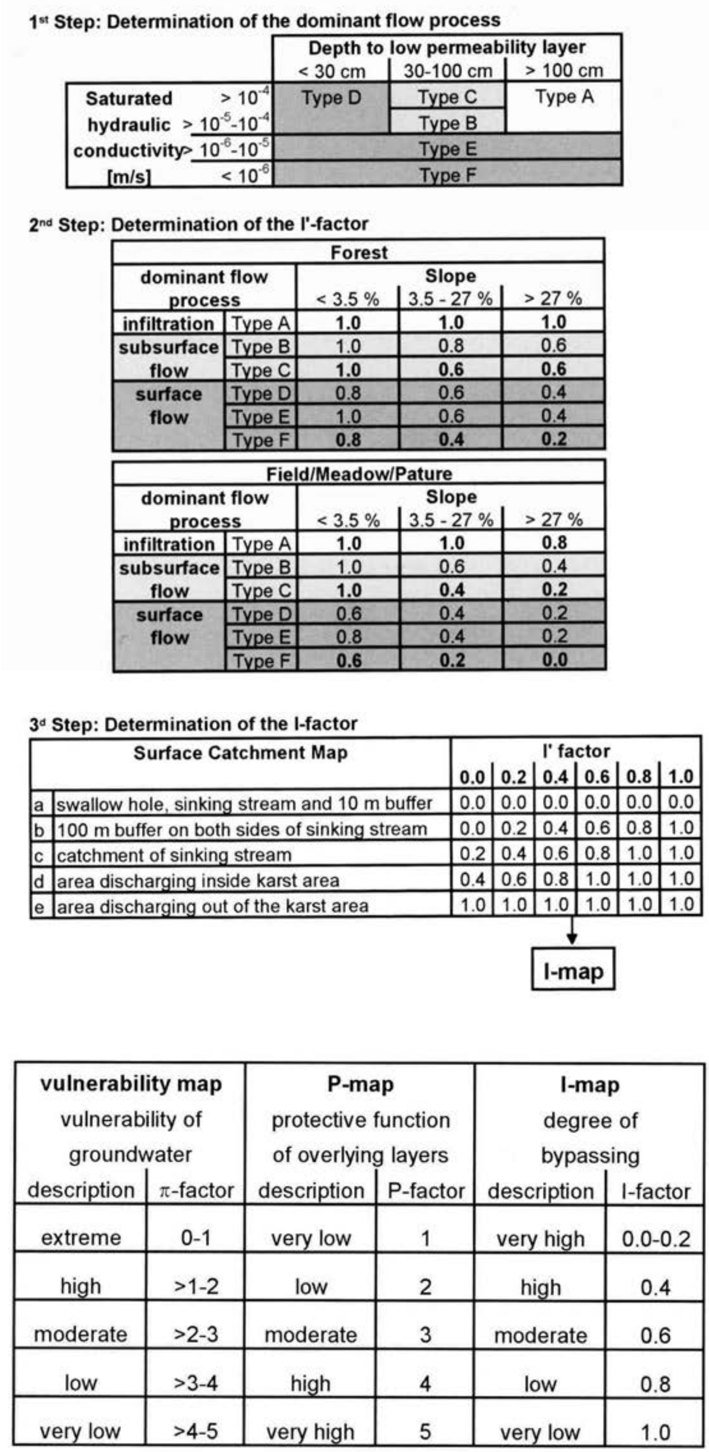
Artesian pressure A
1500 points

Total protective function P_{TS}

$$P_{TS} = \left[T + \left(\sum_{i=1}^{m} S_i \cdot M_i + \sum_{j=1}^{n} B_j \cdot M_j \right) \right] \cdot R + A$$

score P_{TS}	effectiveness of protective cover	P-factor	example
0-10	very low	**1**	0-2 m gravel
>10-100	low	**2**	1-10 m sand with gravel
>100-1000	medium	**3**	2-20 m slightly silty sand
>1000-10000	high	**4**	2-20 m clay
>10000	very high	**5**	> 20 m clay

P-map



1st Step: Determination of the dominant flow process

Saturated hydraulic conductivity [m/s]		Depth to low permeability layer < 30 cm	Depth to low permeability layer 30-100 cm	Depth to low permeability layer > 100 cm
	$> 10^{-4}$	Type D	Type C	Type A
	$> 10^{-5}$-10^{-4}		Type B	
	$> 10^{-6}$-10^{-5}	Type E		
	$< 10^{-6}$	Type F		

2nd Step: Determination of the I'-factor

Forest

dominant flow process		Slope < 3.5 %	Slope 3.5 - 27 %	Slope > 27 %
infiltration	Type A	1.0	1.0	1.0
subsurface flow	Type B	1.0	0.8	0.6
	Type C	1.0	0.6	0.6
surface flow	Type D	0.8	0.6	0.4
	Type E	1.0	0.6	0.4
	Type F	0.8	0.4	0.2

Field/Meadow/Pature

dominant flow process		Slope < 3.5 %	Slope 3.5 - 27 %	Slope > 27 %
infiltration	Type A	1.0	1.0	0.8
subsurface flow	Type B	1.0	0.6	0.4
	Type C	1.0	0.4	0.2
surface flow	Type D	0.6	0.4	0.2
	Type E	0.8	0.4	0.2
	Type F	0.6	0.2	0.0

3d Step: Determination of the I-factor

Surface Catchment Map		I' factor 0.0	0.2	0.4	0.6	0.8	1.0
a	swallow hole, sinking stream and 10 m buffer	0.0	0.0	0.0	0.0	0.0	0.0
b	100 m buffer on both sides of sinking stream	0.0	0.2	0.4	0.6	0.8	1.0
c	catchment of sinking stream	0.2	0.4	0.6	0.8	1.0	1.0
d	area discharging inside karst area	0.4	0.6	0.8	1.0	1.0	1.0
e	area discharging out of the karst area	1.0	1.0	1.0	1.0	1.0	1.0

vulnerability map vulnerability of groundwater		P-map protective function of overlying layers		I-map degree of bypassing	
description	π-factor	description	P-factor	description	I-factor
extreme	0-1	very low	1	very high	0.0-0.2
high	>1-2	low	2	high	0.4
moderate	>2-3	moderate	3	moderate	0.6
low	>3-4	high	4	low	0.8
very low	>4-5	very high	5	very low	1.0

Figure 5.3: Assessment of the P and I parameters, as well as the PI vulnerability map assessment (Goldscheider, 2002).

Even though the PI method uses a minimum number of factors, the assessment of both factors requires rather a large amount of qualitative database.

The PI method is one of the most frequently applied ones and the results have been proved to be consistent in most cases. However, overview of the PI method applications shows that score ranges of the total protective function propose very wide classes (Cichocki *et al.*, 2004; Schmidt, 2004). On the other hand, in areas of extremely developed epikarst independent of the unsaturated zone thickness large areas are classified as "very high" vulnerability (Andreo *et al.*, 2006). As a consequence, the over- or underestimation of the effectiveness of the protective cover might result.

5.3.3 THE SINTACS METHOD

The SINTACS method (Cività and De Maio, 1997) has been introduced into the Slovene groundwater risk assessment expertise (Strokovne podlage …, 2002). Thus, we shortly describe it.

The SINTACS method is a Point Count System Model, developed for Italian circumstances. It takes into account the same seven factors as the DRASTIC method (depth to groundwater, effective infiltration, soil attenuation capacity, unsaturated zone attenuation capacity, hydrogeological characteristics of an aquifer, hydraulic conductivity of an aquifer and topography), but different weighting and rating procedure is considered. Thus, it takes into account the characteristics of the overlying layers thickness and permeability, topography, as well as recharge conditions. However, in many applications, especially to karst aquifer systems, the need to modification and adaptation of the parameters has been demonstrated (Cucchi *et al.*, 2000; Ayub *et al.*, 2001; Longo *et al.*, 2001; Janža and Prestor, 2002; Cucchi *et al.*, 2004).

In comparison to some other methods the SINTACS method takes into account quite large number of parameters, which are according to the degree of vulnerability classified from 1 to 10 (the higher the value the higher the vulnerability). Each of the parameters weighting values in a range from 1 to 5 is assigned.

The method requires large amount of data. This, however, limits the applicability, as very rarely large amount of data is available. Particularly scarce are data in remote and mountainous karst areas. Additionally, the method requires grid input information, which is not very appropriate for the application on karst areas, since karst aquifers are very heterogeneous.

Generally, one of the most significant parameters in vulnerability assessment is the recharge type of an aquifer. Beside diffuse infiltration, karst groundwater is often recharged by the concentrated point inflow of surface water via swallow holes. The SINTACS method does not consider different types of infiltration. It also does not consider karst features, like dolines, swallow holes, karren and caves. Furthermore, it is only applicable for groundwater resource protection.

The SINTACS method also uses a very complex weighting and rating system that makes the application very unfriendly. The resulting map is divided in six classes of vulnerability that is too many and makes the results less easily understood.

5.3.4 THE IRISH METHOD

In Ireland groundwater vulnerability mapping is part of the protection schemes enforced by the environmental legislation (Groundwater Protection Schemes, 1999). The vulnerability mapping comprises assessment of the hydrological settings of an area and their protective function and also foresees the possibility of the water bypassing the overlying layers directly into the karst aquifers. Hence it takes into account the thickness and permeability of the subsoil only and the presence of the karst geomorphological features (e.g. dolines, swallow holes, karren, shafts). All other overlying layers are not considered. In addition to an evaluation of the aquifer and the groundwater flow towards a well or spring a resource vulnerability map can be combined into groundwater source protection zones.

The Irish method provides a simple system how a resource vulnerability map, an evaluation of the aquifer and the groundwater flow towards a well or spring can be combined into resource and source protection zones within the framework of a comprehensive groundwater protection scheme (Fig. 5.4). The idea of superimposition of different maps is included in the Slovene Approach as well.

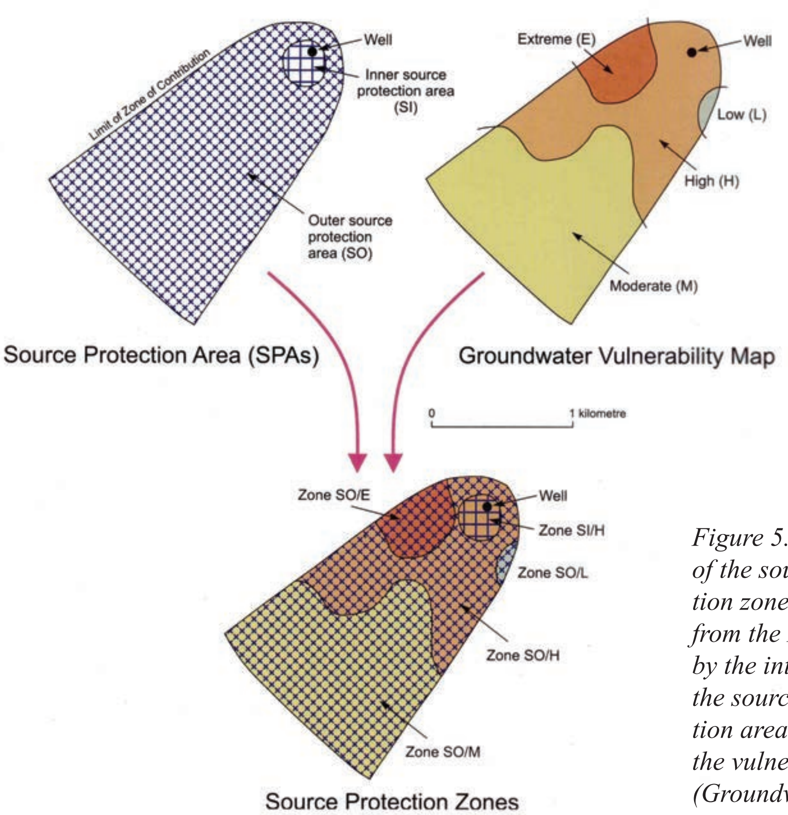


Figure 5.4: Illustration of the source protection zones delineation from the Irish method by the integration of the source protection area map and the vulnerability map (Groundwater Protection Schemes, 1999).

5.3.5 THE EUROPEAN APPROACH

The European Approach is a very general and non-prescriptive approach to intrinsic vulnerability and risk mapping, which could be adopted into methods appropriate for use in individual karst aquifer systems in Europe. It does not specify how the component factors should be considered, measured and categorised nor does it propose detailed guidelines for vulnerability rating. The COST Action 620 favours universal applicability in assessing vulnerability therefore the European Approach is not a completely karst centred approach, but could also be used in other groundwater environments (Zwahlen, 2004).

A significant influence to the European Approach came from the previously developed EPIK and PI methods (Doerfliger and Zwahlen, 1998; Goldscheider, 2002). The later one suggests that the concept of vulnerability mapping should be based on an **origin-target-pathway conceptual model** for environmental management, which has been taken over also by the European Approach.

The **origin** is the term used to describe the location of a contaminant release. The term **pathway** is a flow path of a contaminant from the point of release (origin) to the **target**, which may be the groundwater surface or a drinking water abstraction point e.g. spring or well (Daly *et al.*, 2002; Goldscheider, 2004, 2005).

There are two general approaches of a water protection: **resource** protection aims to protect the whole groundwater body and **source** protection that aims to protect a particular spring or well (Fig. 5.5). Dependent on the relevant purpose of mapping the concept of resource and source protection should be considered (Goldscheider *et al.*, 2000; Daly *et al.*, 2002).

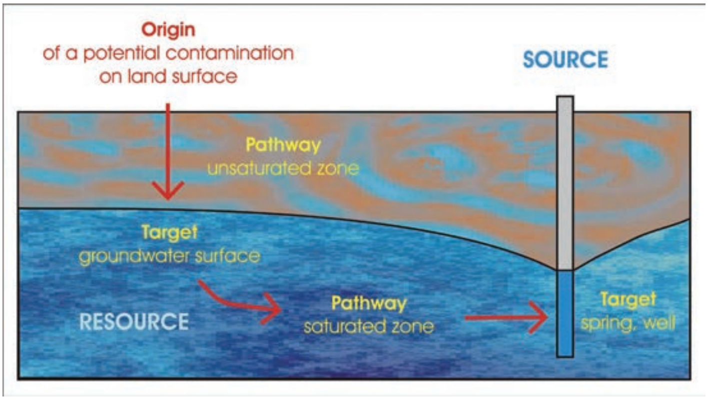


Figure 5.5: Illustration of the origin-target-pathway model and the concept of the resource and source protection (Goldscheider, 2004).

For resource protection the uppermost groundwater surface in the aquifer is the target and the pathway consequently consists of the mostly vertical passage through the unsaturated zone. For source protection the spring or well is a target and the pathway includes also the mostly horizontal flow route in the saturated part of the aquifer. However, the two concepts are closely related to each other – protecting a source usually involves providing protection for the resource as well (Daly *et al.*, 2002; Goldscheider, 2004, 2005).

According to the European Approach karst resource vulnerability assessment is consequently founded on the assessment of basic factors that control infiltration of water and contaminants from the land surface towards the groundwater, such as Overlying layers (O factor), Concentration of flow (C factor) and Precipitation regime (P factor). For source vulnerability assessment additional horizontal flow path in the saturated zone, the Karst network development (K factor) has to be considered. The factors O, C and K represent the internal characteristics of the aquifer system, while the P factor is an external stress applied to the system (Daly *et al.*, 2002).

The O factor may comprise up to four layers – soil, subsoil, non-karst rock and unsaturated karst rock. It is the most important factor, controlling the natural protection of groundwater.

Nevertheless, in karst the overlying layers are frequently bypassed by a runoff of surface flow entering karst aquifer via swallow hole. The C factor represents the degree to which precipitation is concentrated towards places where fast infiltration can occur. The K factor represents the degree of the karst network development in the system (Daly *et al.*, 2002, Goldscheider and Popescu, 2004).

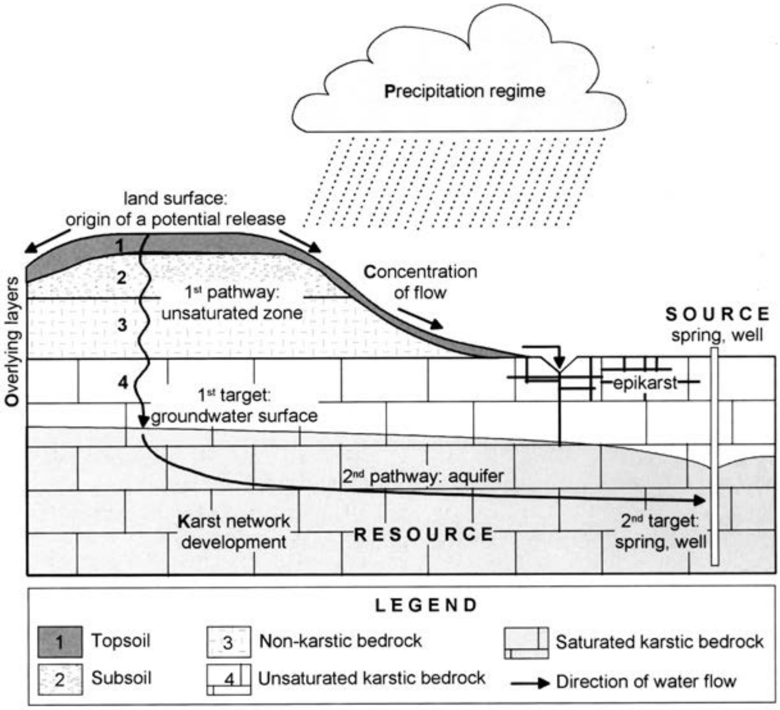


Figure 5.6: According to an approach proposed by COST Action 620, intrinsic karst water vulnerability mapping is founded on the assessment of factors that control the infiltration of water and contaminants from the land surface into the aquifer, such as Overlying layers (O), Concentration of flow (C), Precipitation regime (P) and Karst network development (K) (Goldscheider and Popescu, 2004).

Quite a few of the lately developed methods are based on the work undertaken by the COST Action 620, including the Slovene Approach.

5.3.6 THE COP METHOD

Since the proposed Slovene Approach is mainly based on the COP method, this will be described in greater detail. The critical remarks on this method and the partial incompatibility of some aspects of this method to Slovene karst are presented in chapter 7.

The COP method (Vías *et al.*, 2002; Andreo *et al.*, 2006; Vías *et al.*, 2006c) is based on the European Approach, proposed by COST Action 620. Vulnerability is assessed as a product of three factors: overlying layers (O), concentration of flow (C) and precipitation regime (P). The O and C parameters are evaluated similarly as the P and I parameters in the PI method.

The C and P factors are used as modifiers of the O factor. Moderate and low vulnerability refer to zones where potential protection is low to average and where the C and P factors do not have a decisive influence on vulnerability. The very low vulnerability corresponds to zones in which C and P factors have little influence on protection.

The overlying layers factor refers to the natural protective capability of the unsaturated zone of an aquifer against the contamination. The O parameter takes into account the properties of all protective layers above the saturated zone. Unlike the European Approach, the PI method and some other methods, the parameter O of the COP method does not consider four layers of the unsaturated zone (topsoil, subsoil, non-karst rocks and karst rocks). The protection of an aquifer provided by the layers making up its unsaturated zone is assessed considering only two sub-factors: the soil sub-factor and the lithology sub-factor.

In order to evaluate the soil sub-factor its texture and thickness need to be obtained. The lithology sub-factor is quantified by the type of rocks (which determines its hydrogeological characteristics, mainly effective porosity and hydraulic conductivity) and degree of fracturing, thickness of each stratum and confined situation of the aquifer.

The concentration of flow factor considers the surface conditions that control the water flow towards zones of rapid infiltration, which has less capacity to attenuate the contamination. It takes into account the existence of flow concentrations and of rapid infiltration through karst features, which reduce the aquifer's natural protective capacity. The following division is based on the PI method.

Two possible scenarios are foreseen: catchment area of stream sinking through a swallow hole; and the rest of the area. In the first case distance to swallow hole and distance to sinking stream is considered. In the second scenario geomorphological features are taken into account. Additionally, the slope inclination and vegetation extent are considered in both scenarios.

The precipitation characteristics imply the availability of the transport of contaminants from the surface to the saturated zone of an aquifer. Thus the precipitation

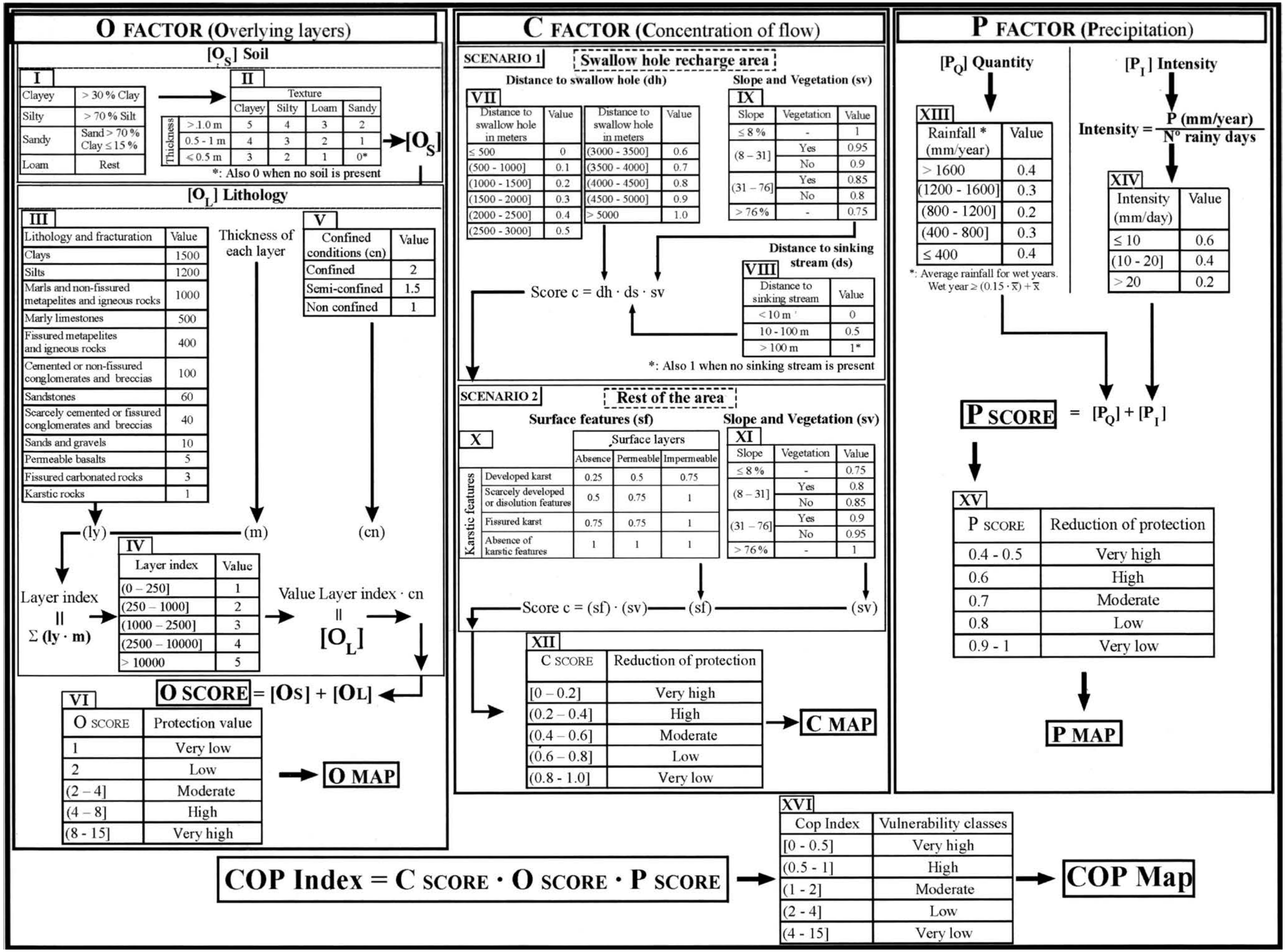


Figure 5.7: Guidelines for the individual parameter assessment, ranking and classification of the COP vulnerability index (Vías et al., 2002).

regime factor takes into consideration the influence of precipitation on the quantity and the infiltration rate of a contaminant. It is therefore evaluated by adding of two factors: quantity and intensity of precipitation.

To assess the quantity of precipitation sub-factor mean annual precipitation values of historical series of wet years are considered. Wet years are defined as those when precipitation values are 15% above average. Minimum precipitation values correspond to the areas having less than 400 mm/year. Increasing precipitation – up to 1200 mm/year – decreases protection, because the authors believe transport processes are more important than the dilution. Furthermore, when precipitation exceeds 1200 mm/year the potential contaminant is diluted (Andreo *et al.*, 2006). This aspect has been presented in the SINTACS method and is slightly differently considered in the PI method.

The intensity sub-factor concerns the temporal distribution of precipitation in a certain period of time. To obtain it, mean annual precipitation for the wet years and the average number of rainy days (in a wet year) have to be considered. Higher intensity provokes higher recharge and thus the reduction of the protection. Considering this sub-factor it is possible to make a comparison between areas with different climate, where precipitation and its intensity conditions highly vary (Vías *et al.*, 2006a).

The final COP index presenting the vulnerability values are obtained by multiplication of all three parameters and divided into five different classes of vulnerability. The O and P parameters can be evaluated for all types of aquifers, while the C parameter is mainly corresponding special characteristics of karst aquifer systems (Fig. 5.7).

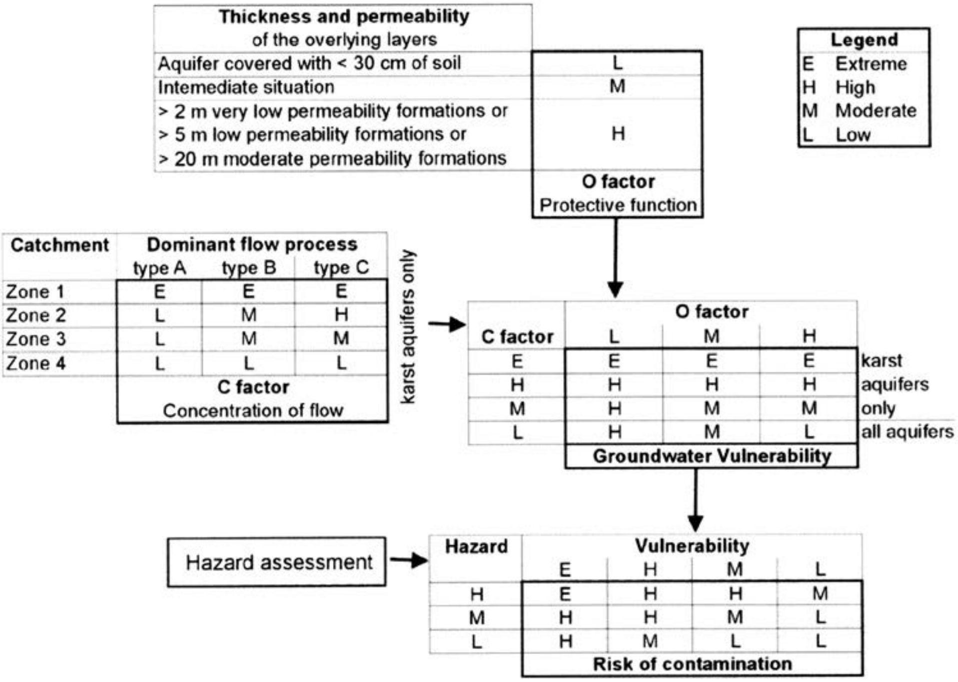
The COP method is made for resource protection. According to the European Approach an introduction of an additional factor describing karst network development inside the aquifer needs to be introduced in order to obtain source vulnerability. So far the COP method has been applied in two test sites in southern Spain (the Sierra de Líbar and Torremollinos) and in Germany (the Bauschlotter Platte) (Vías *et al.*, 2002; Andreo *et al.*, 2006; Vías *et al.*, 2006a).

5.3.7 THE SIMPLIFIED METHOD

The Simplified method is a very easy method to apply, developed for mapping groundwater vulnerability, hazards and risk for areas with restricted data and/or economic resources. Within our study we only focus on the intrinsic vulnerability methodology of this method.

In the Simplified method number of factors has been strongly reduced and the assessment scheme strongly simplified. Nevertheless, the method follows the concepts proposed by the European Approach (Nguyet and Goldscheider, 2006).

It is a method applicable in all types of aquifers, but includes specific tools for karst hydrogeological systems. The intrinsic vulnerability assessment is only based on two factors: the overlying layers (O factor) and concentration of flow (C factor). The O factor takes into account the efficacy of the protective cover as a function of the overlying layers above the aquifer independently of the unsaturated zone depth.



Thickness and permeability of the overlying layers	
Aquifer covered with < 30 cm of soil	L
Intemediate situation	M
> 2 m very low permeability formations or > 5 m low permeability formations or > 20 m moderate permeability formations	H
	O factor Protective function

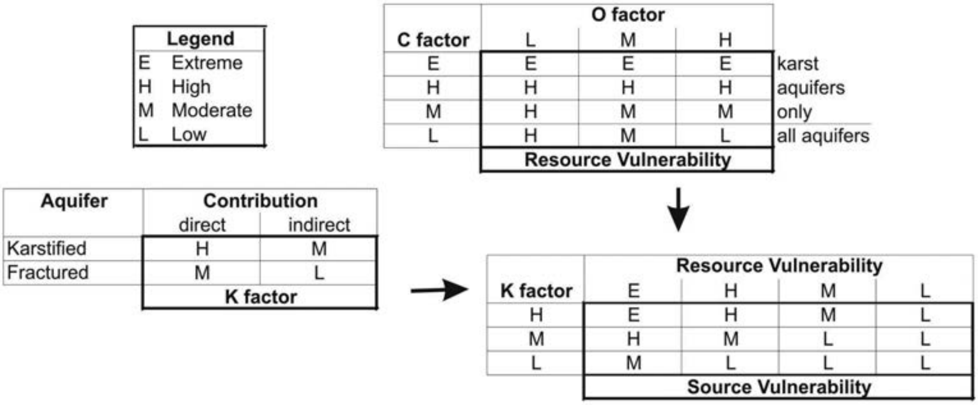
Legend	
E	Extreme
H	High
M	Moderate
L	Low

Catchment	**Dominant flow process**		
	type A	type B	type C
Zone 1	E	E	E
Zone 2	L	M	H
Zone 3	L	M	M
Zone 4	L	L	L
	C factor Concentration of flow		

C factor	**O factor**			
	L	M	H	
E	E	E	E	karst
H	H	H	H	aquifers
M	H	M	M	only
L	H	M	L	all aquifers
	Groundwater Vulnerability			

Hazard	**Vulnerability**			
	E	H	M	L
H	E	H	H	M
M	H	H	M	L
L	H	M	L	L
	Risk of contamination			

Figure 5.8: Assessment scheme for the groundwater vulnerability and risk mapping proposed according to the Simplified method (Nguyet and Goldscheider, 2006).



Legend	
E	Extreme
H	High
M	Moderate
L	Low

C factor	**O factor**			
	L	M	H	
E	E	E	E	karst
H	H	H	H	aquifers
M	H	M	M	only
L	H	M	L	all aquifers
	Resource Vulnerability			

Aquifer	**Contribution**	
	direct	indirect
Karstified	H	M
Fractured	M	L
	K factor	

K factor	**Resource Vulnerability**			
	E	H	M	L
H	E	H	M	L
M	H	M	L	L
L	M	L	L	L
	Source Vulnerability			

Figure 5.9: Assessment scheme for source vulnerability mapping proposed in addition to the Simplified method.

The C factor is, similarly to the PI and COP methods, assessed dependant on the infiltration flow concentration. It expresses the degree to which the overlying layers are bypassed and the existence of allogenic point recharge, merely influenced by the PI method's I factor assessment scheme. However, the method has been simplified to such a degree, that it does not even consider the impact of slope or land use on groundwater vulnerability.

The hazards are classified on the basis of their quality, quantity and likelihood of a potential contaminant release in a very simplistic way. The risk map is obtained (Fig. 5.8) by superimposing the vulnerability and hazard maps.

The methodology has been applied only in a tropical karst area in Northern Vietnam. However, the method has not yet been sufficiently tested and hence critical remarks cannot be given.

During the application of the Simplified method to the Slovene test site on this occasion the authors provided a simplified K factor assessment in order to make the method useful for source vulnerability mapping as well. Due to the parallel development of both K factors (the simplified one and the one included in the Slovene Approach), both assessment schemes are very alike and are founded on similar bases.

According to the simplified K factor proposal, its assessment is considered in an unsophisticated way. Consequently, only two aspects should be considered. Firstly, differentiation between carbonate aquifers that are karstified and those that are only fractured should be done.

Furthermore, parts of an aquifer that are directly or indirectly contributing to the source should be distinguished. Direct contribution means that parts of an aquifer are directly connected to the source, as well as fully, always and certainly contributing to the spring discharge. On the other hand, indirect contribution means that these parts of an aquifer only contribute a small proportion of the water to the source that is separated by an aquiclude. It could also be applied to very remote parts of the aquifer, or to areas that are not always or not surely parts of an aquifer.

When the K factor is combined with the resource vulnerability map a source vulnerability map could be obtained (Fig. 5.9).

6

VULNERABILITY MAPPING IN SLOVENE KARST REGIONS

6.1 PREVIOUS EXPERIENCE

In Slovenia application of vulnerability mapping for karst water source protection zoning and for land use planning would be recommendable due to the special characteristics of karst landscapes (large catchments, lack of protective cover, temporal variations, etc.). There have already been some methodologies for the groundwater vulnerability assessment elaborated (Novak, 1996; Veselič and Petauer, 1997; Špes *et al.*, 2002); however, these do not sufficiently address the special characteristics of water flow within karst aquifers.

Nevertheless, experience with application using methodologies enforced and many times tested in Europe has been very modest. So far only two karst spring vulnerability studies have been done. Janža and Prestor (2002) applied the SINTACS method to the Rižana spring catchment. Furthermore, Petrič and Šebela (2004) used the EPIK method for vulnerability mapping of the Korentan spring catchment area. These applications have never been validated, though.

Furthermore, in Slovenia the concept of vulnerability mapping has been introduced into the national groundwater risk assessment expertise (Strokovne podlage …, 2002), with the vulnerability assessment based on the SINTACS method. Concerning vulnerability mapping of karst regions, it has been proved in many applications worldwide that this method is not particularly well suited for karst areas (see also section 5.3.3).

6.2 GENERAL METHODOLOGICAL PROBLEMS RELATED TO VULNERABILITY ASSESSMENT

Direct application of some methods could meet several difficulties due to the previously described characteristics of Slovene karst regions. Moreover, regarding the peculiarity of individual intrinsic vulnerability mapping methods, the adequacy of the criteria such as parameter selection and the method of parameter weighting, different difficulties might arise when applying a particular method to Slovene karst (Ravbar and Kovačič, 2006a).

Assessment of the protective function of overlying layers would be one of the major problems because of a common shortage of protective cover. In many of the existing methods the characteristics of the layers lying above the saturated zone are the most important factor controlling natural protection of groundwater against contamination (self-cleaning or carrying capacity). Some among the methods provide assessment schemes where protective function assessment consists of up to four layers of the unsaturated zone (topsoil, subsoil, non-karst rocks and karst rocks). Such a very detailed system of protective function assessment requires a vast amount of data, which is a special problem in Slovenia, discussed below. The assessment of the overlying layers protective function has been shown to be one of the major problems in one of the previous applications as well (Janža and Prestor, 2002).

Because of the common absence of soil and/or sediment cover in Slovene karst, the protective function value would mainly be influenced by the depth of the unsaturated zone. Due to the enormous thickness of the unsaturated zone, the protective values would often be classified as "moderate", not showing the vulnerability differences within the aquifer itself. Therefore, the selection of only two parameters (soil and lithological characteristics of the unsaturated zone) together with a not very detailed system of protective function assessment could be suitable as well.

There is a problem in assessing a hydrological function of epikarst, where both storage of water and concentration of flow occur. The first process increases the natural protection of the karst aquifer, while the latter increases the vulnerability of the karst system. The problem of epikarst is that its existence is not always easily recognizable e.g. by the surface karst features. Furthermore, great spatial differences of its development over short distances are present due to heterogeneity of karst landscapes (Kovačič, 2003b). In addition to karst geomorphological features mapping, Petrič and Šebela (2004) introduced mapping of different tectonically crushed zones within the karst aquifer indicating the occurrence of more or less developed epikarst zones.

Knowledge of the subsurface is often not possible, nor the mapping of every single enlarged vertical conduit on a large scale. However, it has been generally acknowledged that the epikarst has a significant influence on the springs' behaviour. Therefore it would be recommendable to evaluate the effective epikarst protective function using indirect indicators like natural tracers or hydrograph and chemograph analysis.

Furthermore, there is still a question how to evaluate areas with great groundwater level oscillations, where groundwater level varies for several tens or even hundreds of metres in a short time and causes great change of drainage divides and flow directions. The protectiveness of the unsaturated zone in highly karstified rocks is generally considered to be rather low. Variable thickness of this zone would consequently have limited impact on final vulnerability value. However, groundwater level fluctuations might alter catchment boundaries, which is crucial for source vulnerability mapping and should therefore be considered also (Ravbar and Goldscheider, 2006).

Due to great groundwater level oscillations, some karst landscapes in Slovenia are also characterised by surface and groundwater flow alteration that is relevant with respect

Figures 6.1 and 6.2: The intermittent lake Petelinjsko Jezero is flooded up to six months per year. At low groundwater level the shallow karst depression is dry (upper), while at high groundwater level it is flooded and forms a lake (lower). The degree of vulnerability of the area may vary drastically depending on respective hydrological conditions (photos: N. Ravbar).

to groundwater vulnerability (Figs. 6.1 and 6.2). Intermittent river flows and lakes, some of which appear several times per year while others occur only very exceptionally, as well as temporary springs, swallow holes and estavelles are significant. Consequently only in a case when a water body (river, lake) is frequently or permanently sinking into karst, would a contaminant release always and rapidly reach the groundwater without significant attenuation. On the other hand, contaminant transport and its attenuation capacities might significantly differ where there are no temporary or perennial water flow conditions (Ravbar and Goldscheider, 2006).

The degree of vulnerability of the area characterised by surface and groundwater flow alteration may vary drastically dependent on respective hydrological conditions. Therefore, when making vulnerability maps, a distinction should be made between zones of concentrated infiltration that are permanently drained into swallow holes and those that are only occasionally drained into karst.

In the vulnerability assessment, special emphasis must be given on the function of the sinking rivers which occur within poljes or recharge in non-karst areas and sink on the contact with carbonates. The latter can have either huge or small catchments, which has to be considered in vulnerability assessment, since swallow holes are points of concentrated inflow, causing fast infiltration of surface waters and contaminants towards the groundwater. A question arises, how to delineate the influence area of such surface flow on the karst aquifer and how to evaluate it, since the surface flows have their own self-cleaning capacities (Kovačič, 2003b).

Furthermore, Slovene legislation demands individual water source protection. Nevertheless, as in some other European countries, no resource protection policy has been provided so far. For source vulnerability assessment where captured springs and wells are the targets (see the origin-pathway-target model in chapter 5), the additional horizontal flow path in the saturated zone, the so-called K factor, has to be considered. So far only few methods, e.g. the EPIK method (Doerfliger and Zwahlen, 1998), the VURAAS method (Cichocki *et al.*, 2001) and the VULK method (Jeannin *et al.*, 2001), provide tools for the K factor assessment. The European Approach foresees incorporation of the K factor into the vulnerability assessment as well, but does not specify how it should be measured or categorized (Daly *et al.*, 2002). Therefore in many methods an additional step from resource to source vulnerability mapping should be done if we would like an application to be adequate to Slovene legislation.

When applying the SINTACS method Janža and Prestor (2002) added an extra criterion of cave density for implementing the unsaturated zone attenuation capacity and hydraulic conductivity range of aquifer into the proposed method. However, it is disputable whether the information on cave density is a relevant criterion for the karstification degree assessment.

The actual speleological data can only show the degree of research work in a certain area. Furthermore, size, connection and density of karst conduits resulting from climate conditions in the past can be misinterpreted. In general, the conduit size aspect cannot be an acceptable criterion, because even a relatively small degree of karstification (e.g.

conduits 10 cm wide) can result in very high travel times and very rapid contaminant transport without significant attenuation if the conduits are well connected. Furthermore, for the mostly horizontal pathway through the saturated karst bedrock to the source, the groundwater flow characteristics and distance to the source have to be considered.

The European Approach foresees the assessment of the P (precipitation regime) factor as well (Daly *et al.*, 2002). Some of the methods (SINTACS, PI and COP) have already introduced the precipitation characteristics into their schemes. The question is whether it is practical to assess the value of precipitation regime within the small area of the same aquifer, since it is not very likely that the differences in intensity and amounts of precipitation vary significantly between particular parts of a catchment and thus they do not essentially influence its vulnerability. However, it has already been shown that when applying the COP method in many different aquifers across Europe, the P factor itself has small correlation with the final vulnerability values and shows important differences only when the method is applied to the aquifers with significantly different climate characteristics (Vías *et al.*, 2006a).

However, there is also a methodological problem, how to evaluate the protective function of a P factor. Do the greater amounts of infiltrating water increase the vulnerability of a karst system (faster contaminant wash-off, shorter transfer time - less time for appropriate intervention) or do they contribute to the groundwater protection (dilution, faster reduction of contaminants' concentrations, shorter duration of contamination)?

Furthermore, degree of vulnerability (i.e. transport velocities, transit times, turbulent/laminar flow, transport of sediments and bacteria, mobilisation of DNAPL – Dense Non-Aqueous Phase Liquid, more surface flow etc.) does not only depend on the actual amount of water infiltrating into the subsurface but also on the previous soil and epikarst zone water saturation.

As mentioned before, in the Slovene karst many areas drain into several abundant springs at the aquifer margins. In the case of spring watersheds overlapping, vulnerability maps of different sources might show different values of vulnerability due to different springs. This raises a question, which source vulnerability map/value should be considered as the more important. In terms of protection degree and spatial planning, the highest degree of vulnerability should be considered. However, when planning the implementation of sanitary provisions in water protection zones, an additional parameter indicating the economic, social and/or ecological importance of a particular water source should also be considered (Daly *et al.*, 2004).

Accurate and detailed studies are essential for vulnerability assessment. Several problems are expected and have also been confirmed while applying some of the existing vulnerability mapping methods in Slovene karst landscapes due to poor database, data availability and assessment. If the method requires very large amount of detailed data, it not only makes vulnerability assessment more expensive, but also makes the application less flexible and often unsuitable, as very rarely is a large amount of data available. Particularly scarce are data in remote and mountainous karst areas.

For groundwater vulnerability assessment detailed studies are essential. Nevertheless, in Slovenia in selecting an appropriate method, lack of data raises additional problems. In some regions the knowledge on catchment areas, their boundaries, groundwater flow and springs characteristics is still relatively poor. Therefore great attention needs to be given to gaining a qualitative database as well.

An additional problem that should be addressed is the question of the mapping scale, which mainly depends on the purpose of the mapping. Karst aquifers are heterogeneous on all scales and thus REV (representative elementary volume) cannot be applied. The scale of mapping must primarily depend on its purpose: land use planning on a national scale or protection zoning and land use planning on a catchment scale. However, the most vulnerable areas must not be eliminated; moreover, such areas must be enlarged and made adequate to a definite mapping scale (e.g. a buffer around a small swallow hole).

In addition, methods that require grid input information (e.g. the SINTACS, the EPIK methods) are not very appropriate for application in karst areas, since the karst aquifers are very heterogeneous systems characterised by great and inherent changes in small area.

6.3 A NEW METHOD PROPOSAL?

Particular karst systems worldwide have their individual characteristics and the circumstances defining underground water flow can differ significantly due to either internal properties of the karst system or the external ones e.g. climate conditions. Thus it is erroneous to expect that in case of vulnerability assessment and mapping one and only one method could be satisfactorily applicable to all karst areas. Nevertheless, besides the natural characteristics of a karst landscape there are exterior stresses as well obstructing reliable results e.g. data availability, poor economic resources etc.

Nowadays, therefore various methodologies for groundwater vulnerability assessment are in use, among which also methods with special consideration of karst aquifers have been introduced. However, experiences of using methods for vulnerability mapping of karst aquifers are very limited in Slovenia.

Thus in future, application of some of the most commonly used methods should be stimulated in order to identify eventual methodological problems that may arise during the application. Comparison of different methods in a single test site is therefore advisable. Considering specific characteristics of Slovene karst (very thin or mostly absent protective cover, very complex and large catchment areas, lack of quality and representative research, poor database, problem of data availability, etc.) selection among the simplest methods would be reasonable. Methods that require very detailed data on protective cover characteristics or require very thorough database on catchment area should thus be avoided.

Since there are already many different satisfactory methods for groundwater vulnerability mapping, it is the author's opinion that setting up a new method would be a repeat of performed work. Furthermore, based on already achieved knowledge and knowing advantages and disadvantages of the previously developed methods, a new, upgrading version can be proposed.

Therefore, our principle aim is to select the most satisfactory among the existing methods for karst water source vulnerability assessment and mapping and to improve it, taking into consideration the characteristics of Slovene karst. We also believe that proposing a common method for karst water source vulnerability mapping on a national basis and its validation using hydrological and statistical methods is essential.

Finally, a common method, which would be the basis for the establishment of water protection zones and regimes, could be used for resource protection and land use planning in karst aquifers. Furthermore, it could be a supplement to the existing legislation for karst source protection.

According to the *Rules on criteria for the designation of a water protection zone* (Ur.l. RS 64/2004), the main criterion for the delineation of the source protection zones is the travel time of groundwater in the aquifer. However, a vulnerability assessment and mapping could be an additional criterion for karst source protection. It could present a supplement for reduction and/or enlargement in the size of the zones where necessary according to the intrinsic properties of a particular catchment area.

Furthermore, source and resource risk maps could be practical tools for future land use management, spatial planning of human activities and for sanitary provisions planning in water protection zones as well.

7
THE SLOVENE APPROACH TO INTRINSIC VULNERABILITY MAPPING

7.1 INTRODUCTORY REMARKS

Experiences of application using methods for vulnerability mapping of karst aquifers are very limited in Slovenia. However, considering the EPIK and the PI method, the contribution of a comprehensive approach of the European COST Action 620 to vulnerability mapping of karst aquifers and the derived methods (cited and described in chapter 5), the advantages and disadvantages of each have been considered in this research. Stress has been laid on potential methodological problems that might arise while applying the existing methods to Slovene karst regions. In these terms we were looking for the most satisfactory method according to adequacy of the criteria of some of the methodologies, such as parameter selection, method of parameter weighting, method of final assessment reckoning.

Comparison of some of the most commonly used methods in karst, as well as the newly proposed Slovene Approach, considered factors, the most important advantages and drawbacks of each method are briefly presented in Fig. 7.1.

Among the methods enforced and many times tested in Europe we found the COP method the most appropriate in case of specific characteristics of Slovene karst:
- very thin or mostly absent protective cover,
- very complex and large catchment areas,
- special structure of karst areas,
- not a lot of research was done in most of the cases,
- poorly known extent of catchment areas,
- problem of data availability,
- lack of quality and representative data especially needed for good evaluation of the protective function of the covering layers, etc.

Even though several examples of successful application of the COP method in different karst systems have been described, we still found the existing COP method to have some weakness and thus we believe that it needs to be improved. While proposing

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Figure 7.1: Comparison of different intrinsic vulnerability methods, considered factors, the most important advantages and drawbacks of each method. →

Parameters	Methods	SINTACS	EPIK	PI	COP	Simplified method	Slovene Approach
OVERLYING LAYERS	Topsoil thickness	✓	✓	✓	✓	✓	✓
	Topsoil texture	✓		✓	✓		✓
	Topsoil structure	✓		✓			✓
	Subsoil permeability	✓	✓	✓	✓	✓	✓
	Subsoil thickness	✓	✓	✓	✓	✓	✓
	Depth of the unsaturated zone	✓		✓	✓		✓
	Fracturation			✓	✓		✓
	Epikarst development / geomorphological features		✓	✓	✓		✓
	Confined situation			✓	✓		✓
INFILTRATION CONDITIONS	Concentration of flow		✓	✓	✓	✓	✓
	Slope gradient	✓	✓	✓	✓		✓
	Land use / vegetation cover		✓	✓	✓		✓
RECHARGE	Autogenic recharge	✓	✓	✓	✓	✓	✓
	Alogenic recharge		✓	✓	✓	✓	✓
KARST NETWORK DEVELOPMENT	Presence of karst network		✓	*	*	*	✓
	Hydrological characteristics of a spring		✓				✓
	Tracer test interpretation		✓				✓
Temporal variability							✓
Source vulnerability			✓				✓
Resource vulnerability		✓		✓	✓	✓	✓
Advantages		Applicable to all types of aquifers.	User friendly, simple, does not need a lot of data, protection zone delineation.	Applicable to all types of aquifers,provides special tools for karst.	Applicable to all types of aquifers, provides special tools for karst, not very detailed data needed.	Applicable to all types of aquifers,provides special tools for karst, very simple application not a lot of data needed.	Applicable to all types of aquifers, provides special tools for karst, protection zone delineation.
Drawbacks		No special tools for karst aquifers, complex weighting and rating system, large amount of data needed, grid input information, too many vulnerability classes.	Only applicable in small areas and only in karst, contradictory values and weighting system, grid input information.	Wide classes, extremly karstified areas highly vulnerable independent of the unsaturated zone thickness, requires large amount of data.	Weaknesses regarding particular parameter evaluation.	Not sufficiently tested yet.	Not sufficiently tested yet.

* - originally developed only for resource vulnerability; can be extended for source vulnerability by including K factor

definite modifications to the existing COP method, we mainly focused on special characteristics of Slovene karst. Since we would like the method to be applicable to source vulnerability mapping as well, an additional step from resource to source vulnerability mapping has also been done.

The Slovene Approach to intrinsic vulnerability, which has been developed within this study, is thus an upgraded version of the COP method, influenced in addition by the EPIK, PI methods and the European Approach (Fig. 1.1).

The adaptation of the COP method includes:

- slight modification and supplementation of the O factor,
- integration of temporal hydrological variations and surface waters consideration,
- modification of the C and P factors.

Furthermore, for the Slovene Approach of vulnerability assessment and mapping to protect karst water sources, an additional K factor supplement and source protection zone determination is proposed.

In the present work we focus mainly on the theoretical background of the proposed method, as well as on the technical details of the assessment scheme. However, when modifying the COP method we endeavour to change the total assessment scheme as little as possible with regard to guidelines for the individual parameter assessment, ranking and classification. The modifications of factors and sub-factors, mentioned in the following sections, mostly relate to Figs. 5.7 and 7.12.

7.2 OVERLYING LAYERS (O FACTOR)

The O factor considers the protection provided to the aquifer to attenuate the potential contamination (Daly *et al.*, 2002; Vías *et al.*, 2002). In Slovene karst regions deep diffuse flow karst plateaux prevail for which an immediate infiltration of the rainwater underground and fast vertical draining in different directions are characteristic. The depth of the unsaturated zone can reach 1,500 m and more. In general, the protective cover of soil and sediments is thin or completely absent.

Therefore, we found the selection of only two layers (soil and lithological characteristics of the unsaturated zone), together with a not very detailed system of protective function assessment for the vast amount of detail data needed, to be very suitable.

7.2.1 SOIL SUB-FACTOR CLASSIFICATION

During the percolation of the infiltrated water through the soil cover and rock above the groundwater table, contaminants in the water may be subjected to mechanical, physicochemical and microbial processes leading to their degradation. The effectiveness of these processes is mainly determined by the residence time of the percolating water in the soil cover and rock. The longer the residence time, the longer the degradation and sorption processes can be effective and thus reduce the input of contaminants into the groundwater. In the most favourable case, contamination does not even reach the groundwater, even in the long term.

The evaluation of the soil protection function is according to the COP method based on the soil texture, i.e. grain size distribution and its thickness. However, the residence time of the percolating water (and/or contaminant) in the soil is considerably affected by soil structure i.e. the presence of cracks, aggregates, mouse-holes, etc. Consequently, these macro pores may principally control the rainwater infiltration and thus enable by-passing of the topsoil. Therefore, it is the author's opinion that the protective function of soils can be assessed on the basis of their thickness, texture and structure.

To assess the protective function of the topsoil, the GLA and the PI methods beside soil thickness take also into consideration the effective field capacity (eFC) that mainly depends on grain size distribution, degree of compaction and humus content. It is generally determined for the profile down to the effective rooting depth (Schachtschabel *et al.*, 1984). Higher values of the eFC indicate high capacity to store water and consequently, to delay and attenuate contaminants, and vice versa.

Clearly, due to lack of data or the high costs of gaining the data, a simplified assessment scheme has been proposed in the frame of the Slovene Approach, taking into account topsoil thickness, porosity and permeability. Due to their small grain size, clayey soils have low porosity which is favourable for the protection of lower lying layers. However, clayey soils could be highly permeable when they are dry due to the deep desiccation fissures and other preferential flow paths and thus have a low eFC, which is not favourable for the protection.

On the contrary, silty and loamy soils are more porous, but have higher eFC, which indicates higher protection. Sandy soils are highly permeable, but have a low eFC, which is not favourable for the protection. As a conclusion, we classify loamy and silty soils as more protective, with clayey and sandy soils as less protective.

In order not to modify the O factor assessment scheme as a whole, we combined previous soil sub-factor values into two classes.

Furthermore, the majority of intrinsic vulnerability methods consider topsoil thickness in order to assess its protective function. However, there is a problem of heterogeneous soil thickness on karst, which significantly complicates its protective function assessment. In case of extremely diverse soil thicknesses or where soil occurs in patches and pockets it is often difficult to decide which value to take into account. Although it is often tempting to interpolate the results, such interpolations can be misleading or even wrong in karst terrains, and may be impossible even to attempt when adjacent measurements display wildly differing characteristics.

In many karst areas soil occurs in pockets of diverse depth with karren of various sizes and frequency area showing on the surface. Where the karren are small and the soil pockets deep, the rainwater would probably not infiltrate into the limestone directly

Figure 7.2: Soil cover removal near Trebnje, SE Slovenia. The recent excavation shows how heterogeneous soil thickness can be and that scarce stones showing on the surface are not real indicators of soil thickness (photo N. Ravbar).

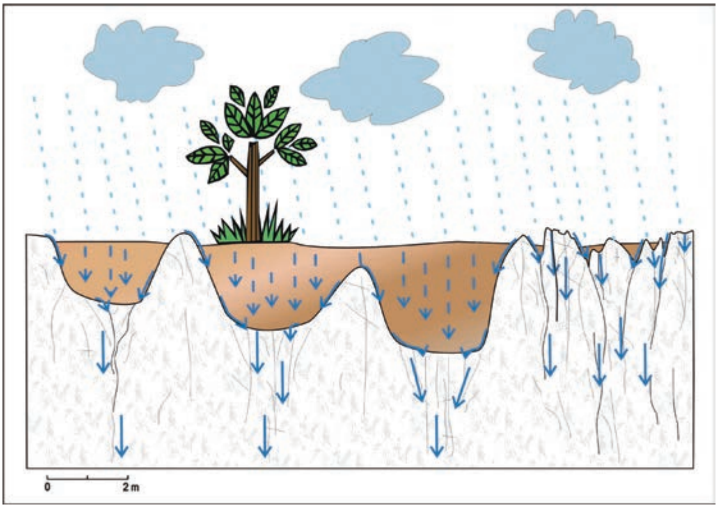


Figure 7.3: When assessing soil depth its effective thickness should be considered.

near the surface, but it will first percolate through the deep pockets filled with soil (Fig. 7.2), in contrast to the vast karren interrupted by small pockets of soil filling the intermediate cracks.

Therefore we suggest consideration of the **effective soil thickness** that provides answer to the question: How long will the water percolate through the soil before it enters into the karst (Fig. 7.3)?

Besides the point measurements using a hand auger, the effective soil thickness could also be assessed by means of indirect information; such as geology, geomorphology, soil type, vegetation cover, drainage density, remote sensing and aerial photographs. Furthermore, the texture, structure and thickness properties of soil are often greatly influenced by the geomorphological type.

7.2.2 EVALUATION OF THE EXTREMELY KARSTIFIED AREAS PROTECTIVE FUNCTION

Figure 7.4: An example of the extremely karstified area of the Ždrocle on the Snežnik mountain, SW Slovenia, where karrenfields are connected with deep shafts (photo: N. Ravbar).

Because of the common absence of soil and/or sediment cover in Slovene karst, the O value will mainly be influenced by the karstification of the unsaturated zone. However, due to the enormous thickness of the unsaturated zone, the application of the COP method would often result in "low" or "moderate" protective values, even for extremely karstified bare karrenfields connected with deep shafts (e.g. the Kaninski Podi, the Kriški Podi, the Rombonski Podi in the Alps and the Ždrocle on the Snežnik mountain, etc., Fig. 7.4). Thus this classification is not plausible.

Therefore, we propose to modify slightly the ly sub-factor by introducing an additional value for extremely karstified areas like described above. The PI method uses a zero, which leads to large areas being assigned an overall very low protection value and it proved not a good solution (Andreo *et al.*, 2006). As a compromise, we propose to use a value of 0.2, which means that these areas will always be assigned a very low to low protective value (i.e. very high to high vulnerability) instead of a moderate protective value/vulnerability (in case of COP).

7.3 INFILTRATION CONDITIONS (C FACTOR)

Regarding the European Approach the C factor evaluates areas with different infiltration conditions (Daly *et al.*, 2002). In the COP method (Vías *et al.*, 2002) the C factor has been distinguished according to the surface conditions that control water flowing towards zones of rapid infiltration. Therefore two scenarios have been introduced: swallow hole recharge area and the rest of the area.

However, we found the guidelines not sufficient in respect to additional attributes such as temporal hydrological variability – which is particularly difficult to handle – and consideration of surface waters. Moreover, we disagree with the proposed scheme also in some particular aspects like the evaluation of the slope inclination and vegetation cover protection.

Therefore we rather fully modified the existing C factor. The alternative solutions are presented in the following sections. Nevertheless, evaluation of the C factor is still based on the zonation of the recharge area of the sinking surface flow and the rest of the area.

7.3.1 INTEGRATING HYDROLOGICAL VARIABILITY

Particular regions of Slovene karst landscapes are characterised by frequent groundwater level oscillations and alternation of surface with underground water. Groundwater level oscillations in karst systems may vary for several tens of metres in a short time.

There is no periodicity in groundwater level oscillations. These strongly depend on meteorological factors (type, amount, intensity and distribution of precipitation, and factors governing snowmelt, such as temperature and wind) and on hydrogeological factors (karst channels dimensions and their connection). Consequently, changing flow directions, intermittent lakes, some of which appear several times per year while others occur only very exceptionally, as well as temporary springs, swallow holes and estavelles, occur in poljes or shallow karst areas (Ravbar and Goldscheider, 2006).

Figure 7.5: Dry swallow holes at the Zadnji kraj (the Cerkniško Jezero) when dry (photo: J. Vías).

The COP method classifies swallow holes and sinking streams as zones of very high vulnerability. Some examples from the Slovene karst show that some swallow holes are frequently or permanently active, while others operate only during exceptional hydrological events, sometimes less than once per year (Fig. 7.5).

The described hydrological variability has many implications for contaminant transport and groundwater vulnerability mapping. Only in the case of a permanently active point infiltration, would a contaminant release always and rapidly reach the groundwater without significant attenuation (Ravbar and Goldscheider, 2006). On the contrary, in the case of occasionally active sinking water bodies (streams, lakes) and swallow holes, a contaminant release might not always directly enter the karst groundwater. Thus their vulnerability rate may also vary drastically dependent on respective hydrological conditions.

Although it is generally acknowledged that such hydrological variations have an impact on contaminant transport, the existing COP method does not provide sufficient tools to cope with hydrological variability. The existing methods also do not sufficiently address the issue of how temporal hydrological variability could be considered within the framework of karst groundwater vulnerability assessment.

Clearly, it is nearly impossible to create different vulnerability maps for different hydrological situations. Furthermore, the characteristics of single hydrological events are impossible to compile within one map. The concept of average hydrological conditions also has drawbacks, because it would eliminate extreme events, which are particularly important for contaminant transport (Ravbar and Goldscheider, 2006). Nevertheless, we should distinguish, e.g. between swallow holes that are permanently active and swallow holes that only operate once in a century.

This could be done, for example, by means of a new sub-factor introduction, describing the occurrence of

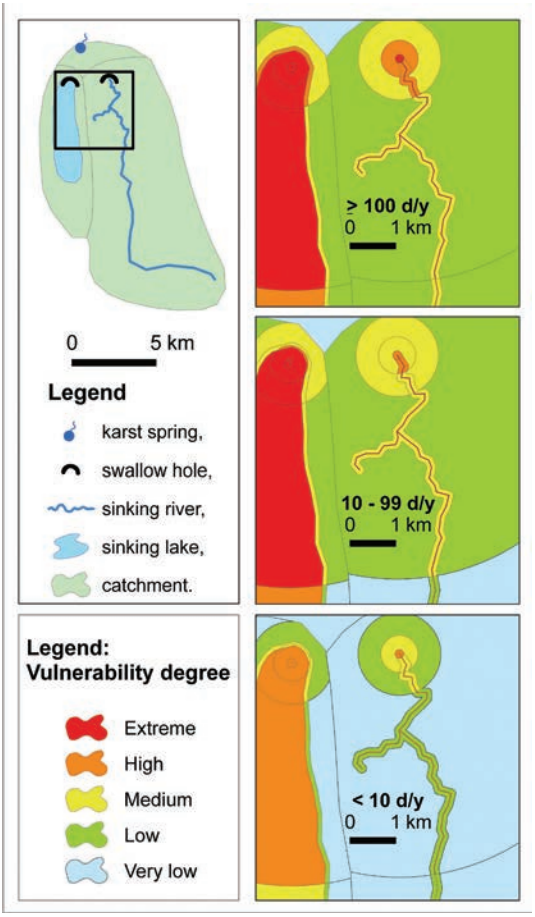


Figure 7.6: Integrating temporal variability tv sub-factor into the existing C score assessment scheme by adding it to the product of dh, ds and sv sub-factors.

hydrological events i.e. the swallow hole activity (frequency and duration). Swallow holes that are permanently or frequently active (e.g. ≥ 100 days/year) should be classified as more vulnerable than those that operate only exceptionally during extreme hydrological events (< 10 day/year). Therefore, we propose incorporation of a temporal variability tv sub-factor to the existing C score assessment scheme (i.e. product of dh, ds and sv sub-factors). Increased tv value means rarer occurrence of water flow and thus lower vulnerability (Fig. 7.6). In order to make the assessment possible without significant modification of the C factor evaluation scheme in general, we also slightly modified the ds sub-factor.

Furthermore, the described hydrological variability results in variable thickness of the unsaturated zone. Rising water levels mean decreasing unsaturated zone thickness and thus decreasing protectiveness i.e. increasing vulnerability. Most of the existing methods preferentially consider the "mean bad conditions" of a hydrological year and do not sufficiently address this issue. In comparison to karst systems with relatively little hydrological variability where, on the contrary, groundwater level oscillations are several tens of metres high, these variations have a major impact on the groundwater vulnerability.

The groundwater level oscillations inside the aquifer are more difficult to deal with, and the required data are often not available. However, the protectiveness of the unsaturated zone in highly karstified rocks is generally considered to be fairly low. Variable thickness of this zone would consequently have limited impact on vulnerability. Therefore, the average groundwater level might be used for resource vulnerability mapping in most cases (Ravbar and Goldscheider, 2006).

On the other hand, groundwater level fluctuations might alter catchment boundaries, which is crucial for source vulnerability mapping. In chapter 7.6 it is demonstrated how variable drainage divides should be considered.

7.3.2 INTEGRATING SURFACE WATERS

Only the integrated management of a karst water resource over its entire catchment area is an efficient way to preserve its quality and quantity. Beside diffuse infiltration, karst groundwater can be recharged by the concentrated point inflow of surface water via swallow holes as well. Thus, when we treat the karst hydrological systems as whole, surface water bodies, sinking into the karst aquifer and their catchments have to be considered also.

In contrast to diffuse infiltration, surface water bodies entering a karst system have a direct connection to karst groundwater, bypassing the protective cover. Therefore surface waters are especially dangerous to karst groundwater when contaminated. However, this is not the only reason to protect surface waters, but also because they are themselves valuable ecosystems and drinking water resources (Goldscheider and Popescu, 2004).

According to the COP method (and most other methods), the entire stream network, sinking into karst, is classified as extremely vulnerable. However, there is a question how to deal with large water bodies (for example long streams and river networks, large lakes) sinking into karst system. Examples from Slovenia show that rivers being several tens of kilometres long (Fig. 7.7) within several tens or even hundreds km^2 of surface catchment area usually enter karst systems (e.g. the Reka river, the Temenica river, the lake of Cerkniško Jezero).

Regarding the concept of swallow holes and sinking streams being extremely vulnerable, this situation would lead to extremely large areas that would additionally have to be protected at the highest level. However, is it really everything that is extremely vulnerable?

On one hand underground water, especially the one in karst conduits, has in comparison to the surface water much lower self-cleaning capacity. There is often a higher aeration and thus a higher biological activity in surface water and therefore more biodegradation. On the other hand, in surface waters there is less filtration and chemical degradation. However, in the case of surface water contamination there is also a travel-time (i.e. time to react) in the stream or lake itself, before it enters the underground.

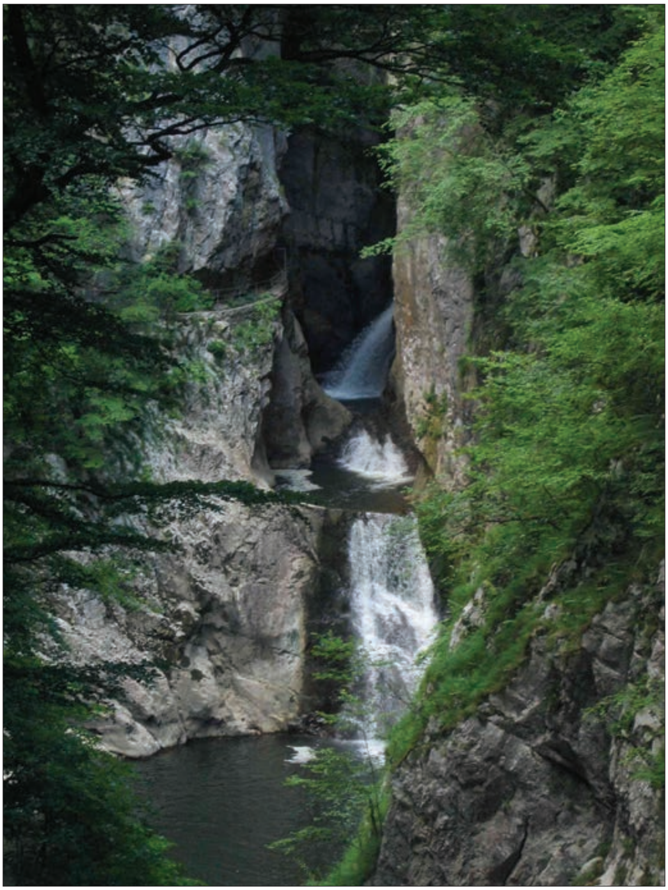


Figure 7.7: The Reka river entering the caves of Škocjanske Jame flows superficially for 55 km before sinking and gathers water from more than 400 km^2 of the Snežnik massif and Brkini hills (photo: N. Ravbar).

Therefore, we propose to take into account a distance of 5 km in the stream or lake and their immediate vicinity in order to assign lower degree of vulnerability upstream from the swallow hole. Furthermore, apart from a certain distance from karst areas, surface waters and their catchments should be protected independently from groundwater vulnerability issues, as proposed by the existing European and national water protection policies.

7.3.3 EVALUATION OF THE SLOPE INCLINATION AND VEGETATION COVER PROTECTION VALUES

In the slope inclination and vegetation cover protection values evaluation there are many aspects where we do not agree with the proposed assessment scheme. Thus, the sv sub-factor has been fully modified.

Regarding the Slovene Approach the most important difference to the COP method is that the same sv sub-factor is applicable in both situations (swallow hole recharge area and in the rest of the catchment).

The Slovene Approach considers that in addition to slope declination and vegetation cover also the flow type controls the infiltration, as is done in the methods PI, EPIK and the Simplified method. Moreover, the strongest impact is given to the type of flow.

Incorporation of the flow processes into the assessment scheme is based on the surface layers permeability. Direct infiltration can be expected on highly permeable rocks and (sub)surface flow predominates on less permeable or impermeable rocks. In the case of (sub)surface runoff the flow can be more concentrated, which consequently reduces the protection.

Concerning the COP method we particularly disagree with the concept of the slope inclination and vegetation cover protection values evaluation (Vías *et al.*, 2002). Within scenario 2 the steeper slope inclination and absence of vegetation cover are considered as being more protective for groundwater.

The Slovene Approach sv sub-factor classification is in general based on the fact that the steeper the slope and sparser the vegetation, the higher is the vulnerability. Denser vegetation always provides protection to groundwater. In such areas there is less runoff, more storage and thus slower infiltration.

We reduced the number of slope classes and only distinguish between really flat (≤ 8%), moderate (8-31%) and steep (> 31%) slopes. Where surface layers are less permeable or even impermeable, surface flow often occurs on very flat and even horizontal surfaces, which eventually infiltrates in more or less concentrated mode. On the other hand, even steep slopes of permeable grounding may drain underground (Fig. 7.8).

Therefore, a definite impact of slope and vegetation on the final vulnerability value is given to the (sub)surface flow type. However, these aspects do not present significant impact on final vulnerability value, where direct infiltration occurs.

Furthermore, the classification “vegetation yes/no” and the distinction between

Figure 7.8: Permeable rocks even in very steep slopes provide infiltration of precipitation underground through fissures and cracks (photo: N. Ravbar).

the two are not clear enough. The definition is not always applicable, as in the karst landscapes with arid or sub-arid climate there is always some vegetation cover (e.g. isolated grass cover or bushes). Thus we propose differentiation between "less dense vegetation cover" comprising bare areas and areas with scarce vegetation, cultivated land (such as fields, orchards, meadows, grassland), urban areas and communications, where the protective cover is absent or very scarce and/or human activities intensive. On the other hand "dense vegetation cover" would comprise overgrowing areas, bushes and densely wooded areas, where vegetation offers considerable protective cover and human activities are not intensive.

7.3.4 ASSESSMENT OF THE C FACTOR

The C factor expresses the degree to which the protective cover is bypassed by lateral surface flow. In the proposed Slovene Approach the recharge area of a sinking water body (river, lake) is considered to be especially dangerous, because the potential contaminants can directly enter the karst groundwater. As in the COP method the reduction of protection (C score) is evaluated by multiplication of the distance to swallow hole (dh), distance to sinking stream (ds) and slope and vegetation sub-factors (sv). If the sinking water bodies are not always present, the temporal variability sub-factor (tv) should be added.

Moreover, we consider the dh classes proposed within the COP assessment scheme too large. In this way swallow holes are surrounded by large extremely vulnerable areas, which are not always justified. Therefore we suggest a more radical solution, e.g. classes limited with 10, 100, 500, 1000 and 5000 m distant from a swallow hole.

Resembling the PI and some other methods, in cases where an aquifer under consideration is overlain by a higher aquifer, the protection of the highest aquifer principle has to be considered and graphically symbolized on the map. Furthermore, in areas that discharge by surface or subsurface flow out of the karst system under consideration and do not have contact with the groundwater considered, the C score value 1 should be assigned.

Like the existing COP method the Slovene Approach also proposes to assess the C score for the rest of the catchment area on bases of the slope and vegetation (sv) and surface morphological features (sf) sub-factors values combined. At this, the sv sub-factor evaluation scheme has not been modified. When applied, certain karst features (caves, karren, dolines and others) should be identified; when these are absent the values depend on dissolution or fissured karst or non-karst areas. Where karst is overlaid by permeable or impermeable subsoil layers (e.g. dolines, valleys or poljes covered by sediments) the protection of the underlying layers is increased.

7.4 PRECIPITATION REGIME (P FACTOR)

The P factor has been fully modified for different reasons. Firstly, Vías *et al.* (2002) suggest that more precipitation means shorter transit time, which increases the vulnerability up to the precipitation amount 1,200 mm/y. Precipitation higher than 800-1,200 mm/year means higher dilution i.e. lower vulnerability. However, the affirmation that the estimated value is considered to be the range beyond which the dilution predominates has not been sufficiently supported theoretically.

There is a question if moderate quantities of precipitation amount (800-1,200 mm/year) are the most dangerous, while both lower and higher annual rainfall quantities represent lower vulnerability. The higher rainfall quantity means higher transport velocity, shorter transit time, more turbulent flow, more effective transport of sediments and bacteria, mobilisation of DNAPL (Dense Non-Aqueous Phase Liquid), more surface flow, etc.

Furthermore, we do not agree with the way intensity is defined. Intensity is the quantity of water that falls in a certain period of time; therefore it should be estimated as precipitation amount (mm) divided by the duration of the event (h).

However, we do agree that the two aspects – quantity and intensity – should be considered within the P factor. Therefore, we propose an alternative system. The daily precipitation amount for the 30-year period should be the basis for the P factor assessment. Two sub-factors should be considered (rd and se). The rd sub-factor indicates rainy days, while the se sub-factor indicates the days when intensive storm events occur. To assess the first one the average annual number of days when rain quantity was between 20 and 80 mm/day should be ascertained. To assess the se sub-factor average annual number of days with more than 80 mm/day should be taken into account. The final value of the P factor should be obtained by multiplication of both sub-factors and ranged in five classes.

7.5 KARST NETWORK DEVELOPMENT (K FACTOR)

For source vulnerability assessment where captured springs and wells are the targets, the additional horizontal flow path in the saturated zone has to be considered. The COST Action 620 (Goldscheider and Popescu, 2004) suggests a combination of O, C, P and K factors.

For implementing karst network development into the proposed approach, specific transport processes in karst have to be considered. Thus, it is very important which characteristic we take into account. An attempt how to assess the K factor has been presented in some of the methods (e.g. the EPIK method, the VURAAS method, the VULK method).

Since the karst drainage system and the underground water flow paths are often not known, detailed mapping of the karst network is nearly impossible. Furthermore, the classification of K factor by degree of karstification can often be very subjective, because it can hardly be measured.

To assess karst network development by means of speleological objects mapping it is not relevant as they can reflect the degree of research work in a certain area. Size, connection and density of karst conduits or caves are often results of previous climate conditions. The conduit size aspect cannot be an acceptable parameter either, because even a relatively small degree of karstification (e.g. conduits 5 cm wide) can result in very high travel times and very rapid contaminant transport without significant attenuation.

Furthermore, an additional very important element of source vulnerability mapping is the determination of the spring catchment area. In Slovene karst landscapes and in many other karst landscapes catchments are often extremely large and hydraulically connected over long distances. Watersheds are often very difficult to determine due to their high variability in time and strong dependence on the respective hydrological conditions. Catchments of several individual springs often overlap and the flow paths proved by tracer tests often cross each other (for example see Fig. 2.8).

Drainage divides and flow directions that change in response to hydrological conditions also have strong implication for vulnerability mapping. If the catchment boundaries vary by several tens of kilometres this raise a question which boundaries should be considered for source vulnerability mapping (Ravbar and Goldscheider, 2006).

In order to be able to categorise the K factor we should refer to the three important questions a vulnerability map should give us answers on (Brouyère *et al.*, 2001; Daly *et al.*, 2002; Brouyère, 2004, see also Fig. 5.1):

– after what time will a contaminant arrive at the source (days, weeks, months…),
– what proportion of the contaminant will arrive (only traces, 1%, 10% or all) and
– how long a contamination will last.

Therefore we suggest that the K factor assessment be based mainly on groundwater flow velocities, connection and contribution to the source, which are in the most important contamination aspects. In contrast, duration of a contamination could be an optional aspect. However, reliable information on active conduit network should be considered as well.

The assessment of the K factor is hence mainly found in the hydraulic properties of the aquifer as well as the geological, geomorphological, speleological and hydrological characteristics of the aquifer. Besides conventional survey techniques, such as speleological surveys, geological mapping, borehole analyses, hydrograph analyses, chemical and isotopical analyses, tracing experiments, remote sensing, geophysical measurements and the quantitative characterization of karst hydrological systems is important. Nevertheless, the transit time and recovery rate information is the fundamental concept for the K factor assessment.

However, the information on travel time and recovery rates cannot be mapped, so we suggest identification of additional criteria that can be mapped in the field. Thus we propose an assessment scheme that considers the following sub-factors:

The **t sub-factor** (travel time) basis on the groundwater flow velocities within the saturated zone and is independent from the drainage system within the unsaturated zone. Due to very high heterogeneity of karst aquifers and their strong dependence on various hydrogeological conditions the assessment of the t sub-factor may present several difficulties. The groundwater flow information gained in high water conditions should be taken into account. Such conditions are more favourable for contaminant mobilisation and transport, when the flow is faster and may be more turbulent. The contamination can thus more rapidly and without considerable attenuation reach the spring, consequently increasing its vulnerability. A classification system of the t sub-factor provides its application to either non-karstified carbonate rocks with only intergranular porosity to karst aquifers with highly karstified active network system as previously suggested by the COST Action 620 (Goldscheider and Popescu, 2004).

Classes for the groundwater apparent pathway (passed within >1 day, 1-10 days, <10 days), delineated by the contour lines according to similar hydrogeological settings are proposed. However, the limits of the zones can also be adapted to the state's national legislation. By classifying aquifer systems according to the groundwater travel time, areas with conduit systems, which are not very effective in transmitting water, and areas with extensively developed karst network systems, which are efficient in draining the aquifer, could be differentiated.

Hence, individual areas of different water flow velocities and hydrodynamic behaviour can be distinguished. Consequently the distance to the source would e.g. in fractured aquifers significantly contribute to the final vulnerability reckoning, but much less significantly so in highly karstified aquifers. Thus the degree of karstification is a decisive factor, as less karstified carbonate aquifers show behaviour similar to most non-karst ones.

The **n sub-factor** (information on karst network) indicates the presence of an active conduit network. If there is a clear evidence and/or information on location of the underground water flow paths, it should be included. To obtain this information also evident indirect indication such as major fracture zones, geomorphological features etc. can be included. However, it must be noted that such information is not reliable evidence in every karst aquifer system!

The purpose of this sub-factor is to assign higher vulnerability of the conduits wider area (Fig. 7.9). Clearly, it is consistent to indicate main groundwater flow passages and to provide protection or manage the area with care. However, in most cases the underground water flow paths are unknown. The active conduit network is thus an optional class. If there is no clear evidence on the underground water flow paths location, it is better to avoid any approximations. The lower vulnerability areas correspond to zones where only fractures exits.

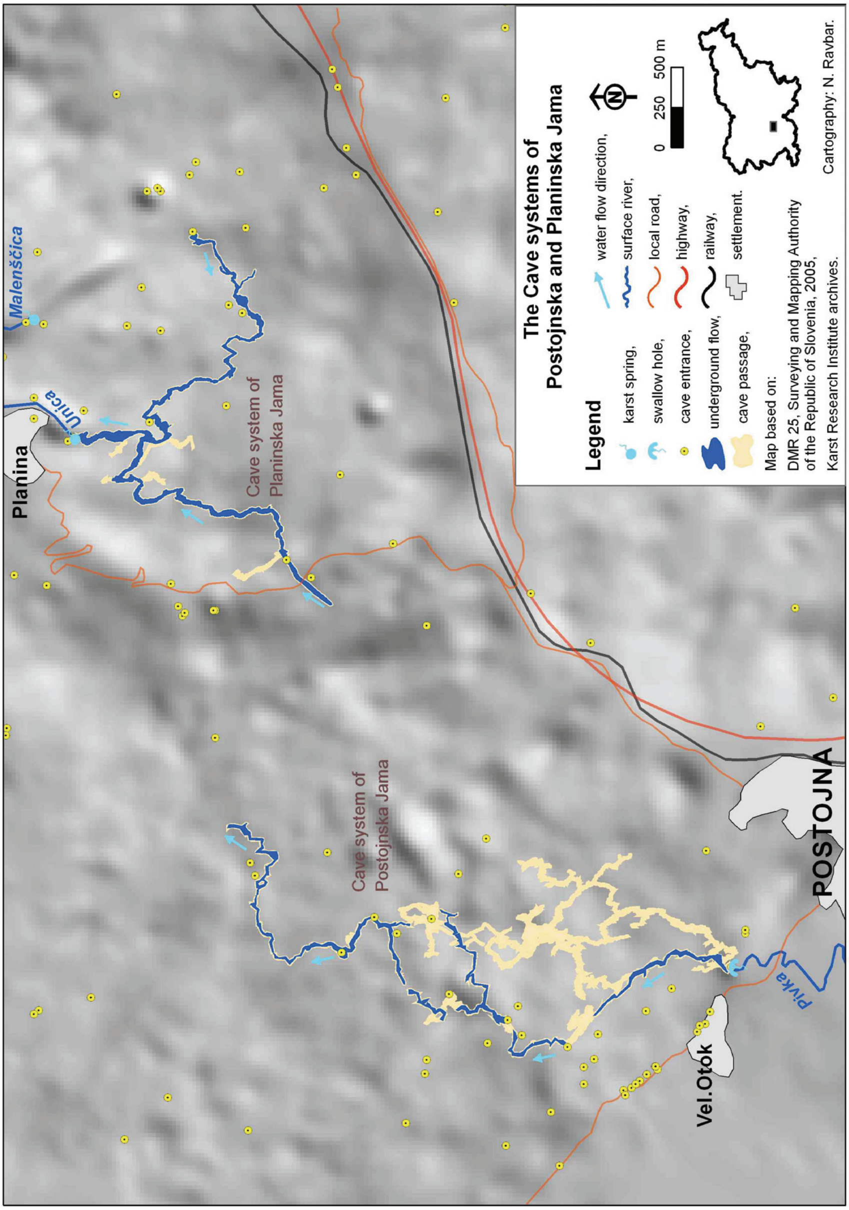


Figure 7.9: Where there is clear evidence on location of the underground water flow paths, as in case of the cave system of Postojnska and Planinska Jama in the immediate vicinity of the Malenščica water source, the area directly above them should be assigned higher vulnerability.

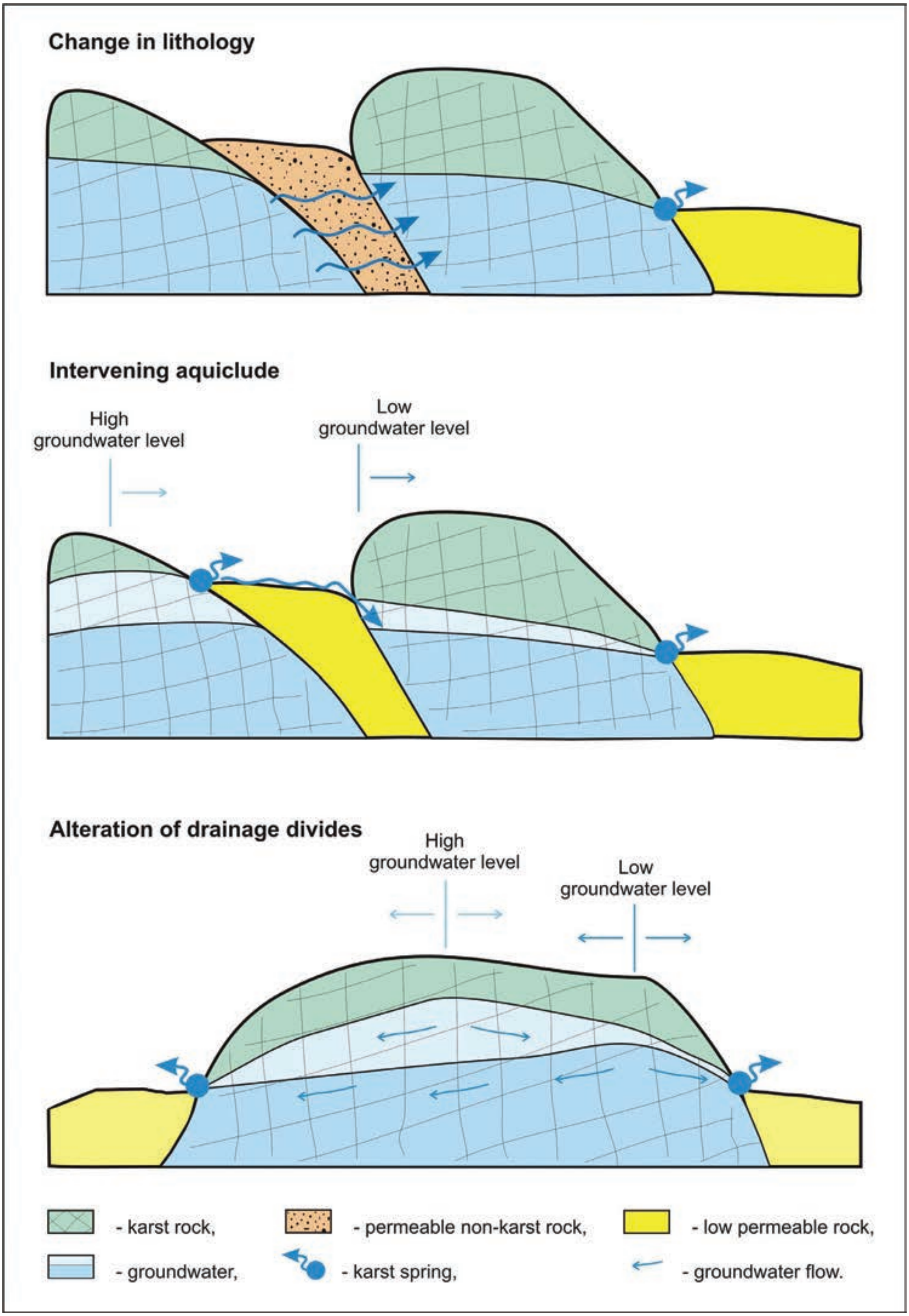


Figure 7.10: Different hydrogeological settings may drastically influence the extent of a spring's catchment area.

The **r sub-factor** (connection and contribution) indicates parts of the aquifer system that either always or rarely contribute to the source and are either directly or indirectly connected to and drained by the source (Fig. 7.10).

In this context we propose an assessment scheme that considers the hydrogeological structure of the aquifer system. We propose to distinguish between an inner zone that is always part of the catchment area, and an outer zone. A similar system is used in Ireland (Groundwater Protection Schemes, 1999).

The inner zone comprises parts of the system that always contribute to the spring and are directly connected to and drained by the spring. The groundwater velocities flowing towards the spring are very high. Therefore these areas should be classified as extremely vulnerable.

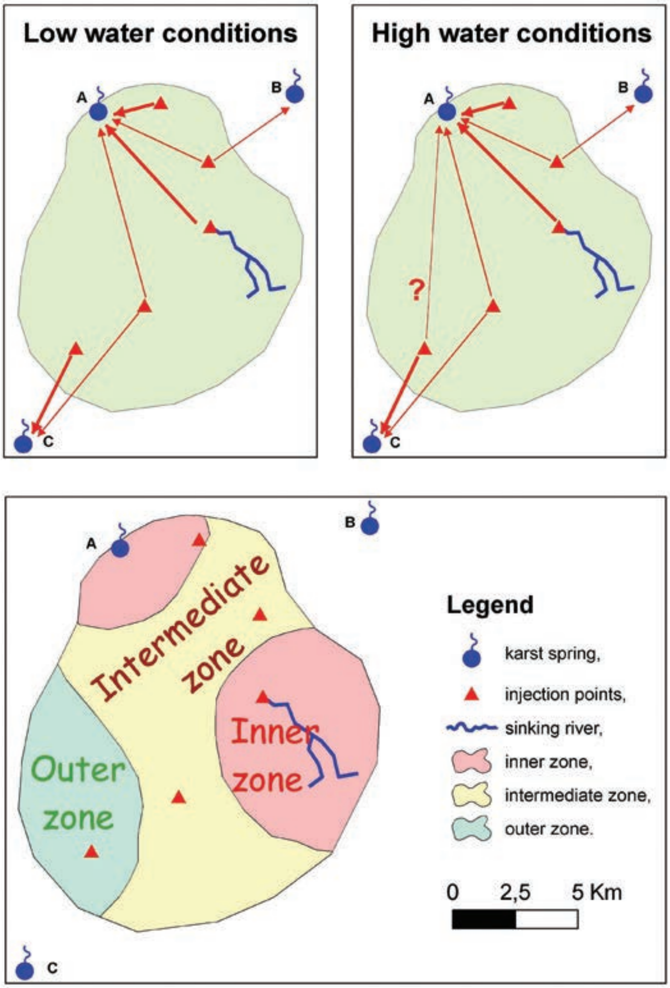


Figure 7.11: Illustration of the A source catchment division into inner, intermediate and outer zones.

The outer zone comprises parts of the system that contribute only a small portion of the total amount, are far away and/or groundwater flow velocities towards the spring are low. The outer zone could also comprise parts of the aquifer system that only temporarily (e.g. during high water conditions) contribute to the source, are indirectly connected to the spring (e.g. are separated by an aquiclude), as well as the parts for which we are not sure if they contribute to the source. Therefore the outer zone is classified as of low vulnerability. A moderate vulnerability is assigned to intermediate situations (Fig. 7.11).

The final K factor is a product of all three factors ranging from 0-125. Final values are subdivided into three classes. Values from 0-1 indicate high vulnerability of a source to contamination. Values from 1-30 indicate medium vulnerability and values from 30-125 indicate a high degree of protection and a very low vulnerability. The spatial distribution of the K factor is shown on the K map.

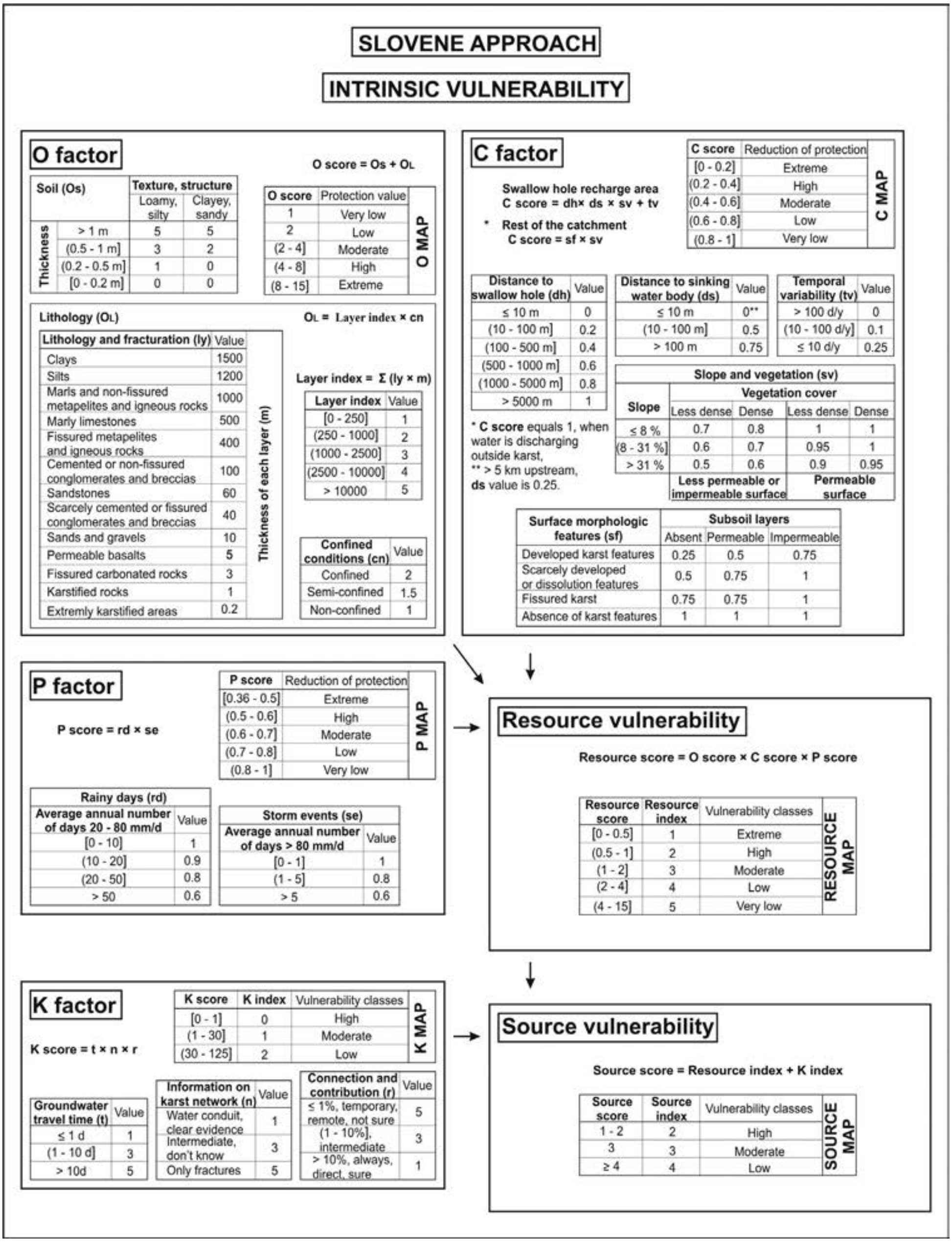
Within the proposed Slovene Approach the source vulnerability map is consequently obtained by combining the K factor and the resource vulnerability maps.

7.6 SOURCE PROTECTION ZONES DETERMINATION

In order to obtain a source vulnerability map, the K factor map should be superimposed on the resource vulnerability map. To enable combination of both scores, primarily K scores and resource scores have to be transformed in the pertinent indexes as shown in the assessment scheme (Fig. 7.12).

Consequently, the resulting source vulnerability equals the resource one where K factor value indicates high vulnerability. Where K factor value indicates medium or low vulnerability, the source vulnerability values are reduced in comparison to the resource ones.

The obtained source vulnerability map can be used as a basis for the delineation of source protection zones by simple transformation of the vulnerability classes into the protection zones. Insets of the separate factors’ maps should be added to the final presentation enabling the end user immediate insight of the situation and understanding which factor controls the final values of the particular area.



SLOVENE APPROACH

INTRINSIC VULNERABILITY

O factor

O score = Os + OL

Soil (Os)		Texture, structure	
		Loamy, silty	Clayey, sandy
Thickness	> 1 m	5	5
	(0.5 - 1 m]	3	2
	(0.2 - 0.5 m]	1	0
	[0 - 0.2 m]	0	0

O score	Protection value	
1	Very low	O MAP
2	Low	
(2 - 4]	Moderate	
(4 - 8]	High	
(8 - 15]	Extreme	

Lithology (OL)

OL = Layer index × cn

Lithology and fracturation (ly)	Value	Thickness of each layer (m)
Clays	1500	
Silts	1200	
Marls and non-fissured metapelites and igneous rocks	1000	
Marly limestones	500	
Fissured metapelites and igneous rocks	400	
Cemented or non-fissured conglomerates and breccias	100	
Sandstones	60	
Scarcely cemented or fissured conglomerates and breccias	40	
Sands and gravels	10	
Permeable basalts	5	
Fissured carbonated rocks	3	
Karstified rocks	1	
Extremly karstified areas	0.2	

Layer index = Σ (ly × m)

Layer index	Value
[0 - 250]	1
(250 - 1000]	2
(1000 - 2500]	3
(2500 - 10000]	4
> 10000	5

Confined conditions (cn)	Value
Confined	2
Semi-confined	1.5
Non-confined	1

C factor

Swallow hole recharge area
C score = dh× ds × sv + tv

* Rest of the catchment
C score = sf × sv

C score	Reduction of protection	
[0 - 0.2]	Extreme	C MAP
(0.2 - 0.4]	High	
(0.4 - 0.6]	Moderate	
(0.6 - 0.8]	Low	
(0.8 - 1]	Very low	

Distance to swallow hole (dh)	Value
≤ 10 m	0
(10 - 100 m]	0.2
(100 - 500 m]	0.4
(500 - 1000 m]	0.6
(1000 - 5000 m]	0.8
> 5000 m	1

Distance to sinking water body (ds)	Value
≤ 10 m	0**
(10 - 100 m]	0.5
> 100 m	0.75

Temporal variability (tv)	Value
> 100 d/y	0
(10 - 100 d/y]	0.1
≤ 10 d/y	0.25

* **C score** equals 1, when water is discharging outside karst,
** > 5 km upstream, **ds** value is 0.25.

Slope and vegetation (sv)				
Slope	Vegetation cover			
	Less dense	Dense	Less dense	Dense
≤ 8 %	0.7	0.8	1	1
(8 - 31 %]	0.6	0.7	0.95	1
> 31 %	0.5	0.6	0.9	0.95
	Less permeable or impermeable surface		Permeable surface	

Surface morphologic features (sf)	Subsoil layers		
	Absent	Permeable	Impermeable
Developed karst features	0.25	0.5	0.75
Scarcely developed or dissolution features	0.5	0.75	1
Fissured karst	0.75	0.75	1
Absence of karst features	1	1	1

P factor

P score = rd × se

P score	Reduction of protection	
[0.36 - 0.5]	Extreme	P MAP
(0.5 - 0.6]	High	
(0.6 - 0.7]	Moderate	
(0.7 - 0.8]	Low	
(0.8 - 1]	Very low	

Rainy days (rd)	
Average annual number of days 20 - 80 mm/d	Value
[0 - 10]	1
(10 - 20]	0.9
(20 - 50]	0.8
> 50	0.6

Storm events (se)	
Average annual number of days > 80 mm/d	Value
[0 - 1]	1
(1 - 5]	0.8
> 5	0.6

Resource vulnerability

Resource score = O score × C score × P score

Resource score	Resource index	Vulnerability classes	
[0 - 0.5]	1	Extreme	RESOURCE MAP
(0.5 - 1]	2	High	
(1 - 2]	3	Moderate	
(2 - 4]	4	Low	
(4 - 15]	5	Very low	

K factor

K score = t × n × r

K score	K index	Vulnerability classes	
[0 - 1]	0	High	K MAP
(1 - 30]	1	Moderate	
(30 - 125]	2	Low	

Groundwater travel time (t)	Value
≤ 1 d	1
(1 - 10 d]	3
> 10d	5

Information on karst network (n)	Value
Water conduit, clear evidence	1
Intermediate, don't know	3
Only fractures	5

Connection and contribution (r)	Value
≤ 1%, temporary, remote, not sure	5
(1 - 10%], intermediate	3
> 10%, always, direct, sure	1

Source vulnerability

Source score = Resource index + K index

Source score	Source index	Vulnerability classes	
1 - 2	2	High	SOURCE MAP
3	3	Moderate	
≥ 4	4	Low	

Fig. 7.12: Slovene Approach to resource and source intrinsic vulnerability assessment scheme.

8

THE SLOVENE APPROACH TO HAZARD AND RISK MAPPING

8.1 INTRODUCTORY REMARKS

Karst aquifers are particularly susceptible to contamination from generally surface derived contaminants. The reason can mainly be found in specific characteristics of water flow within karst aquifers, for which the limited protection function of the overlying layers and concentration of flow enable an easy and rapid pathway to the saturated zone, already described in chapter 2.

Since there is little opportunity for attenuation of contaminant until it reaches groundwater, spring or well, some serious contamination problems may result from different human activities. Therefore, studies on human impacts and its effects on karst groundwater and/or karst springs are becoming more and more important for proper protection.

Some countries use the concept of vulnerability evaluation as a basis to maintain good water quality. Nevertheless, vulnerability is not always a sufficient criterion for proper land use planning, since intrinsic vulnerability maps generally display the nature of an aquifer and do not consider the nature of a contaminant, nor the degree to which the aquifer is already under pressure.

Therefore information on actual and potential contamination, the likelihood of contaminant release and the importance or value of the groundwater or source should be considered as additional aspects for proper karst water management. In general, within the framework of (karst) water protection specific vulnerability maps, hazard and risk maps are often considered. Thus risk assessment and risk management techniques are increasingly used.

According to the European Commission emphasis (WFD, 2000) the European COST Action 620 proposed an approach to comprehensive risk assessment for the protection of carbonate aquifers (Daly *et al.*, 2002). It is based on intrinsic or specific vulnerability and hazard assessment, and has so far been applied in several different karst areas.

Furthermore, both the European Approach, as well as the Slovene legislation require evaluation of the water body importance as well (Daly *et al.*, 2004; Ur.l. RS 64/2004) and emphasize that consequently such applications would be more specific, sophisticated and contain more information on actual and potential contamination. The Irish protection scheme provides an example how the importance of the groundwater together with the vulnerability maps can be taken as a basis for the protection zoning (Groundwater

Protection Schemes, 1999). However, until now, no general cost-orientated evaluation of the possible damage has been accepted.

8.2 BASIC CONCEPTS

Even though an integrated approach on hazard and risk assessment, emanating from the European COST Action 620, is quite a complex concept and requires detailed data that are often not available in Slovenia, we used it as a background for the comprehensive proposal for the protection of karst water sources in Slovenia.

Based on the **origin-pathway-target model** (Fig. 5.5) the European conceptual framework implies a **vulnerability-hazard-risk approach** that allows generating maps for different purposes (i.e. for groundwater, source protection, for specific contaminants, etc.).

In the context of groundwater contamination, a **hazard** is defined as an existing and potential source of contamination resulting from human activities taking place mainly at the land surface (De Ketelaere *et al.*, 2004). Hazard classification is based on the type of human activities placed above and in the background of associated karst resources and sources. For this purpose the intensity, extent and duration of an imposed stress need to be quantified.

With regard to possible damage of groundwater, the term **risk** is used for the probability of a specific adverse consequence occurring. It takes into account the interaction between the natural characteristics of an aquifer i.e. the vulnerability of the aquifer, and the infiltrating contaminant load, pointing out the consequences for the groundwater if a hazardous event occurs (Daly *et al.*, 2004).

Within risk assessment, hazard poses actual and potential polluting activity (equivalent to origin), when it is likely to affect something of value – groundwater or source (equivalent to target). The risk of contamination of groundwater or source depends on the intrinsic vulnerability (equivalent to pathway) (De Ketelaere and Daly, 2004). Thus risk assessment is achieved by combining the intrinsic vulnerability map and hazard map.

Some initiatives have already highlighted a stronger inclusion of groundwater or source **importance** aspects in addition to the proposed risk assessment scheme. By the supplemented risk assessment scheme appropriate precautionary principles, preventive measures and actions can be taken (Novak, 1993b). In case of a contamination ecological, social and economical consequences can better be predicted, and also exposure to a hazard can to some extent be minimised and further risk reduced.

8.3 HAZARD ASSESSMENT

As regards the conceptual framework proposed by the COST Action 620 a hazard assessment considers the potential degree of harmfulness for each type of hazard. The purpose of the proposed hazard inventory is to cover all the various hazards that are considered relevant and to allow mapping, evaluation and assessment of the hazards in an economically feasible and practical manner. Thus, hazard evaluation is determined on hazard type and identification of noxiousness, quantity and likelihood of a contaminant release (De Ketelaere *et al.*, 2004).

8.3.1 HAZARD WEIGHTING

The differentiation of actual and potential hazards is primarily based on three main types of land use: infrastructure, agricultural and industrial activities, which are then subdivided in detail. A weighting value determining harmfulness of a hazard (H) is assigned to each hazard regarding a qualitative comparison of the potential damage to the groundwater or source (Fig. 8.1). The main criteria for weighting different hazards concern the toxicity of relevant substances associated with each type of hazard as well as their properties regarding solubility and mobility (De Ketelaere *et al.*, 2004).

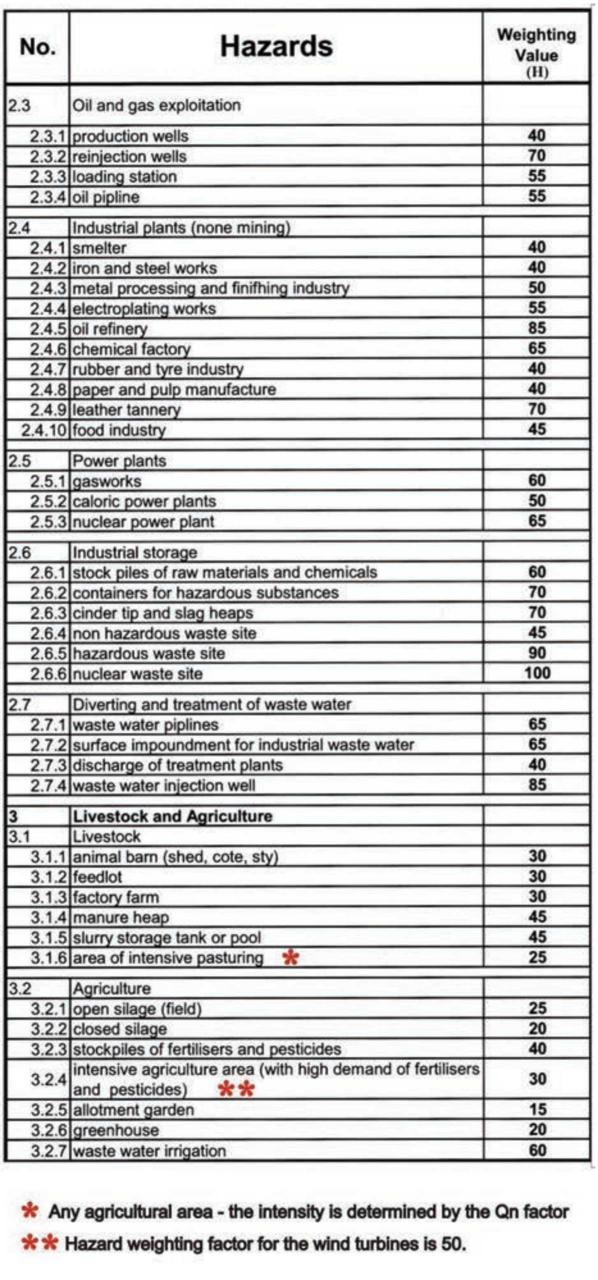
Regarding agriculture, very extensive agricultural activities can result in strong contamination of the groundwater mainly in case of accidental spillages. In contrast to the existing hazard weighting values proposed

No.	Hazards	Weighting Value (H)
1	**Infrastructural development**	
1.1	Waste Water	
1.1.1	urbanisation (leaking sewer pipes and sewer systems)	35
1.1.2	urbanisation without sewer systems	70
1.1.3	detached houses without sewer systems	45
1.1.4	septic tank, cesspool, latrine	45
1.1.5	sewer farm and waste water irrigation system	55
1.1.6	discharge from an inferior treatment plant	35
1.1.7	surface impoundment for urban waste water	60
1.1.8	runoff from paved surfaces	25
1.1.9	waste water discharge into surface water courses	45
1.1.10	waste water injection well	85
1.2	Municipal Waste	
1.2.1	garbage dump, rubbish bin, litter bin	40
1.2.2	waste loading station and scrap yard	40
1.2.3	sanitary landfill	50
1.2.4	spoils and building rubble depository	35
1.2.5	sludge from treatment plants	35
1.3	Fuels	
1.3.1	storage tank, above ground	50
1.3.2	storage tank, underground	55
1.3.3	drum stock pile	50
1.3.4	tank yard	50
1.3.5	fuel loading station	60
1.3.6	gasoline station	60
1.3.7	fuel storage cavern	65
1.4	Transport and traffic	
1.4.1	road, unsecured	40
1.4.2	road tunnel, unsecured	40
1.4.3	road haulier depot	35
1.4.4	car parking area	35
1.4.5	railway line	30
1.4.6	railway tunnel, unsecured	30
1.4.7	railway station	35
1.4.8	marshalling yard	40
1.4.9	runway	35
1.4.10	pipline of hazardous liquids	60
1.5	Recreational facilities	
1.5.1	tourist urbanisation	30
1.5.2	camp ground	30
1.5.3	open sport stadion	25
1.5.4	golf course	35
1.5.5	skiing course	25
1.6	Diverse hazards	
1.6.1	graveyard	25
1.6.2	animal burial	35
1.6.3	dry cleaning premises	35
1.6.4	transformer station	30
1.6.5	military installations and dereliction	35
2	**Industrial activities**	
2.1	Mining (in operation and abandoned)	
2.1.1	mine, salt	60
2.1.2	mine, other non-metallic	70
2.1.3	mine, ore	70
2.1.4	mine, coal	70
2.1.5	mine, uranium	80
2.1.6	outdoor stock piles of hazardous raw material	85
2.1.7	ore milling and enrichment facilities	70
2.1.8	mine waste heap and dirt refuse	70
2.1.9	ore tailings	70
2.1.10	mine drainage	65
2.1.11	tailing pond	65
2.2	Excavation sites	
2.2.1	Excavation and embankment for development	10
2.2.2	gravel and sand pit	30
2.2.3	quarry	25

by the European Approach (De Ketelaere *et al.*, 2004) we propose not to distinguish between intensive and extensive agriculture, as the intensity is determined (reduced or increased) by ranking procedure.

Moreover, in Slovenia there are serious plans to build wind power stations on some karst mountain ridges. Wind exploitation is indeed an environmentally undisputed way of gaining energy; however, each wind turbine holds about 200 l of different oils for its uninterrupted operation. In operation under normal conditions the influences of the wind power stations to the karst water is negligible, however, the risk of contamination is higher in times of construction, maintenance (oil exchange) and in case of unexpected events or accidents when the turbines would be damaged or even pulled down e.g. due to gust of wind, earthquake, a lightning strike or fire. In such cases dangerous substances could directly enter karst underground and contaminate groundwater (Ravbar and Kovačič, 2006b).

Therefore also wind power stations should be classified as hazards and thus their degree of harmfulness appropriately evaluated. Considering hazard weighting values classified for the fuels and power plants ranging from 50 to 65, we estimate wind power stations as being least dangerous, resembling



No.	Hazards	Weighting Value (H)
2.3	Oil and gas exploitation	
2.3.1	production wells	40
2.3.2	reinjection wells	70
2.3.3	loading station	55
2.3.4	oil pipline	55
2.4	Industrial plants (none mining)	
2.4.1	smelter	40
2.4.2	iron and steel works	40
2.4.3	metal processing and finifhing industry	50
2.4.4	electroplating works	55
2.4.5	oil refinery	85
2.4.6	chemical factory	65
2.4.7	rubber and tyre industry	40
2.4.8	paper and pulp manufacture	40
2.4.9	leather tannery	70
2.4.10	food industry	45
2.5	Power plants	
2.5.1	gasworks	60
2.5.2	caloric power plants	50
2.5.3	nuclear power plant	65
2.6	Industrial storage	
2.6.1	stock piles of raw materials and chemicals	60
2.6.2	containers for hazardous substances	70
2.6.3	cinder tip and slag heaps	70
2.6.4	non hazardous waste site	45
2.6.5	hazardous waste site	90
2.6.6	nuclear waste site	100
2.7	Diverting and treatment of waste water	
2.7.1	waste water piplines	65
2.7.2	surface impoundment for industrial waste water	65
2.7.3	discharge of treatment plants	40
2.7.4	waste water injection well	85
3	**Livestock and Agriculture**	
3.1	Livestock	
3.1.1	animal barn (shed, cote, sty)	30
3.1.2	feedlot	30
3.1.3	factory farm	30
3.1.4	manure heap	45
3.1.5	slurry storage tank or pool	45
3.1.6	area of intensive pasturing *	25
3.2	Agriculture	
3.2.1	open silage (field)	25
3.2.2	closed silage	20
3.2.3	stockpiles of fertilisers and pesticides	40
3.2.4	intensive agriculture area (with high demand of fertilisers and pesticides) **	30
3.2.5	allotment garden	15
3.2.6	greenhouse	20
3.2.7	waste water irrigation	60

*** Any agricultural area - the intensity is determined by the Qn factor**

**** Hazard weighting factor for the wind turbines is 50.**

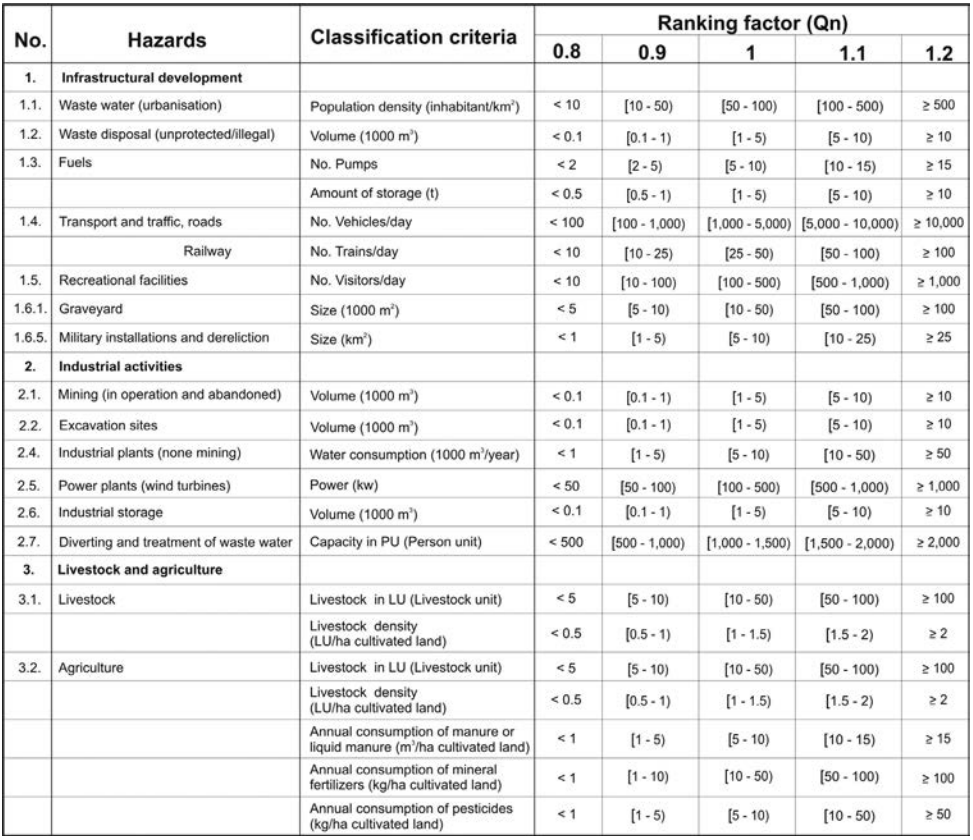
Figure 8.1: Hazard weighting values proposed by the European Approach (De Ketelaere et al., 2004).

storage tanks. Therefore we propose a weighting value 50. However, further evaluations should confirm or reject this view.

8.3.2 HAZARD RANKING

Furthermore, ranking procedure (Qn factor) for a comparison between hazards of the same type is foreseen. However, according to the proposed framework COST Action 620 it is only recommended ranking factor to range between 0.8 and 1.2 regarding the evaluation within the same category of hazards. Definitive classification within each hazard type is left to the individual users.

Therefore we suggest supplementing the hazard assessment in the proposed Slovene Approach. Thus in the enclosed list of selected human activities relevant ranking factors are proposed (Fig. 8.2). Regarding the European Approach references (De Ketelaere *et al.*, 2004) the proposed values depend mainly on the degree of toxicity of relevant



No.	Hazards	Classification criteria	Ranking factor (Qn)				
			0.8	0.9	1	1.1	1.2
1.	**Infrastructural development**						
1.1.	Waste water (urbanisation)	Population density (inhabitant/km^2)	< 10	[10 - 50)	[50 - 100)	[100 - 500)	≥ 500
1.2.	Waste disposal (unprotected/illegal)	Volume (1000 m^3)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
1.3.	Fuels	No. Pumps	< 2	[2 - 5)	[5 - 10)	[10 - 15)	≥ 15
		Amount of storage (t)	< 0.5	[0.5 - 1)	[1 - 5)	[5 - 10)	≥ 10
1.4.	Transport and traffic, roads	No. Vehicles/day	< 100	[100 - 1,000)	[1,000 - 5,000)	[5,000 - 10,000)	≥ 10,000
	Railway	No. Trains/day	< 10	[10 - 25)	[25 - 50)	[50 - 100)	≥ 100
1.5.	Recreational facilities	No. Visitors/day	< 10	[10 - 100)	[100 - 500)	[500 - 1,000)	≥ 1,000
1.6.1.	Graveyard	Size (1000 m^2)	< 5	[5 - 10)	[10 - 50)	[50 - 100)	≥ 100
1.6.5.	Military installations and dereliction	Size (km^2)	< 1	[1 - 5)	[5 - 10)	[10 - 25)	≥ 25
2.	**Industrial activities**						
2.1.	Mining (in operation and abandoned)	Volume (1000 m^3)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
2.2.	Excavation sites	Volume (1000 m^3)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
2.4.	Industrial plants (none mining)	Water consumption (1000 m^3/year)	< 1	[1 - 5)	[5 - 10)	[10 - 50)	≥ 50
2.5.	Power plants (wind turbines)	Power (kw)	< 50	[50 - 100)	[100 - 500)	[500 - 1,000)	≥ 1,000
2.6.	Industrial storage	Volume (1000 m^3)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
2.7.	Diverting and treatment of waste water	Capacity in PU (Person unit)	< 500	[500 - 1,000)	[1,000 - 1,500)	[1,500 - 2,000)	≥ 2,000
3.	**Livestock and agriculture**						
3.1.	Livestock	Livestock in LU (Livestock unit)	< 5	[5 - 10)	[10 - 50)	[50 - 100)	≥ 100
		Livestock density (LU/ha cultivated land)	< 0.5	[0.5 - 1)	[1 - 1.5)	[1.5 - 2)	≥ 2
3.2.	Agriculture	Livestock in LU (Livestock unit)	< 5	[5 - 10)	[10 - 50)	[50 - 100)	≥ 100
		Livestock density (LU/ha cultivated land)	< 0.5	[0.5 - 1)	[1 - 1.5)	[1.5 - 2)	≥ 2
		Annual consumption of manure or liquid manure (m^3/ha cultivated land)	< 1	[1 - 5)	[5 - 10)	[10 - 15)	≥ 15
		Annual consumption of mineral fertilizers (kg/ha cultivated land)	< 1	[1 - 10)	[10 - 50)	[50 - 100)	≥ 100
		Annual consumption of pesticides (kg/ha cultivated land)	< 1	[1 - 5)	[5 - 10)	[10 - 50)	≥ 50

Figure 8.2: Slovene Approach to hazard ranking classification.

substances associated with each type of human activity, time and duration a hazard is posed, as well as its quantity.

The proposed ranking procedure has been developed for Slovene circumstances in order to indicate lower or higher amounts respectively toxicity of the hazards of the same type and particularly to enable hazard comparison within the country. Thus also the classification criteria for the hazardous activities involved basis on the extreme ranges present in Slovenia, which, on the other hand, could be much more different in other countries. In the proposal only the most frequent hazards are listed. To deal with hazards that are not included in the list, the user is encouraged to extend it.

Urban areas with or without sewage systems have been ranked according to the population density from < 10 to ≥ 500 inhabitants/km^2, considering that the higher the density the higher the environmental impact deriving from greater paved surface, greater wastewater quantity and other kind of contamination.

Waste disposal, mining and excavation sites, as well as industrial storage sites have been ranked according to their volume from < 100 to ≥ 10,000 m^3 considering that the greater the volume the greater the environmental impact due to the bigger amounts of garbage or removed material. In addition, the bigger the mining and excavation site the bigger is the intensity of production.

Fuel stations or depots have been ranked according to the number of pumps ranging from < 2 to ≥ 15 or according to the amount of fuel storage ranging from < 0.5 to ≥ 10 t. Roads and railways have been ranked considering the average number of vehicles or trains per day. Roads are classified from < 100 to ≥10,000 vehicles per day and railways from < 10 to ≥ 100 trains per day.

Recreational facilities have been ranked according to the number of visitors per day from < 10 to ≥ 1,000. Graveyards and military installations have been ranked according to their spatial extension. Graveyards are classified from < 5,000 to ≥100,000 m^2 and military installations, together with their derelictions from < 1 to ≥ 25 km^2.

Industrial plants have been ranked according to average annual water consumption ranging from < 1,000 to ≥ 50,000 m^3/year. The wastewater treatment plants have been ranked according to their capacity in PU (Person units) ranging from < 500 to ≥ 2,000. The wind turbines have been ranked according to their power from < 50 to ≥ 1,000 kW.

Agriculture often includes several different types of hazards (e.g. farm buildings, fertilizers, etc.). The agriculture harmfulness to the environment depends mainly on its intensity, which can be indirectly assessed on the basis of land use, i.e. of cultivated land percentage. The intensity of agriculture reflects in consumption of fertilizers and pesticides as well. Furthermore, higher concentration of livestock indicates higher environmental impact, as well as the amount of manure or liquid manure used up in the cultivated areas. Consequently, the average annual nitrogen input reflects the intensity of agriculture as well.

Based on these facts, we ranked farms with prevailing animal husbandry, farming areas or objects according to their size by number of livestock in LU (Livestock units) ranging from < 5 to ≥ 100 or livestock density ranging from < 0.5 to ≥ 2 LU/ha cultivated land. In addition, agricultural areas and objects have been ranked according to either number of livestock, livestock density, annual consumption of manure or liquid manure from < 1 to ≥ 15 m^3/ha cultivated land, annual consumption of mineral fertilizers from < 1 to ≥ 100 kg/ha cultivated land or annual consumption of pesticides from < 1 to ≥ 50 kg/ha cultivated land. Thus an appropriate criterion for each hazard type should be chosen.

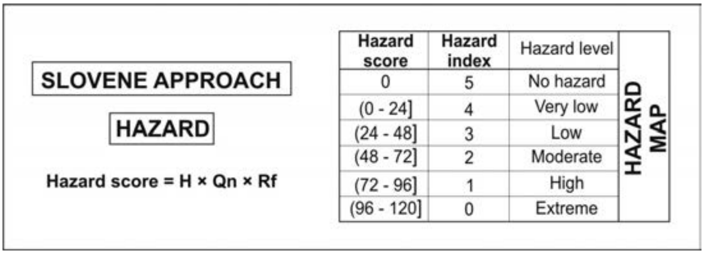
8.3.3 LIKELIHOOD OF A CONTAMINANT RELEASE

Furthermore, in order to provide an assessment of the probability for a contamination event to occur, for each hazard a reduction factor (Rf) is considered in addition according to the conceptual framework proposed by the COST Action 620. When assessing the probability that a contamination might occur, the technical status, level of maintenance, surrounding conditions, security measures and other factors should be considered.

According to the European Approach the reduction factor is 1 when no information on the probability for a contamination event to occur is available. Lower values imply positive information concerning the reduction of the likelihood. However, the authors recommend using small deviations from 1 and even the square root of the reduction values in order to avoid minimization of the effects of hazards with high toxic potential (De Ketelaere *et al.*, 2004). We propose to use the same concept for the reduction factor assessment in the Slovene Approach as well.

8.3.4 PRODUCTION OF HAZARD MAPS

The final hazard score describes the degree of harmfulness of each hazard. It is assessed by multiplying the hazard weighting (H), ranking (Qn) and reduction factors (Rf) for each hazard as proposed by the COST Action 620 (De Ketelaere *et al.*, 2004). In the Slovene Approach the resulting hazard values are transformed in six hazard index values to enable further evaluation of hazard score for the risk assessment. The hazard index values are then ranked according to six possible levels of impact and shown on the map (Fig. 8.3). Even though the COST Action 620 suggests that "no/very low hazard" level is



Hazard score = H × Qn × Rf

Hazard score	Hazard index	Hazard level
0	5	No hazard
(0 - 24]	4	Very low
(24 - 48]	3	Low
(48 - 72]	2	Moderate
(72 - 96]	1	High
(96 - 120]	0	Extreme

Figure 8.3: Hazard assessment scheme.

considered as one class, we propose rather to make two classes, distinguishing between "no hazard" and "very low hazard".

A hazard assessment thus requires the spatial information (location, distribution) and the description information of the existing and potential degree of harmfulness. Information on various hazards can be gained from the topographical maps, digital orthographic photographs, governmental and local databases, direct inquiries and field surveying.

The distribution and location of different kinds of hazards can be simply shown on an unclassified map, where hazards are represented by means of symbols and signatures. On the basis of the hazard index ranking, the classified map indicates their potential degree of harmfulness (De Ketelaere *et al.*, 2004).

8.4 IMPORTANCE OF WATER RESOURCE OR SOURCE

Prior considerations of risk analysis were mainly restricted to the protection capability and the adverse consequences in case of contamination. In this framework (karst) resources have mainly been considered to have a high value. Such appraisal derives from the European legislation, by which all groundwater is regarded as an important natural resource and therefore requires the highest protection against contamination and safety measures.

Nevertheless, distinction should be made to enable prioritisation procedure for protection and sanitation. Moreover, the population and economic expansion, growing demand of land for urbanisation and industrialisation, as well as numerous other socio-economic processes, increase the pressures on the environment and the need for drinking water. Therefore, a (cost-oriented) evaluation of the possible damage to water resource or source is necessary. Thus, the COST Action 620 programme proposes risk estimation to be supplemented by the evaluation of the damage to the ecological, social and economic aspects (Hötzl *et al.*, 2004).

Therefore, in the proposed Slovene Approach we suggest a water importance assessment, which has been developed considering Slovene circumstances. Regarding Slovene legislation each individual water source should be protected. Consequently, the source importance should be evaluated, but the proposed scheme could also be applied to a resource importance assessment.

The evaluation of (re)source importance considers its social importance, conducive to public benefit, economic importance for either agricultural or other (industrial, tourist, etc.) activities and ecologic importance. Therefore three sub-factors are considered.

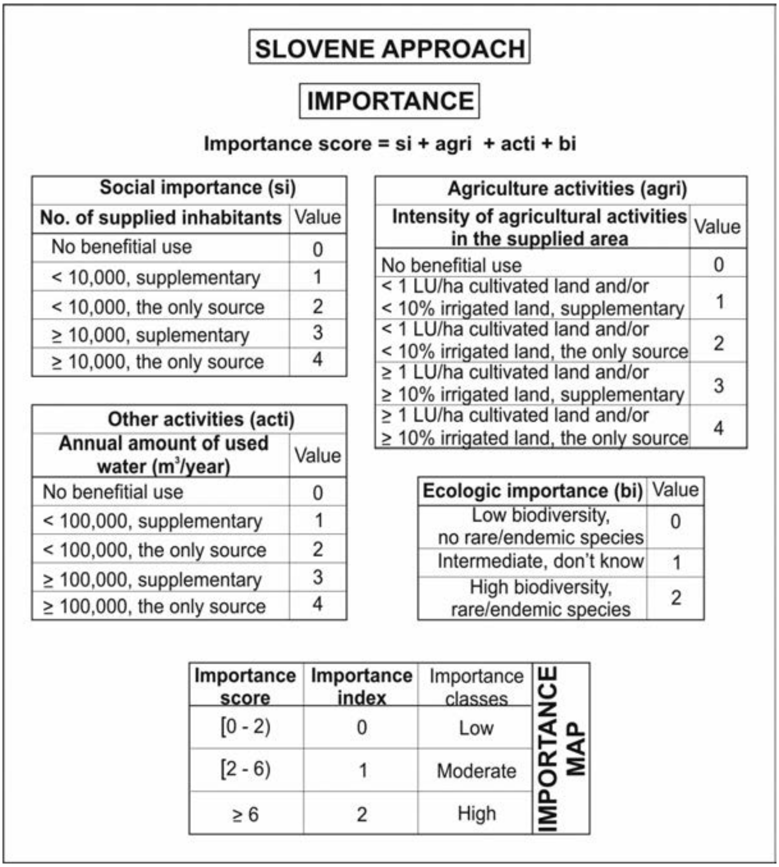
The **si sub-factor** (social importance) is evaluated on basis of the number of inhabitants that are supplied by the water source. The **agri sub-factor** (agricultural activities) is obtained by the intensity of the agricultural activities in the area supplied by a respective source – the livestock density and intensity of irrigation as a basis (expressed in LU/ha cultivated land or percentage of irrigated land). The **acti sub-factor** (other activities) is obtained by the average annual amount of used water in m^3. The **bi sub-factor** (ecologic importance) is obtained by the evaluation of the spring as an especially valuable ecosystem.

Each sub-factor, except the bi sub-factor (ecologic importance), is determined also regarding its function, whether the source is:

– momentarily the only possible source, irreplaceable and there is no economic or technologic possibility of gaining any other water source,
– a supplementary source, occasionally in use or covers a part of the needs,
– not used source or source of no beneficial use.

The final value is obtained by summing up all the sub-factors values and is then subdivided in three classes of importance. In order to enable further evaluation of the importance score for the risk assessment the resulting values are transformed in three importance index values (Fig. 8.4).

Source importance assessment thus requires information that can be gained from various governmental and local databases, expert appraisals, direct inquiries and field surveying.



SLOVENE APPROACH

IMPORTANCE

Importance score = si + agri + acti + bi

Social importance (si)	
No. of supplied inhabitants	Value
No benefitial use	0
< 10,000, supplementary	1
< 10,000, the only source	2
≥ 10,000, suplementary	3
≥ 10,000, the only source	4

Agriculture activities (agri)	
Intensity of agricultural activities in the supplied area	Value
No benefitial use	0
< 1 LU/ha cultivated land and/or < 10% irrigated land, supplementary	1
< 1 LU/ha cultivated land and/or < 10% irrigated land, the only source	2
≥ 1 LU/ha cultivated land and/or ≥ 10% irrigated land, supplementary	3
≥ 1 LU/ha cultivated land and/or ≥ 10% irrigated land, the only source	4

Other activities (acti)	
Annual amount of used water (m^3/year)	Value
No benefitial use	0
< 100,000, supplementary	1
< 100,000, the only source	2
≥ 100,000, supplementary	3
≥ 100,000, the only source	4

Ecologic importance (bi)	Value
Low biodiversity, no rare/endemic species	0
Intermediate, don't know	1
High biodiversity, rare/endemic species	2

Importance score	Importance index	Importance classes	IMPORTANCE MAP
[0 - 2)	0	Low	
[2 - 6)	1	Moderate	
≥ 6	2	High	

Figure 8.4: Slovene Approach to water resource/source importance assessment scheme.

Similar to the approach taken in Ireland (Groundwater Protection Schemes, 1999), we propose to take the importance of the source together with the vulnerability map as the basis for the protection zoning. Moreover, the importance of the sources can also be included in the risk assessment in order the better to plan land use and human activities. Namely, in precautionary measures and remediation programmes a priority should be given to the source that has higher importance.

8.5 RISK ASSESSMENT

The risk analysis identifies the existing or potential hazards and exposure to contamination that need to be addressed in order to provide the basis for taking action to ensure groundwater or source protection (Daly *et al.*, 2004). The areas marked with high risk highlight the necessity to act, e.g. by improving, sanitizing and/or removing hazards or adjusting land use practices.

For risk assessment COST Action 620 distinguished two types of risk; risk intensity and risk sensitivity forming total risk assessment. We propose to use the same concept for the risk assessment in the Slovene Approach as well.

8.5.1 RISK INTENSITY

Risk intensity provides an overview, on which surfaces a contamination is likely to occur and estimates the processes that can lead to reduction of the contamination. It describes the portion (or concentration) of contaminants reaching the target. Risk intensity maps can thus be evaluated by the intersection of intrinsic vulnerability and hazard maps (Hötzl, 2004).

8.5.2 TOTAL RISK ASSESSMENT

COST Action 620 also highlighted the importance of risk sensitivity being incorporated into the risk assessment, valuating mainly ecological and economical aspects (value of a groundwater and/or source) and hence the damage that may result from a given risk intensity. Thus, total risk can be assessed, which is a linkage of the degree of a potential contamination event with the evaluation of the consequences if the event actually occurred (Hötzl, 2004).

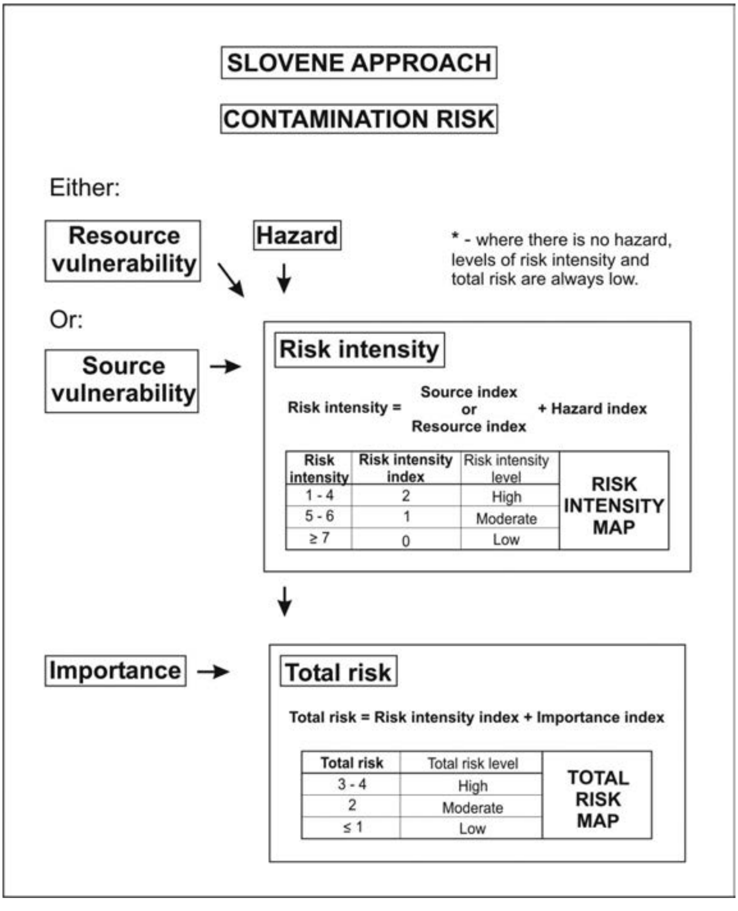
It should be emphasised that within COST Action 620 no particular guidelines for the risk sensitivity assessment have been given. Nevertheless, in this research the framework of the particular water resource or source valuation assessment scheme and its inclusion in total risk assessment has been proposed, as presented in the previous section.

Furthermore, in this research detailed risk assessment scheme incorporating the intrinsic vulnerability assessment has been developed, together with hazard assessment proposed by the European Approach and the water sources importance value.

Resembling the European Approach also the Slovene Approach foresees the final risk intensity map to be obtained by taking into account both intrinsic vulnerability map (resource or source) and a hazard map. Thus, vulnerability and hazard indexes should be summed up.

The final results are divided in three risk intensity classes. After the European Approach recommendations even very low or low hazard level can subscribe to medium or high risk if the vulnerability is extreme or high.

Adding a resource or source importance index to the risk intensity index, a total risk of a resource or source can be obtained. The final values are classified in three total risk



Risk intensity	Risk intensity index	Risk intensity level
1 - 4	2	High
5 - 6	1	Moderate
≥ 7	0	Low

Total risk	Total risk level
3 - 4	High
2	Moderate
≤ 1	Low

Figure 8.5: Slovene Approach to total risk assessment.

levels implicating higher degrees if the source or resource importance is high and lower degrees if the source or resource importance is low. Thus, where there are hazards, there is high risk everywhere where vulnerability is extreme or high independently of hazard level and if source or resource importance is high; however, there is no high risk if the source or resource importance is low. Where there is no hazard, levels of risk intensity and total risk are always low (Fig. 8.5).

The Slovene Approach hence provides a comprehensive risk analyses (karst groundwater and source vulnerability analyses, hazard and risk analyses) that should be suitable for the proper karst groundwater and source management. It is applicable to solving questions arising from resource and/or source protection and land use strategies. Furthermore, it is a practical tool by helping to avoid the contamination of water present beneath contamination land as well.

II
APPLICATION

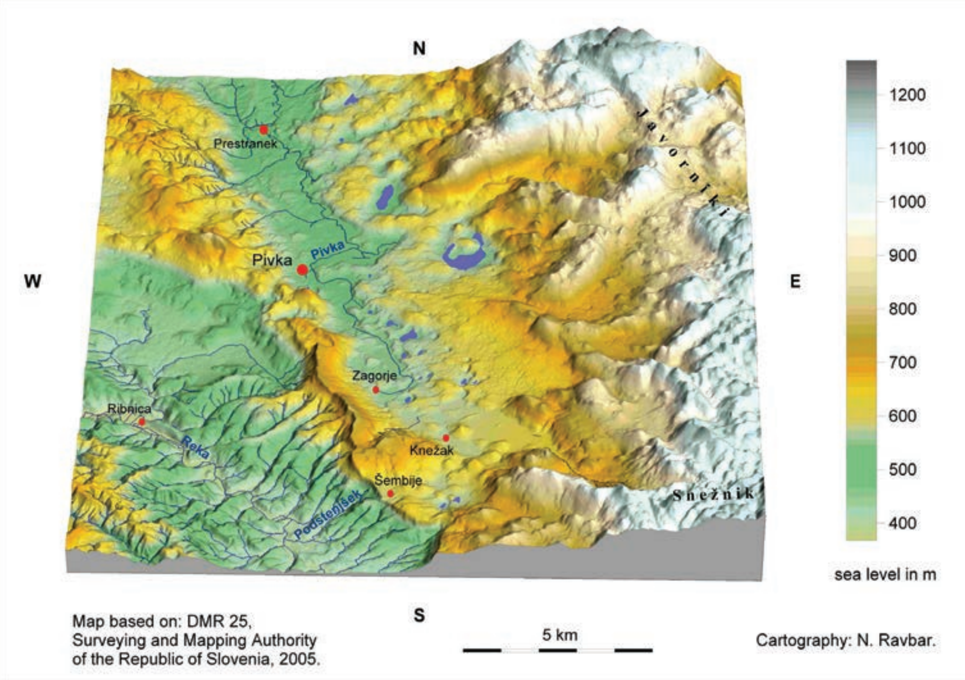
9

HYDROGEOLOGICAL CHARACTERISATION OF THE STUDIED AREA

9.1 THE PODSTENJŠEK KARST SPRINGS

Karst springs of the Podstenjšek are situated near the Šembije village under the Snežnik mountain in south-western Slovenia. Karst water outflows in five permanent springs. At high waters numerous smaller springs are activated also. At times of extremely high water conditions water also bursts from the cave of Kozja luknja, which is situated 35 m above the springs.

All the water joins in a common stream, called the Podstenjšek stream. After ap-



Map based on: DMR 25,
Surveying and Mapping Authority
of the Republic of Slovenia, 2005.

Cartography: N. Ravbar.

Figure 9.1: Geographical situation of the studied area.

proximately three kilometres it flows into the Reka river as its right tributary. Since 1992 one of the springs has been captured for local drinking water supply.

9.2 OVERVIEW OF PREVIOUS RESEARCH

Despite one of the springs being captured for drinking water supply, no integrated studies have been done yet. Only a few general and detailed geological and hydrological researches have been done so far. Some early data about the Podstenjšek can be found in the study of the practical needs of the water management and drinking water supply plans of Trieste made in 1882, where Podstenjšek is mentioned as a potential source for drinking water supply (Relazione ..., 1882). Nevertheless these data are very modest.

In the beginning of the 20th century Putick (Anonim., 1928) and Cumin (1929) described geological, morphological and hydrological characteristics of the Upper Pivka valley where also the major part of the springs' catchment area extends.

General geological, hydrological and speleological investigations of the wider region have also been carefully studied in the monograph *Il Timavo*. There periodical measurements of the Podstenjšek discharges made in the second half of the 19th century and in the first half of the 20th century are noted and plans of the caves of Kozja luknja and the nearby Zatrep are published (Boegan, 1938).

A plan of the Kozja luknja has also been published in the book *Duemila Grotte* (Bertarelli and Boegan, 1926), while the first cave mentioned from this area was the cave Pod Jamo Tabor (Luknja pod gradom), already described by the Slovene nobleman and historian Valvasor in his *Die Ehre deß Hertzogthums Crain* (1689, 1877a, 1877b; Rupel, 1978).

In the second half of the 20th century a few works discussing the geological circumstances of the Upper Pivka valley have been published. Pleničar studies tectonic window near Knežak (1959) and fossil fauna of Cretaceous layers of the Snežnik mountain (1960). Placer (1981) studies the thrusted structural units of the Snežnik thrust sheet that is covering the Komen thrust sheet within the framework of *Geologic structure of southwest Slovenia*. In a study *The contribution to Water Economy Basis of Pivka* Gospodarič (1989) collects, discusses and supplements some data about the geological structure and hydrogeological characteristics of the western part of the Pivka valley.

In the paper *Pliocene Pivka* Melik (1951) discusses hydrological characteristics and changes of the Pivka river flow in the past. He also defines the course of the watershed between the Adriatic and the Black Sea that was according to Melik formed already in the Pliocene. Jenko (1959) and Habič (1984, 1989) have written about the karst bifurcation on the Adriatic and the Black Sea watershed as well.

Hydrological circumstances, groundwater connections and intermittent lakes' appearance at the high water level in the Upper Pivka valley are described in numerous articles (Habič, 1968, 1975; Kranjc, 1985; Ravbar and Šebela, 2004;

Figure 9.2: One of the Podstenjšek springs (photo: N. Ravbar).

Kovačič and Habič, 2005) and others.

Klemenčič (1959) publishes a complex overview of the natural and human characteristics of the region between the Snežnik and the Slavnik mountains. Also Melik describes natural and human characteristics of the Upper Pivka and the Reka river valley (1960). Brodar (1992) writes about the stone tool from the Mesolithic site of Pod Črmukljo near Šembije, a rock shelter, in which people at least periodically lived for some length of time. The bone remains of the Holocene fauna from this site are described by Pohar (1986).

In the period between 1983 and 1988 detailed hydrological investigation of the Upper Pivka valley have been accomplished for the increase of the drinking water needs. In these investigations fundamental hydrogeological and hydrological research of the Kozja luknja and hydrogeological mapping of the surrounding were accomplished for the determination of the protection area of the Podstenjšek water source (Krivic *et al.*, 1983, 1984, 1986, 1987, 1988). Furthermore, in his diploma Kovačič (2001) discusses the degree and the importance of the Ilirska Bistrica municipality water sources protection among which is also the Podstenjšek water source.

In 2002 *Expert basis for the water sources of the Ilirska Bistrica protection* has been elaborated due to the changed legal definitions considering European directives. These include groundwater vulnerability maps and water protection zones of the water sources of the Ilirska Bistrica municipality (Petauer *et al.*, 2002). For this purpose detailed geological and hydrogeological mapping was carried out. Hence, hydrogeological maps and groundwater vulnerability maps, but no source vulnerability maps, were prepared. Unfortunately within water protection zones delineation the necessary study of the recharge relations, hydrodynamic characteristics of flow, discharge relations or tracing tests in the water sources catchment areas have not been done.

Recently quite some specific studies have been carried out such as the diploma works of Logar (2005) describing geographical characteristics of the Podstenjšek springs and Guglielmetti (2007) applying two of the intrinsic vulnerability methods to the springs' catchment. Furthermore the physico-chemical properties of the Podstenjšek travertine deposition have been studied by Kogovšek (2006) and the relief evolution of the Upper Pivka has been discussed by Kovačič (2006).

The Podstenjšek water source is not yet protected, even though the expert basis for the water source protection and the proposal of the decree on water protection zones have already been made.

9.3 GEOLOGICAL AND HYDROLOGICAL SETTINGS

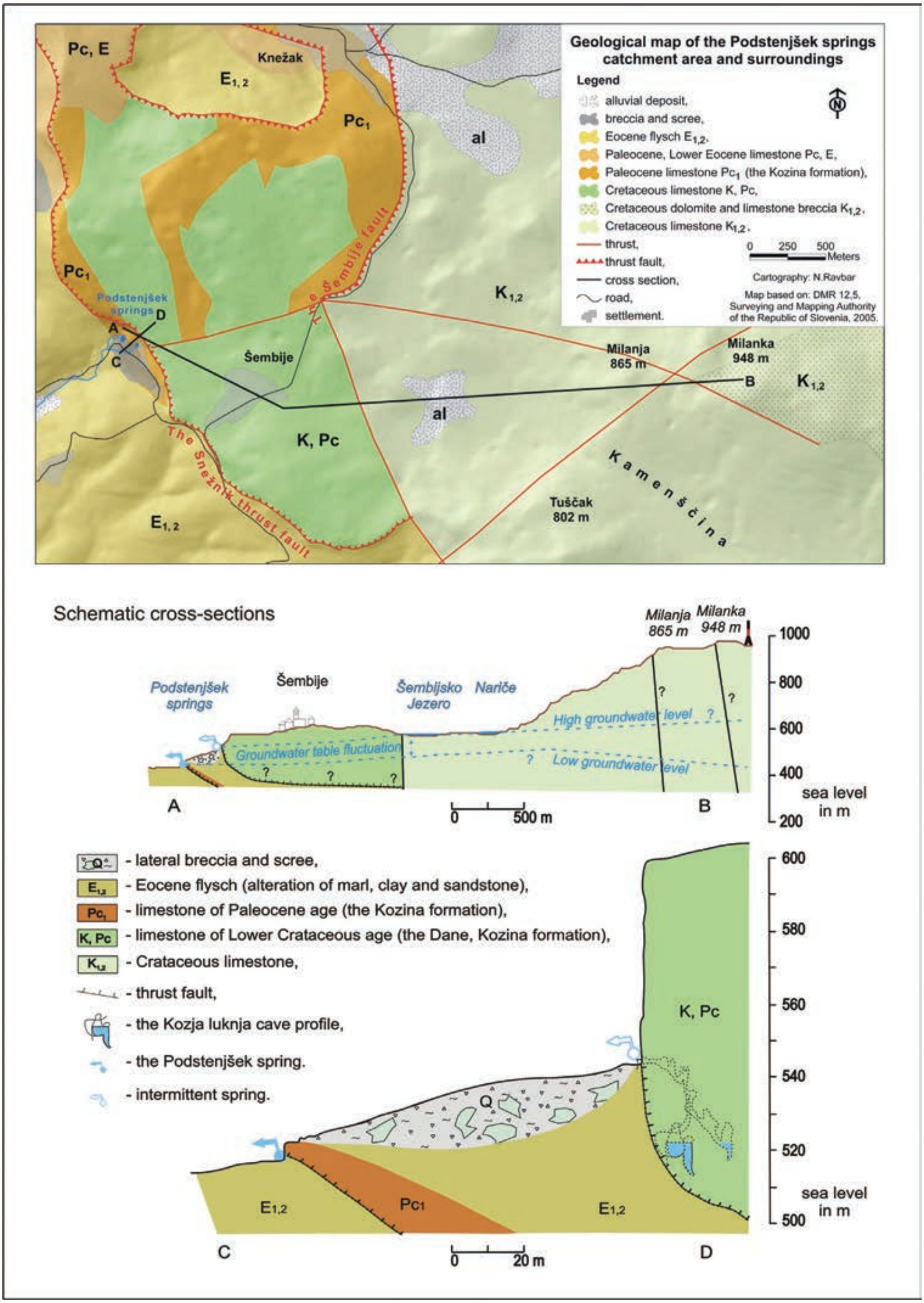
According to geotectonic division of Slovenia, southwestern Slovenia belongs to the Adriatic-Dinaric plate, specifically to the area of the Outer Dinarids (Placer, 1981). Thus, for this region explicit thrusted structure is characteristic. In the studied area the Lower Cretaceous and Upper Cretaceous layers lie over the Palaeocene and Eocene layers, because the Snežnik thrust sheet, which extends over part of the Pivka basin, the Postojna plain, the Javorniki and the Snežnik mountains, partly covers the Komen thrust sheet. Displacement of the Snežnik thrust sheet over the Komen one is estimated to be about seven kilometres; however intensity of the thrusting of the Snežnik thrust sheet is less and less distinctive towards the northwest (Placer, 1981).

The thrust fault is clearly expressed in a geomorphological step, which in places rises 200 – 400 m above the upper stream of the Reka river. Two tectonic windows near Knežak and near Zagorje where the higher lying Palaeocene limestone surrounds flysch layers prove the thrusted structure also (Pleničar, 1959).

The thickness of the limestone layers above the flysch ones is practically unknown. Only the borehole near Zagorje has bored through all the carbonate rocks layers and reached flysch rocks at 109 m under the surface (444 m a.s.l.) situated only about 2 km from the thrust edge (Krivic *et al.*, 1983). However, the flysch layers extension is very heterogeneous, since in the immediate vicinity they outcrop as a tectonic window.

The catchment area of the Podstenjšek springs occupies moderately karstified limestone and limestone breccias of Cennomanian age and limestone of Palaeocene age that are over-thrusted to the impermeable flysch layers of Eocene age (Fig. 9.3). Limestone of Lower Cretaceous age, containing very high percentage of $CaCO_3$ (93-98%) but very poor in fossils, prevails (Šikić and Pleničar, 1975).

Figure 9.3: Geological map of the Podstenjšek springs catchment area and surroundings and schematic cross-sections of the hydrogeological characteristics of the area (after Šikić et al., 1972; Šikić and Pleničar, 1975; Buser, 1976; Placer, 1981; Krivic et al., 1983; Poljak, 2000). →


Geological map of the Podstenjšek springs catchment area and surroundings
Legend
alluvial deposit,
breccia and scree,
Eocene flysch E1,2,
Paleocene, Lower Eocene limestone Pc, E,
Paleocene limestone Pc1 (the Kozina formation),
Cretaceous limestone K, Pc,
Cretaceous dolomite and limestone breccia K1,2,
Cretaceous limestone K1,2,
thrust,
thrust fault,
cross section,
road,
settlement.
0 250 500 Meters
Cartography: N.Ravbar
Map based on: DMR 12,5, Surveying and Mapping Authority of the Republic of Slovenia, 2005.
N
Pc, E
Knežak
E1, 2
Pc1
al
Pc1
Podstenjšek springs
A
B
C
D
The Šembije fault
Šembije
K1,2
Milanja 865 m
Milanka 948 m
K1,2
al
K, Pc
The Snežnik thrust fault
E1, 2
Tuščak 802 m
Kamenščina
Schematic cross-sections
Podstenjšek springs
Šembije
Šembljsko Jezero
Nariče
Milanja 865 m
Milanka 948 m
High groundwater level
Groundwater table fluctuation
Low groundwater level
?
A
B
0 500 m
1000
800
600
400
200
sea level in m
- lateral breccia and scree,
- Eocene flysch (alteration of marl, clay and sandstone),
- limestone of Paleocene age (the Kozina formation),
- limestone of Lower Crataceous age (the Dane, Kozina formation),
- Crataceous limestone,
- thrust fault,
- the Kozja luknja cave profile,
- the Podstenjšek spring.
- intermittent spring.
Q
E1,2
Pc1
K, Pc
K1,2
Q
E1,2
Pc1
E1,2
K, Pc
C
D
0 20 m
600
580
560
540
520
500
sea level in m

Between the Snežnik thrust fault and Šembije fault there are the limestone beds that belong to the period between Cretaceous and Palaeocene. Palaeocene limestone (the Kozina formation) outcrops in the western part of the catchment. Limestone breccias can only be found east of the Milanja mountain.

The underlying Eocene flysch layers consist of marl, clay and sandstone (Šikić *et al.*, 1972; Šikić and Pleničar, 1975). Flysch beds that are visible in the tectonic window are overturned as well as also all carbonate beds from the Lower Cretaceous to Eocene (Pleničar, 1959). The overthrusted structure is also visible at the thrust contact of limestone over flysch.

According to Šikić *et al.* (1972) and Šikić and Pleničar (1975) there are Quaternary alluvial deposits in the area of the intermittent lakes of Šembijsko Jezero and Nariče.

Because of the explicit thrusted structure, tectonic deformation of the area is characteristic and numerous faults cross it (Šikić and Pleničar, 1975). The border between the Snežnik and Komen thrust sheets is the Snežnik thrust fault that continues into Rakulik thrust fault on the northwest (Poljak, 2000). According to Buser (1976) the Šembije fault diverges from the Raša fault between Ilirska Bistrica and Zabiče and displaces the Snežnik thrust. Further towards the north it converts to thrust fault near Knežak (Šikić *et al.*, 1972). The area is also intersected by numerous other less significant neotectonic faults.

From the hydrological point of view, the Snežnik plateau is a deep diffuse karst for which an immediate infiltration of the rainwater underground and fast vertical draining in different directions – towards springs on the border of the plateau – is characteristic and groundwater generally flows via rapid drainage through karst conduits.

The Snežnik massif is a watershed area. From the southeastern part of the massif water drains to the Riječina river (Republic of Croatia), its northeastern part belongs to the Ljubljanica river basin and its western part belongs to the Reka river basin.

Furthermore, the western part of the Snežnik massif holds important drinking water resources and supplies the following water sources: the Bistrica spring, the Podstenjšek spring, boreholes near Knežak and some other smaller local captures in Podgora.

The catchment area of the Podstenjšek springs stretches over the area where the outermost Snežnik massive slopes extend into the Pivka river valley – the so-called Upper Pivka valley. The Podstenjšek catchment interweaves with the catchment areas of the Bistrica and the Pivka springs. Borders between them are not clear because the area of the southern part of the Upper Pivka valley is an area of groundwater bifurcation and the drainage divide changes in different hydrological situations. Waters from a certain zone thus partly drain into the Black and partly into the Adriatic Sea (Habič, 1984, 1989).

Flysch layers in the grounding that was caused by tectonics is an impermeable barrier for the groundwater that runs from the area of the Snežnik and of the Javorniki mountains. Unfortunately, it is not precisely known how deep the flysch layers are situated and to what extent they widen towards the east, but obviously they prevent water from draining towards the Reka river. The major part of the water, drained from under the Snežnik mountain, rebounds from the flysch barrier and thus flows northwards towards the Pivka spring. Just locally the flysch barrier is broken and a smaller part of the underground water outflows in the Podstenjšek springs (Krivic *et al.*, 1983).

There is no surface running water in the Podstenjšek springs catchment area. Due to the presence of the underlying flysch rocks a shallow karst aquifer is formed and thus two intermittent lakes appear during extremely high water conditions. Detailed data about the depth of the groundwater level in dry conditions is not available; however from observations of the Kozja luknja and Šembijsko Jezero we can deduce some assumptions of the piezometric level in different hydrological conditions.

During low waters the groundwater level in permanent springs reaches an elevation of approximately 510 m a.s.l. After more intensive precipitation and/or snowmelt it may rise for about 35 m, and some fissures and the Kozja luknja may be activated.

The intermittent lakes of Šembijsko Jezero and Nariče, located at altitudes of 559 m and 571 m a.s.l. form in doline-like depressions when the groundwater level is sufficiently high. As groundwater level is rising, water pours out through innumerable fissures and voids at the bottoms or edges of the depressions. These features are often small and morphologically not very distinctive. In periods of falling water level, the water sinks underground through the same fissures and voids, which consequently act as small estavelles.

However, these lakes appear very rarely – the Šembijsko Jezero appears approximately once every two years, while the appearance of the Nariče has only been recorded twice in years 1929 and 2000 (Kovačič and Habič, 2005).

In Šembijsko Jezero the level of high waters can reach the surface and varies between 559 and 570 m a.s.l., since in the dry period groundwater level between 540 and 545 m a.s.l. has been measured in a borehole situated in the area of a lake (Krivic *et al.*, 1983; Kovačič and Habič, 2005) proving around 30 m of groundwater level fluctuation.

9.4 CLIMATE CONDITIONS

Climate conditions of the Upper Pivka valley are mostly dependent on geographical position on transition from the submediterranean to continental Slovenia. They depend on the vicinity of the Adriatic Sea and position on the karst border under the orographic barrier of the Snežnik and the Javorniki mountains.

Thus, in summer time the region of the Upper Pivka valley is under submediterranean climate influence, but in wintertime it falls under the continental influence, characterized by dry hot summers and cold winters with the cold northeast bora wind (Gams, 1972). Since this is a transitional area, the climatic borders are not very sharp.

The region of the Upper Pivka is relatively well watered. The amount of precipitation depends on altitude increase and on exposure to the warm and humid air masses coming from southwest. Towards the central part of the Snežnik plateau the amount of precipitation increases (Mašun 2,041 mm, Gomance 2,738 mm of precipitation yearly) and exceeds 3,000 mm of precipitation yearly at the highest parts (Klimatografija Slovenije, Količina padavin, 1995). According to the precipitation amounts that were measured at the measuring station in Ilirska Bistrica for the 1961-1990 period and at the measuring station in Knežak for the 1961-1978 period (Klimatografija Slovenije, Količina padavin, 1995; MOP ARSO, 2006, 2007) the amount of precipitation in the studied area ranges between 1,500 and 1,600 mm per year; however, the amount increases towards the east due to the orographic barrier.

Precipitation is distributed relatively equally throughout the year, and practically no month is climatically dry. The climax of the precipitation occurs during autumn (November and December), which reflects the influence of the southwestern winds blowing from the sea especially at the Ilirska Bistrica measuring station. Due to the continental influences, a secondary climax is evident during the transition period from spring to summer (June) and it is evidently expressed in the Knežak measuring station. The least precipitation occurs in February, and there is a secondary minimum in July at both stations (Fig. 9.4).

In the winter masses of cold air move from the continent over the warm sea, causing blasts of a cold northeast bora wind. In the summer southwestern wind brings soothing influences from the sea.

The air temperature for the 1961-1990 periods measured at the measuring stations in Ilirska Bistrica (Klimatografija Slovenije, Temperatura zraka, 1995) show the average yearly temperature 9.6°C, average temperature in January 0.8°C, average temperature in July 18.8°C. Towards the central part of the Snežnik plateau and with the altitude increase the average yearly temperatures decrease. Average yearly temperature of Gomanci comes to 6.7°C and of Mašun to 5.6°C.

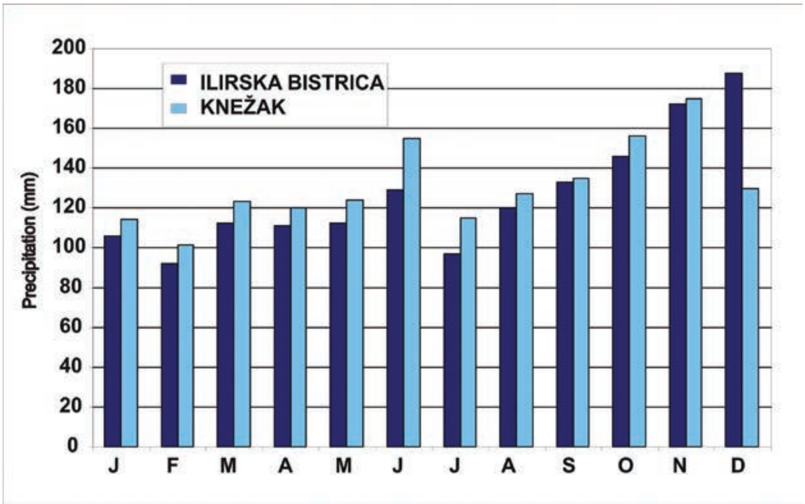


Figure 9.4: Average annual precipitation amount for the period 1961-1990 in Ilirska Bistrica and for the period 1961-1978 in Knežak (Source: Klimatografija Slovenije, Količina padavin, 1995).

9.5 SOIL AND VEGETATION COVER

Thin soil layer is unevenly spread and appears in patches. Its depth on the heterogeneous karst surface changes at short distances. The thickest layers of soils can be found in the bottom of the concave relief shapes, while the rest of the surface is pretty rocky. Shallow chromic Cambisol that is interwoven with Rendzina covers the studied area (Pedologic map, 1988).

The area between Šembije and Knežak is overgrown with the submediterranean association of *Seslerio autumnalis-Quercetum petraeae*. These stands have trees 15 m high (Vegetacijska karta gozdnih združb Slovenije, 2005). On abandoned meadows in places *Pinus nigra* and *Pinus sylvestris* are rife. Where there is no forest, different meadow-pasture associations are thriving.

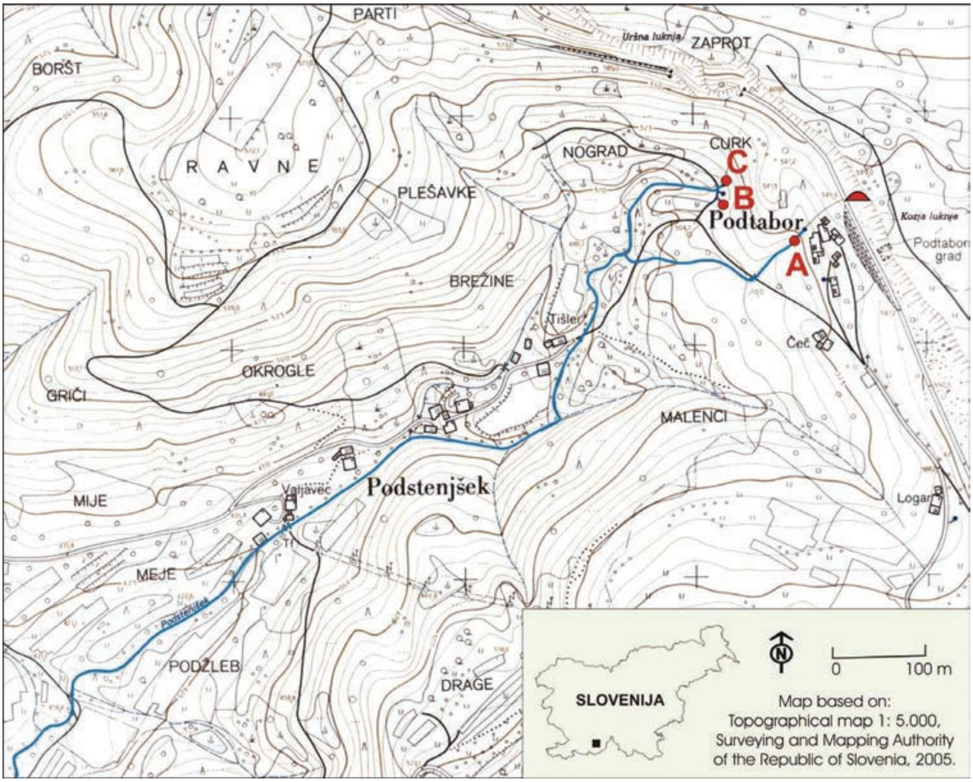
9.6 HYDROLOGICAL CHARACTERISTICS OF THE PODSTENJŠEK SPRINGS

The Podstenjšek springs are situated on the limestone and flysch contact that blocks groundwater flow. Therefore these are of barrier type. Karst water outflows on the thrust front in five smaller but permanent springs – the groundwater flows out through lateral scree and breccia formed below the limestone wall (karst edge).

For clearest distinction we nominated the most distinctive springs with successive letters as springs A, B, C from left to right downstream (Fig. 9.5). At high waters numerous smaller springs are activated. At times of extremely high water conditions water also bursts from the Kozja luknja, which then acts as an overflow spring.

The Kozja luknja is situated 35 m above the springs. It is a 20 m deep vertical cave with a single passage that with depth divides in several conduits developed along fractures and joints. When Kozja luknja acts as a spring also the intermittent lake of Šembijsko Jezero is filled with water. However, the permanent groundwater level can always be reached inside the cave. It fills up the siphon lakes, which recharge the Podstenjšek permanent springs.

Since May 2005 we have been measuring water level of all springs and water temperature and electrical conductivity of an individual spring every 15 minutes. For logging we use Eijkelkamp's TD Diver, BaroDiver and CTD Diver. TD Diver measures and records water and air pressure, as well as temperature and we placed it in the riverbed after all the springs join in one stream. In order to obtain water pressure we used BaroDiver that measures and records pressure and temperature. We calibrated water pressure with discharge values measured by a salt-dilution method (Käss, 1998). CTD Diver that measures and records pressure, specific electrical conductivity and temperature was placed in one of the springs (spring A).



Map based on: Topographical map 1: 5.000, Surveying and Mapping Authority of the Republic of Slovenia, 2005.

Figure 9.5: Topographical map of the Podstenjšek springs' location.

Occasional manual measurements of water temperature and electrical conductivity of the permanent springs showed identical values indicating that the karst springs discharge from the same groundwater body. For all the analyses precipitation data gained from the Slovene Environmental Agency (MOP ARSO, 2007) has been used. The precipitation is measured at the nearby Ilirska Bistrica precipitation station every half hour.

The springs demonstrate typical karst hydrological regime with very high short-term flow rates and prolonged periods of medium and low waters. In the period between May 2005 and March 2007 the lowest observed discharge was 6 l/s and the highest was 1.6 m^3/s. The average discharge is about 140 l/s. The ratio between low, medium and high waters is thus approximately 1:26:267, which is one of the highest ratios recorded among Slovene springs. On contrast, the Vipava spring's ratio is 1:9:96 and the Hubelj spring's ratio is 1:16:322 (Trišič, 1997).

In contrast, the springs do not show high water temperature variations. Water temperature ranges between 9 and 10.6°C in the same period. According to the almost constant water temperature being almost identical to the mean annual air temperature of the area (9.6°C) we can deduce to long residence times of the underground water.

Specific electrical conductivity ranges between 366 and 487 µS/cm. In general, rapid changes of discharge are followed by distinctive changes of conductivity and smaller but noticeable changes in water temperature, which also reflects the significant karst character of the Podstenjšek springs (Fig. 9.6).

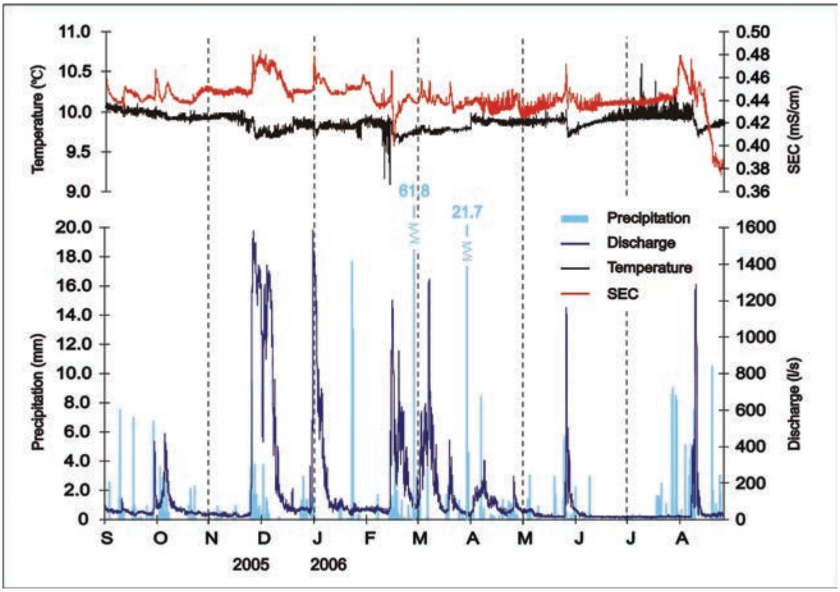


Figure 9.6: Discharges, water temperature and specific electrical conductivity of the Podstenjšek springs for one hydrological year supplemented by precipitation data gained from the Slovene Environmental Agency (MOP ARSO, 2007). Half hour values are displayed on the graph.

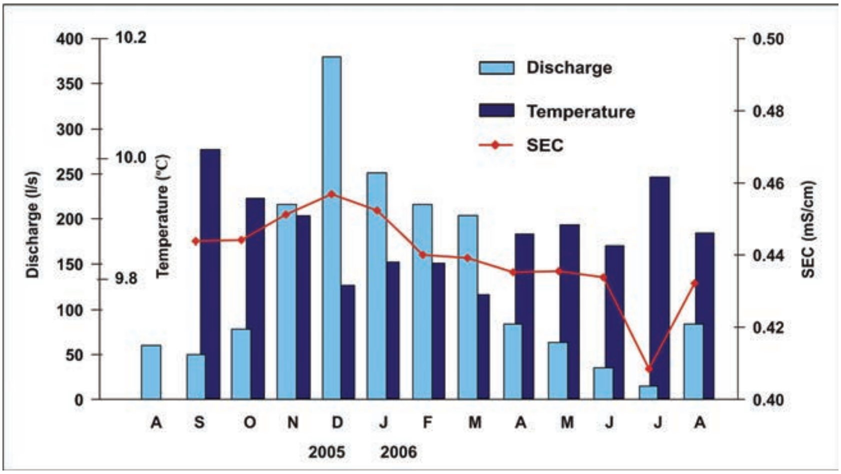


Figure 9.7: Average monthly discharges, temperature and specific electrical conductivity values of the Podstenjšek springs.

In the hydrological year 2005/06 Podstenjšek's highest average discharges were in December. The lowest discharges were measured in July. The highest values of specific electrical conductivity were in December and the lowest in July. In contrast the highest water temperature values were in July and September, but the lowest in March and December (Fig. 9.7).

9.7 OUTLINING THE RECHARGE AREA OF THE SPRINGS

Delineation of the recharge area boundaries was based upon an understanding of the geological structure, geomorphological observation, calculation of water balance, hydrograph analyses and upon results obtained by the tracer test.

Figure 9.8: The Podstenjšek at high waters (photo: N. Ravbar).

9.7.1 WATER BALANCE AND HYDROGRAPH ANALYSES

The calculation of water balance was based upon the premise that within a period of one hydrological year the overall runoff from the karst system is equal to the amount of precipitation that has in the same period fallen on the entire recharge area, but reduced by the evaporation. For this estimation the data of Podstenjšek discharges for the hydrological year 2005/06, the amount of precipitation measured at the nearby Ilirska Bistrica precipitation station (MOP ARSO, 2007) and the approximate values of this area's evaporation (Kolbezen and Pristov, 1998) have been used. The mean discharge of the Podstenjšek springs for this period is 140 l/s, the amount of precipitation is 1502 mm and the average amount of the evaporation is 625 mm. Thus it could be assessed that the size of the catchment area of the springs is approximately 5 km^2.

In addition to the comparison between recharge and discharge, the springs' response to precipitation events has been studied in more detail. Five precipitation events of the hydrological year 2005/06, followed by significant discharge increase, are presented and compared with specific electrical conductivity and temperature of spring water.

The springs have torrential properties and are characterised by extremely fast reactions to hydrological events – the extreme peaks of the discharges appear within a short time after excessive precipitation events. Usually the discharges of the Podstenjšek springs start to increase with a delay of just few hours or even less.

However, individual reactions depend on the distribution and intensity of the precipitation. Moreover, the response of the springs is significantly controlled by the soil and epikarst water saturation, as well as the pre-stored water volume.

As an example, reaction of the springs to heavy rain and snowmelt in the period between 25th November and 15th December 2005 was observed. The low discharge, high water temperature and low electrical conductivity values were followed by extremely fast response of the springs. The discharge increased from about 30 l/s to 1 m^3/s within 36 hours coinciding with decreasing temperature and increasing electrical conductivity. In the following 18 hours the discharges increased up to 1.6 m^3/s. At the time of the peak discharge values, the specific electrical conductivity begins to decrease and lower hardness storm water reaches the spring.

Nine hours after the inflow of the new infiltrated water it is followed by the increase of specific electrical conductivity values indicating the arrival of water that has been stored underground for a longer period before the spring. This could be water that arrived from the other parts of the aquifer. Additional rains on 3rd and 5th December caused increase of the discharge, as well as slight increase of the electrical conductivity of the springs' water (Fig. 9.9).

In the second example in the period between 25th December 2005 and 11th January 2006 it came to increase of discharge and specific electrical conductivity values only after a week of temperate raining and snowing. Nevertheless, afterwards the hydrograph pattern resembles the first one – that is the low discharge, high water temperature and low electrical conductivity values were followed by extremely fast discharge increase

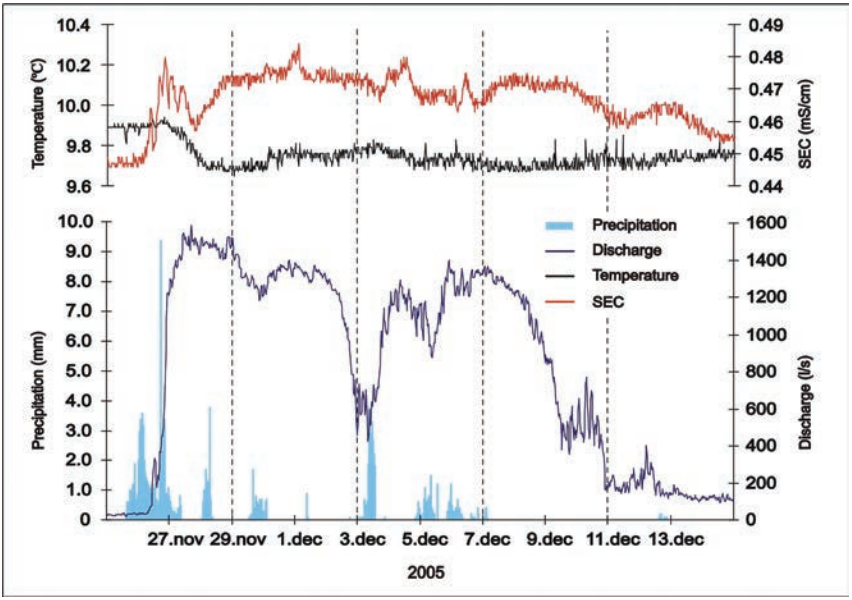


Figure 9.9: Hydrograph of the Podstenjšek springs in the period between 25th November and 15th December 2005 supplemented by precipitation data gained from the Slovene Environmental Agency (MOP ARSO, 2007). Half hour values are displayed on the graph.

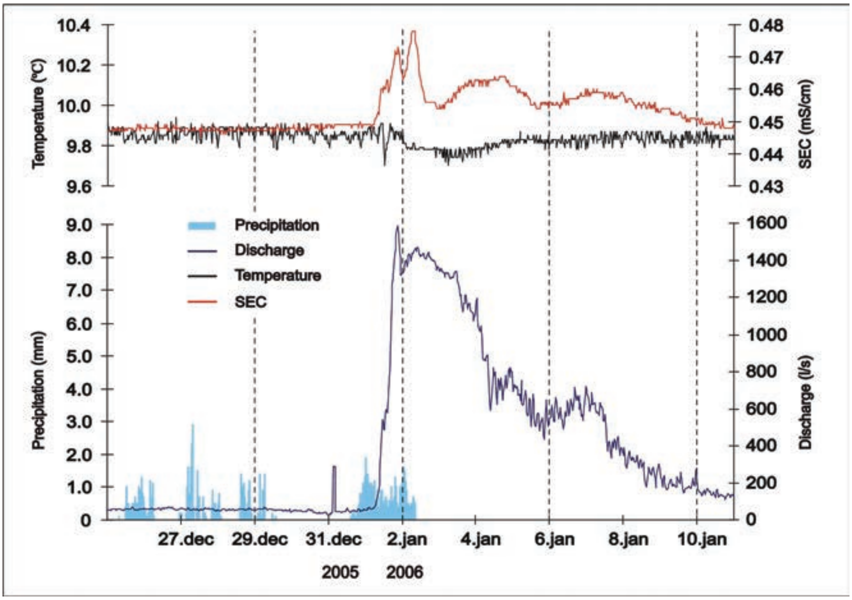


Figure 9.10: Hydrograph of the Podstenjšek springs in the period between 25th December 2005 and 11th January 2006 supplemented by precipitation data gained from the Slovene Environmental Agency (MOP ARSO, 2007). Half hour values are displayed on the graph.

coinciding with decreasing temperature and increasing electrical conductivity practically simultaneously. The short decrease of the specific electrical conductivity values was followed by two slight increases (Fig. 9.10).

The hydrographs showing Podstenjšek springs hydrological characteristics in the period between 15th February and 18th March 2006 and in the period between 29th May and 6th June 2006 correspond to a typical karst spring hydrograph with a typical piston effect.

The increasing discharge values coincided with decreasing temperature and increasing electrical conductivity values. When the discharges started to decrease, the specific electrical conductivity began to decrease as well, achieving values that were the same or even lower than before the precipitation event (Figs. 9.11 and 9.12).

The period between 2nd and 18th August 2006 shows a completely different hydrodynamic behaviour. Due to strong evapotranspiration, the series of separate storm cycles initially did not affect the discharge values at the Podstenjšek springs. However, the specific electrical conductivity value increased significantly within the two days after a very strong rainy event. Only after three days of additional abundant rain did the discharges increase and were followed by atypical rise of the electrical conductivity values (Fig. 9.13).

Such behaviour can mean that at first a reservoir of "old infiltrated water" with higher

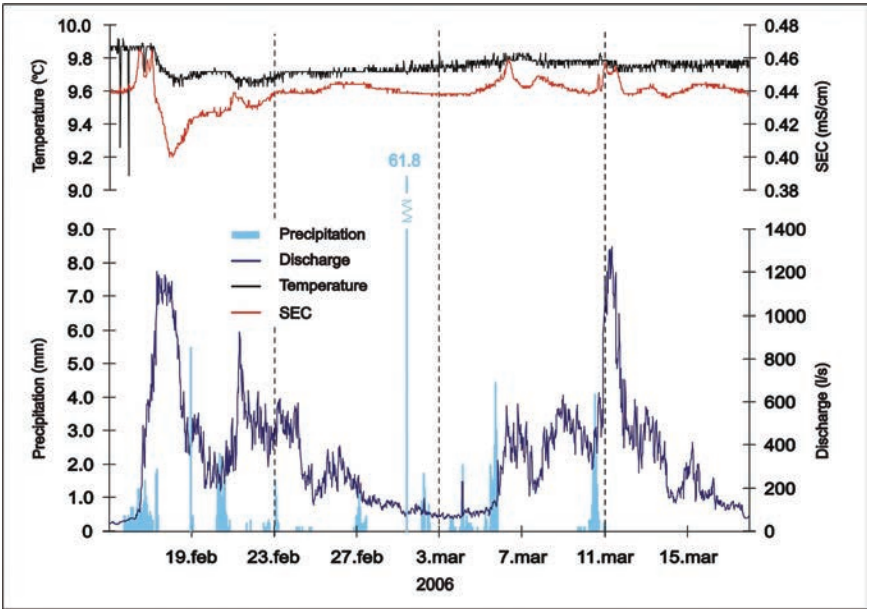


Figure 9.11: Hydrograph of the Podstenjšek springs in the period between15th February and 18th March 2006 supplemented by precipitation data gained from the Slovene Environmental Agency (MOP ARSO, 2007). Half hour values are displayed on the graph. Temporal variations of the discharge, temperature and electrical conductivity show typical piston effect.

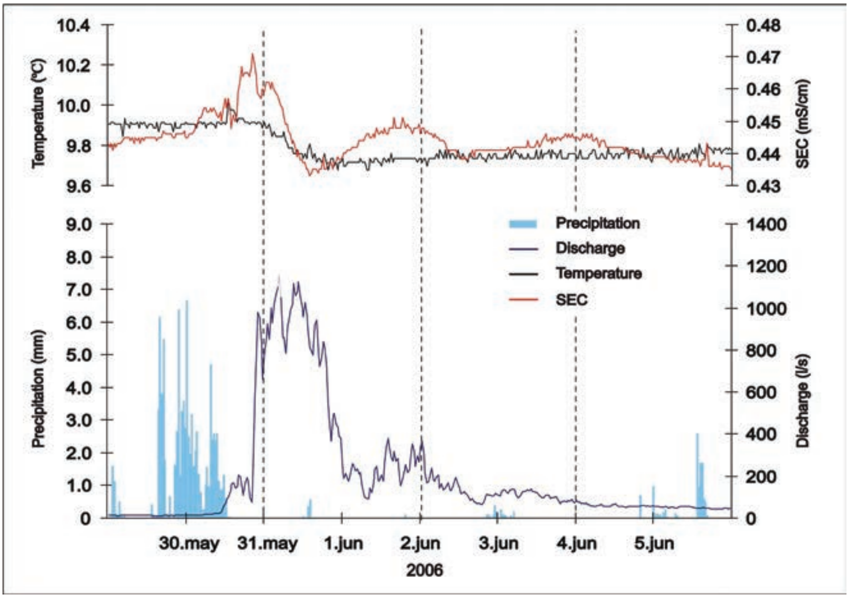


Figure 9.12: Hydrograph of the Podstenjšek springs in the period between 29th May and 6th June 2006 supplemented by precipitation data gained from the Slovene Environmental Agency (MOP ARSO, 2007). Half hour values are displayed on the graph. Temporal variations of the discharge, temperature and electrical conductivity show typical piston effect.

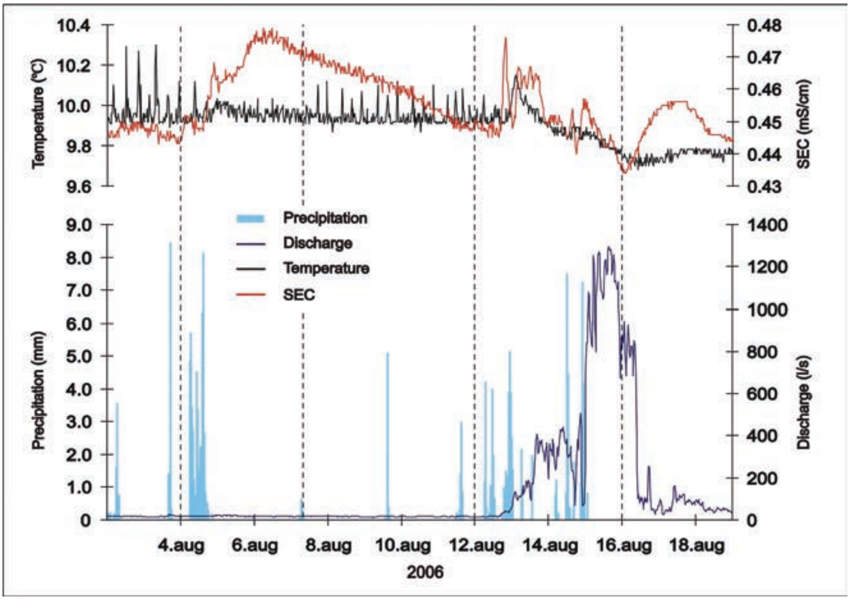


Figure 9.13: Hydrograph of the Podstenjšek springs in the period between 2nd and 18th August 2006 supplemented by precipitation data gained from the Slovene Environmental Agency (MOP ARSO, 2007). Half hour values are displayed on the graph.

mineralization was discharging for a longer period of time, hydraulically stimulated by the slow infiltration of the rainwater, without significant increase in springs discharges. Only after abundant and intensive raining on 12th August was the fast and strong infiltration into underground enabled, firstly causing dilution in highly mineralised water and then a resumed increase of the specific electrical conductivity values succeeded by the discharge increase and water temperature decrease.

Based on the observations of the springs' response to precipitation events it can be concluded that the lag between the onset of the infiltration of precipitation and the rising limb of springs discharges is very short. This means that the infiltrated water quickly reaches the saturated zone causing the rise of the water table and consequently the rise of the discharges at the spring.

However, some reactions of the springs to the intensive recharge show an interesting and peculiar positive correlation between the discharge and electrical conductivity values. Washout of water stored in the soil and low permeability volumes of the epikarst could cause simultaneous increase of the discharge and electrical conductivity values, but not in longer period.

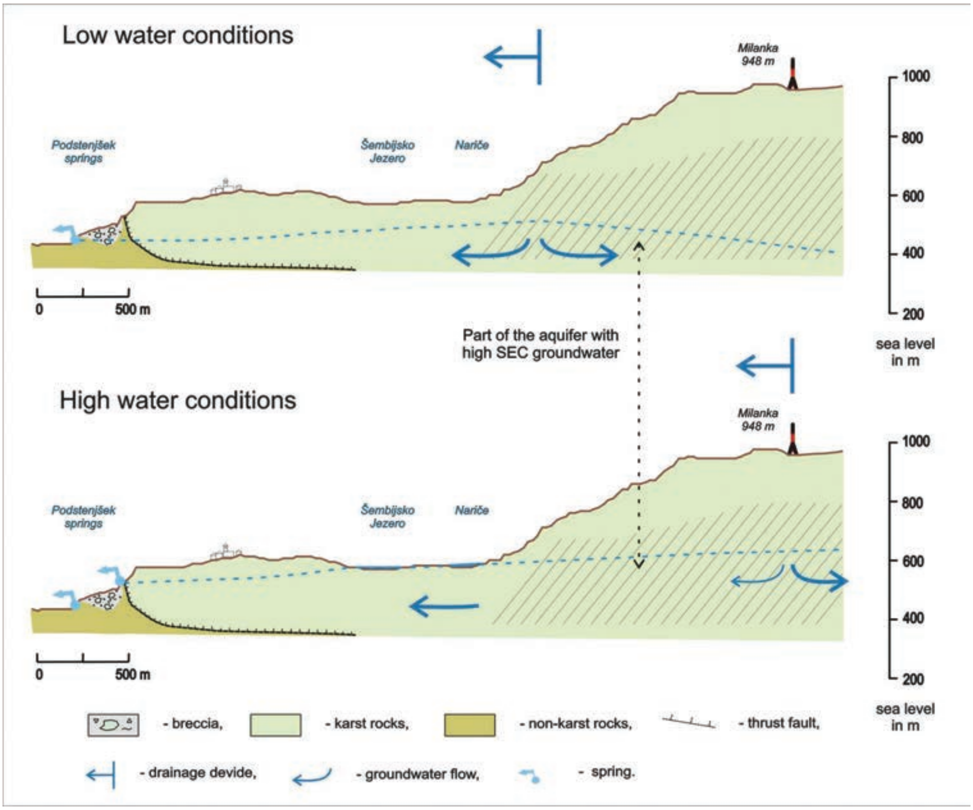


Figure 9.14: Variable drainage divide during low and high water conditions.

Long-term high electrical conductivity behaviour of the springs after a storm event could indicate the variations of the catchment size and contribution of other parts of the aquifer. When groundwater level in the Javorniki-Snežnik aquifer is sufficiently high the Podstenjšek becomes an overflow spring and its catchment boundary expands towards the north, northeast and east. Parts of the aquifer with higher groundwater electrical conductivity values (from the Javorniki and Pivka valley and/or from the Milanka mountain) are then also drained by the Podstenjšek (Fig. 9.14). In addition to larger recharge quantities, greater catchment area also explains very high discharge variations of the Podstenjšek. However, this assumption should be further researched also in relation to the Bistrica and Pivka springs studies.

9.7.2 HYDROCHEMICAL AND MICROBIOLOGICAL PROPERTIES

In order to illustrate the chemical characteristics of the Podstenjšek karst spring we compiled existing information on field temperature, pH, SEC, Ca^{2+}, Mg^{2+} and HCO_3^{2-} from Kogovšek (2006). In year 2005 we made some occasional analyses at the laboratory of the Karst Research Institute of Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-} and PO_4^{2-} under different hydrological conditions. The calcite saturation index was calculated on the basis of these data.

In addition, in 2006 some other parameters of the Podstenjšek, Pivka and Bistrica springs, like Ca^{2+}, Mg^{2+}, Cl^-, Br^-, F^-, Na^+, K^+, Sr^+, Li^+, NO_2^-, NO_3^-, SO_4^{2-}, PO_4^{2-}, NH_4^+were analysed at the laboratory of University of Neuchâtel, Centre of Hydrogeology using ion chromatography (Guglielmetti, 2007).

The Podstenjšek spring water is nearly saturated or significantly over-saturated ($-0.08 < SI > 0.59$), which indicates intensive water-rock interaction (White, 1988; Dreybrodt *et al.*, 2005). Thus we can infer longer residence times and a moderately karstified aquifer system, proved also by the tracer test.

The Podstenjšek water has low mineralization (Fig. 9.15, 9.16 and 9.17). The dominant ions are HCO_3^{2-} ranging from 207-273 mg/l and Ca^{2+} ranging from 66-89 mg/l. Mg^{2+} is generally low, ranging from 3.3-7.8 mg/l. The concentrations of other ions are also low, Na^+ ranging from 2.4-4.6 mg/l, K^+ ranging from 0.4-1.1 mg/l, Cl^- ranging from 3.7-8 mg/l, NO_3^- ranging from 5.8-14.6 mg/l, SO_4^{2-} ranging from 4-7 mg/l and PO_4^{2-} ranging from 0.02-0.04 mg/l. F^-, Br^-, Sr^+, Li^+, PO_4^{2-}, NO_2^-, NH_4^+ were below the detection limit. The concentration of all inorganic dissolved solvents is significantly below the limits given by the Slovene drinking water ordinance (Ur.l. RS 19/2004).

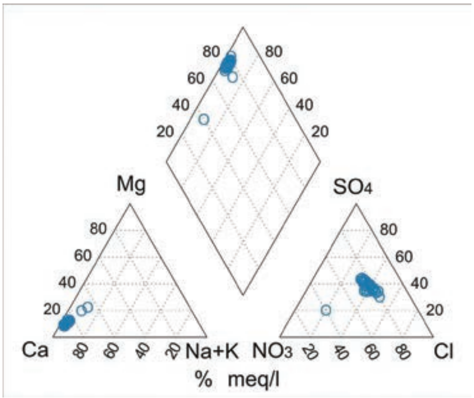


Figure 9.15: The PIPER diagram of the Podstenjšek springs.

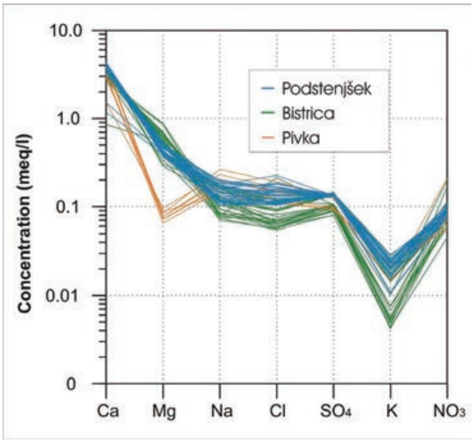


Figure 9.16: Schöller diagram of the Podstenjšek, Bistrica and Pivka springs (Guglielmetti, 2007).

The mineralization of the Bistrica and Pivka karst springs is also low. Hydrochemical characteristics of the springs, including the Podstenjšek springs, are similar to each other. The Pivka spring shows slightly lower Mg^{2+} concentrations and the Bistrica spring shows very low K^{+} concentrations (Fig 9.16). Among the studied springs the Pivka shows the highest Ca/Mg ratio (based on the mg/l values), ranging from 53.8-91.0, while the Podstenjšek springs show variation between 11.4-18.4 and similarly also the Bistrica spring between 6.9-23.9.

The highest values of total hardness show water from the Podstenjšek, ranging from 3.7-4.8 meq/l, and insignificantly lower from the Bistrica, ranging from 3.2-4.6 meq/l. The total hardness at the Pivka spring is lower, ranging from 3-4.3 meq/l. Comparing results from the simultaneously taken samples, the Podstenjšek generally shows the highest values and the Pivka the lowest (Fig. 9.18). However, the data are not enough to draw definite conclusions.

The Podstenjšek spring water is from the hydrochemical point of view satisfactory, however, few of the analyses done by the Institute of Public Health Koper (Zavod za … 2001, 2002, 2003) show that the water is rich in bacteria. In the

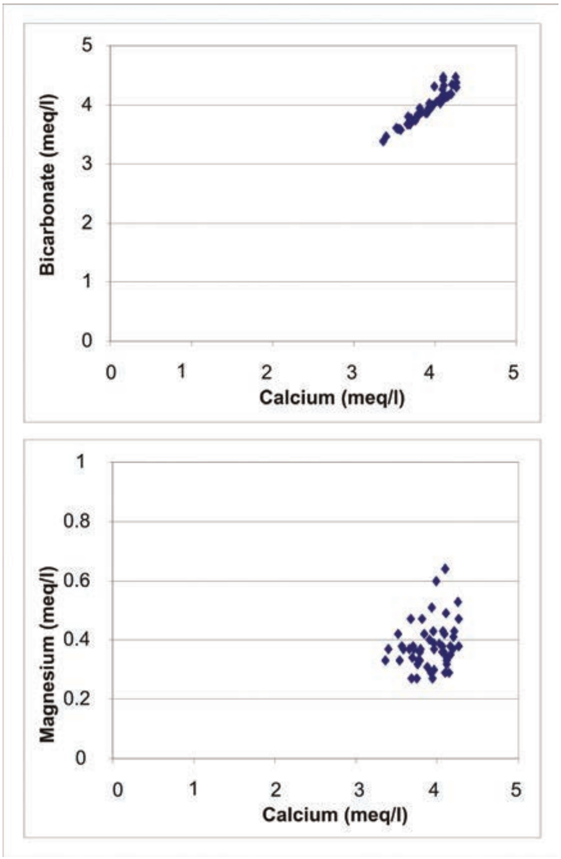


Figure 9.17: Calcium, bicarbonate and magnesium concentrations of the Podstenjšek springs (source: Kogovšek, 2006).

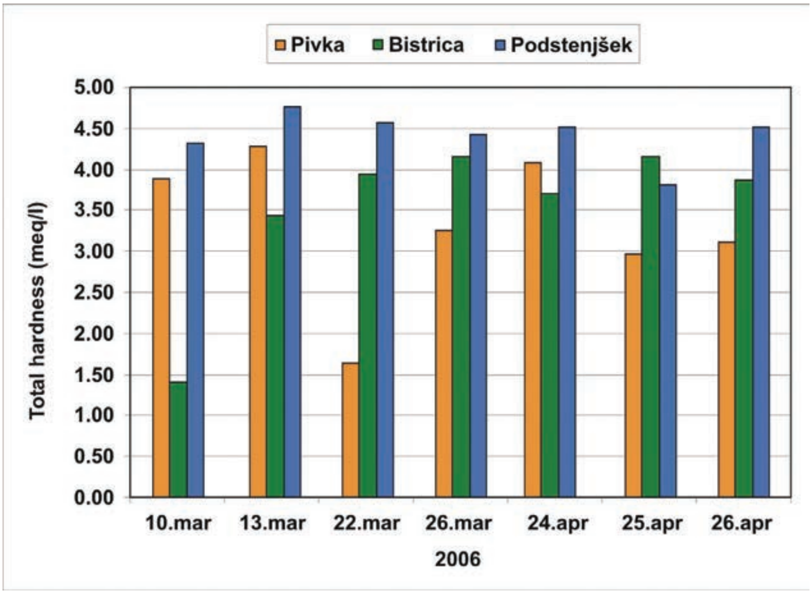


Figure 9.18: Comparison of the total hardness values of the simultaneously taken samples at the Pivka, the Bistrica and the Podstenjšek springs.

period 1987-2003 altogether only five samples have been taken. Of course, such a small number of results are not representative, but only give a general review. We only took into consideration the latest three results.

In 1 ml of water 2-40 colony forming units were found at 37ºC and 15-75 at 22ºC, at 37ºC 9-43 coliform bacteria, 9-43 *Escherichia coli* and 0-4 *Streptococcus faecalis* were detected in 100 ml of water. These bacteria are indicators of faecal contamination (Fig. 9.19).

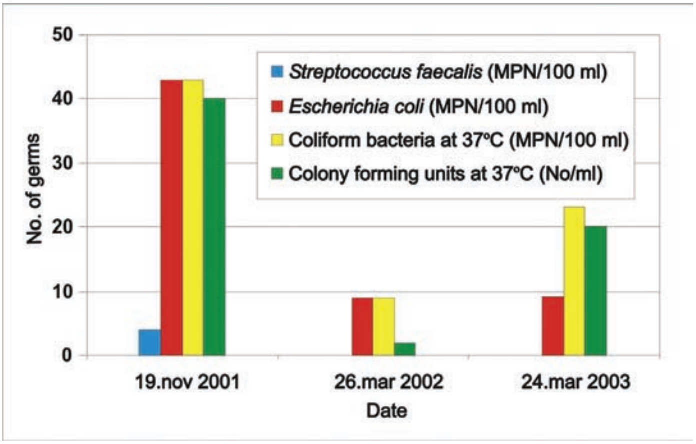


Figure 9.19: Microbiological properties of the Podstenjšek spring (MPN = most probable number; source: Zavod za zdravstveno varstvo Koper, 2001, 2002, 2003).

The microbiological properties exceed the drinking water law limits that prescribe drinking water to be free of disease-causing agents. There must be no *Escherichia coli*, no Enterococci, no coliform bacteria in a water sample of 100 ml and less than 100 colony forming units at 22ºC and at 37ºC in a water sample of 1 ml (Ur.l. RS 19/2004). However, the spring's water is disinfected before use.

9.7.3 TRACER TEST FINDINGS

The observations of the Podstenjšek hydrograph implies that its catchment area interweaves with the catchment area of the Bistrica and the Pivka respectively the Malenščica springs. The hydraulical connections were not precisely known until recently. The tracer tests executed for our study were the first in the immediate catchment area of the Podstenjšek springs.

The purpose of the first tracer test that was carried out in March 2006 was to determine the underground water flow connections, to find out the hydraulic properties and hydrodynamic behaviour of the aquifer, to delineate the catchment area of the Podstenjšek springs and to locate the Adriatic - Black Sea watershed more precisely. Therefore two injection points, which location is shown on the Fig. 9.22, have been selected.

On 7th March 94 g of sulforhodamine B was injected in the estavelle in the lake of the Šembijsko Jezero (Fig. 9.20) and 500 g of eosine was injected in the karren below the Milanka mountain. For the first injection 0.5 m^3 of flushing water was used and 0.9 m^3 for the second one.

The injection was carried out under high water conditions and was followed by a strong and efficacious precipitation event with a height of 23.9 mm on 10th March measured at the Ilirska Bistrica precipitation station within 12 hours. The next abundant rainfall was on 21st and 22nd March when 33.3 mm of rain fell within 36 hours.

After the injections, all karst springs in the area were observed for up to 64 days. Besides three of the Podstenjšek springs we also observed the Pivka, the Bistrica, the Sušec, the Kovačevec, the Kozlek and the Pila springs. Additionally the K-2 borehole near Zagorje was sampled as well, but only for seven days due to the technical reasons (for location of the sampling sites see Fig. 9.22). The samples were taken manually in dark glass bottles as frequently as precipitation circumstances required and afterwards stored in a dark and cool place.

At the time of injection the Podstenjšek springs' discharges were 300 l/s and were increasing. The maximum discharge was attained on 11th March at 1.3 m^3/s (Fig. 9.21).

The sample analyses have been performed at the Karst Research Institute's laboratory using luminescence spectrometer LS 30, Perkin Elmer. Scanning of the emission spectra was done by the method of simultaneously changing excitation and emission wavelengths (E_{ex} = 564 nm, E_{em} = 583 nm for sulforhodamine B with detection limit of 0.02 ppb and E_{ex} = 516 nm, E_{em} = 538 nm for eosine with detection limit of 0.05 ppb) (Käss, 1998; Benischke *et al.*, 2007).

Figure 9.20: Injection of a tracer into an estavelle of the Šembijsko Jezero (photo: A. Delost).

Table 9.1: Distance and altitude difference from the injection points and the connected springs (for location see Fig. 9.22).

Sampling points	Podstenjšek springs	Bistrica springs	Injection points
Distance / altitude difference from the injection points	1.9 km / 34 m	3.8 km / 139 m*	1. Estavelle
	3.9 km / 195 m	3.7 km / 300 m	2. Karrenfield

* - no connection

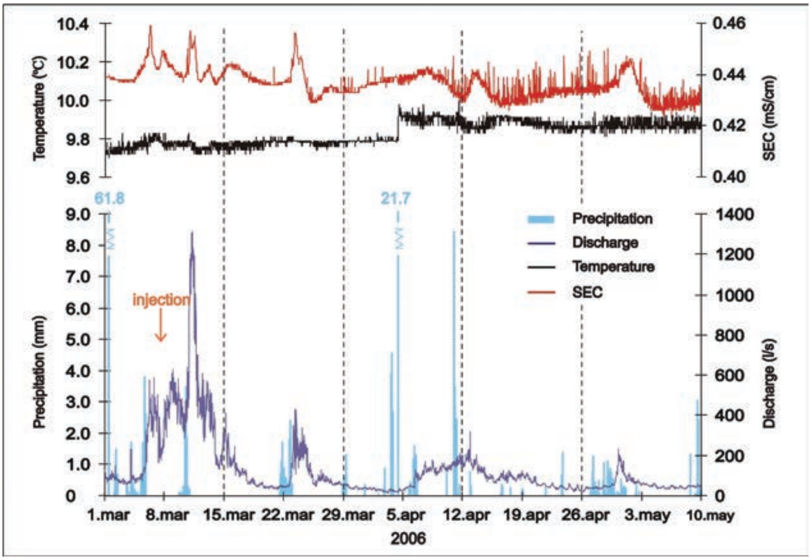


Figure 9.21: Hydrological conditions of the Podstenjšek springs in the time of the tracing test. Half hour values are displayed on the graph. Precipitation data was gained from the Slovene Environmental Agency (MOP ARSO, 2007).

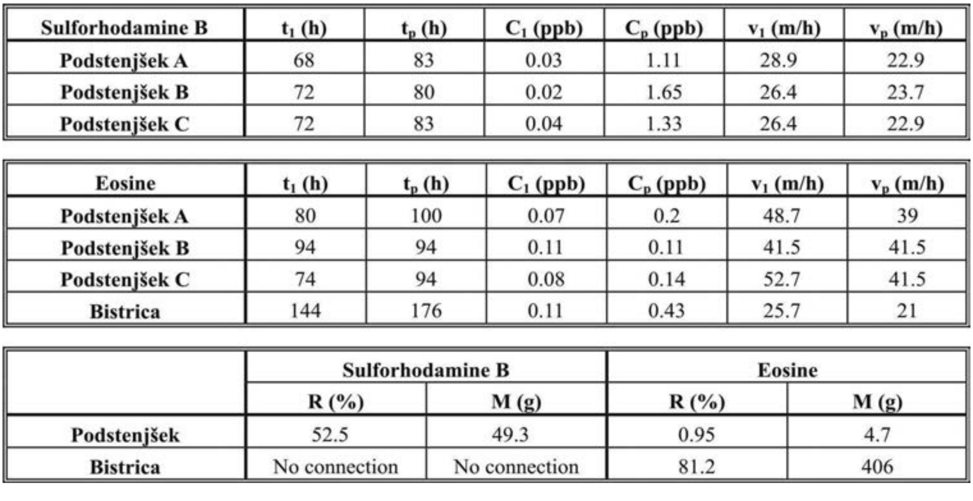
After abundant rainfall on 10th March the tracers from both injection points were obtained in the Podstenjšek springs. Sulforhodamine B was detected until 14th March with maximal concentration of 1.65 ppb and then again in higher concentrations between 23rd and 26th March. Afterwards it only appeared after a rainy event in small concentrations as shown in the figure 9.23. The appearance of sulforhodamine B has been more or less simultaneous in all three observed springs of the Podstenjšek. Altogether 52.5% of the sulforhodamine B has been recovered (Tab. 9.2).

In the Podstenjšek springs the eosine appeared at practically the same time like the sulforhodamine B. It was first detected in the C spring, after 6 hours in the A spring and lastly (94 hours after the injection) in the B spring (for location see Fig. 9.5). The peak concentration 0.2 ppb was observed in the A spring. At all, the eosine concentrations were low and only few samples were eosine positive. The breakthrough curve is not a classical breakthrough curve – the tracer rather appeared discontinuously and irregularly. The total recovery rate of 0.95% was observed in the Podstenjšek springs (Fig. 9.24 and Tab. 9.2).

Compared to the Bistrica spring only the eosine was obtained with a distinct delay of the tracer breakthrough – on 13th March. It reached a maximum of 0.43 ppb the next day. The breakthrough tailing lasted until 29th March with the secondary peak on 22nd March. The total recovery rate of 81.2% was observed in the Bistrica spring (Fig. 9.25 and Tab. 9.2).

In the other sampled springs and in the borehole neither sulforhodamine B nor eosine were detected.

Table 9.2: Overview of the tracer results (t_1 – the time of first arrival, t_p – the time of peak concentration, C_1 – the concentration of first arrival, C_p – the peak concentration, v_1 – the velocity of first arrival, v_p – the velocity of peak concentration, R – recovery rate, M – recovery mass).



Sulforhodamine B	**t_1 (h)**	**t_p (h)**	**C_1 (ppb)**	**C_p (ppb)**	**v_1 (m/h)**	**v_p (m/h)**
Podstenjšek A	68	83	0.03	1.11	28.9	22.9
Podstenjšek B	72	80	0.02	1.65	26.4	23.7
Podstenjšek C	72	83	0.04	1.33	26.4	22.9

Eosine	**t_1 (h)**	**t_p (h)**	**C_1 (ppb)**	**C_p (ppb)**	**v_1 (m/h)**	**v_p (m/h)**
Podstenjšek A	80	100	0.07	0.2	48.7	39
Podstenjšek B	94	94	0.11	0.11	41.5	41.5
Podstenjšek C	74	94	0.08	0.14	52.7	41.5
Bistrica	144	176	0.11	0.43	25.7	21

	Sulforhodamine B		**Eosine**	
	R (%)	**M (g)**	**R (%)**	**M (g)**
Podstenjšek	52.5	49.3	0.95	4.7
Bistrica	No connection	No connection	81.2	406

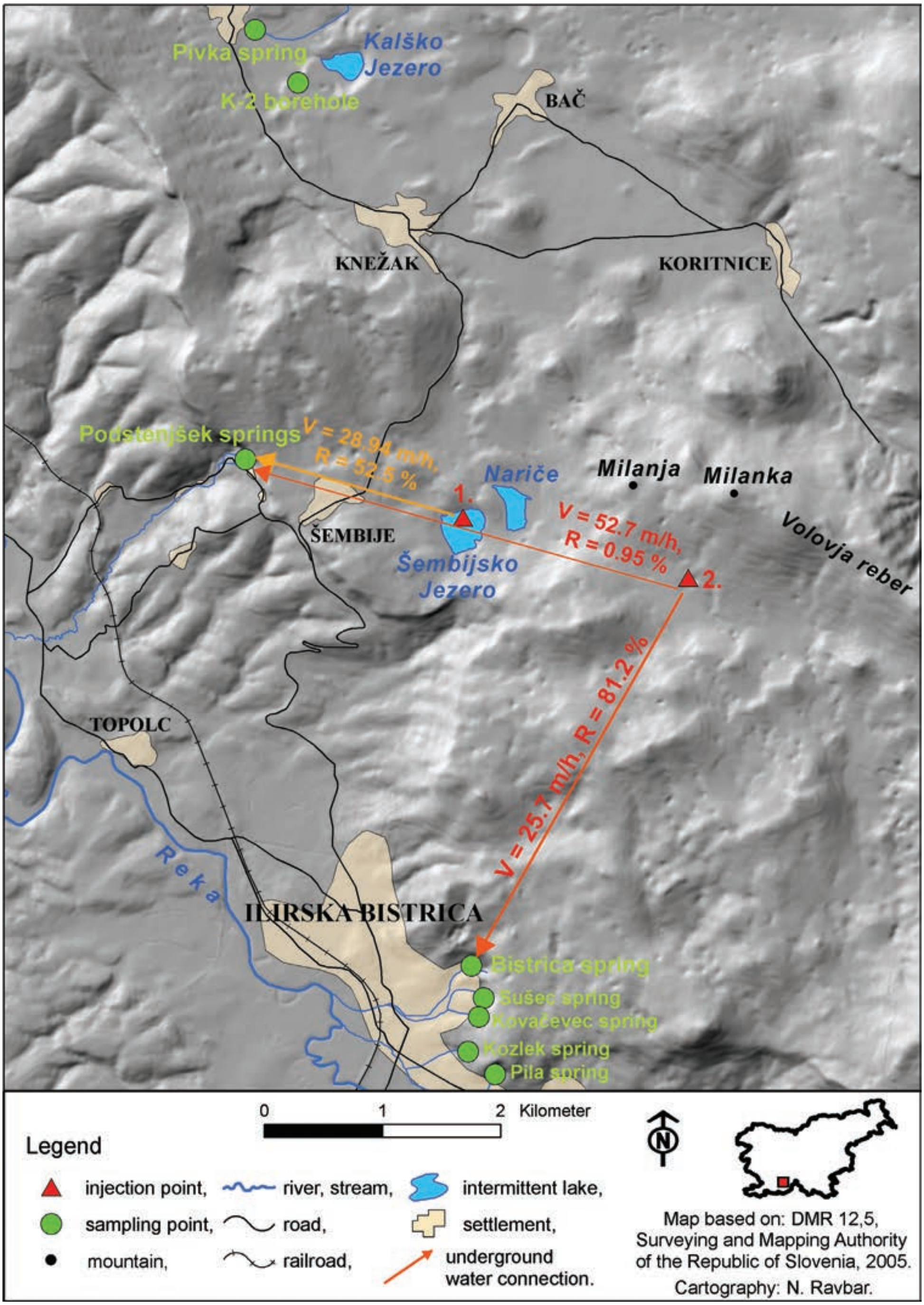


Figure 9.22: Overview of the tracer test results, location of the injection points, the sampling points and the proved underground flow paths.

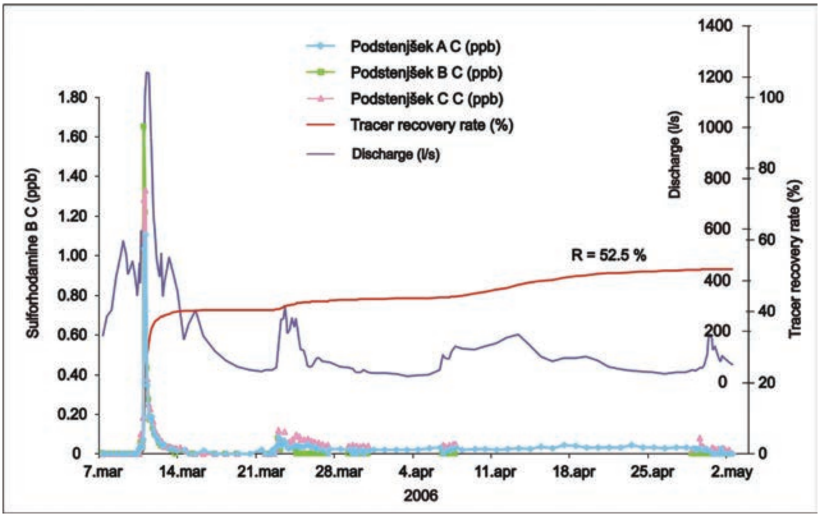


Figure 9.23: Sulforhodamine B breakthrough curve observed in the Podstenjšek springs.

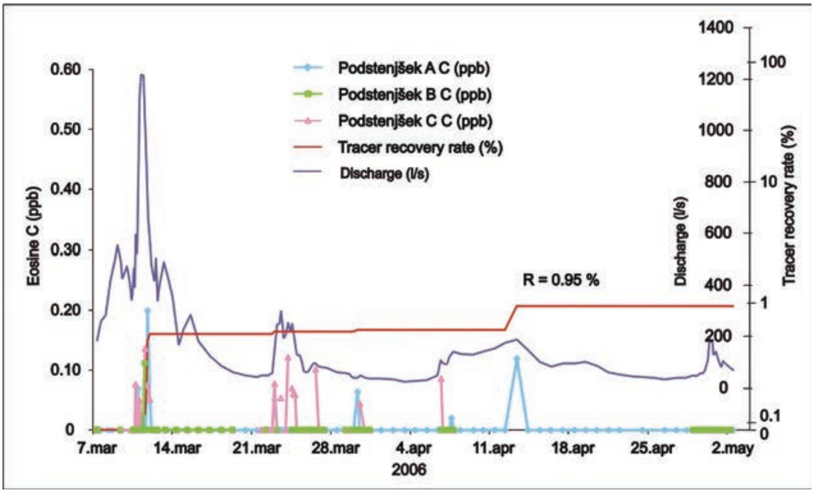


Figure 9.24: Eosine breakthrough curve observed in the Podstenjšek springs.

The tracer test results proved the underground connection between the lake of the Šembijsko Jezero and the area below the Milanka mountain and the Podstenjšek springs. The results also proved that the catchment area of the Podstenjšek and Bistrica springs overlap. The area below the Milanka mountain contributes only a small portion to the Podstenjšek springs, but is directly connected to and mainly drained by the Bistrica spring. The peak concentrations and recovery rates of eosine observed in the Podstenjšek springs are significantly lower than of sulforhodamine B.

The maximum (v_1) and dominant (v_p) flow velocities of groundwater are not very

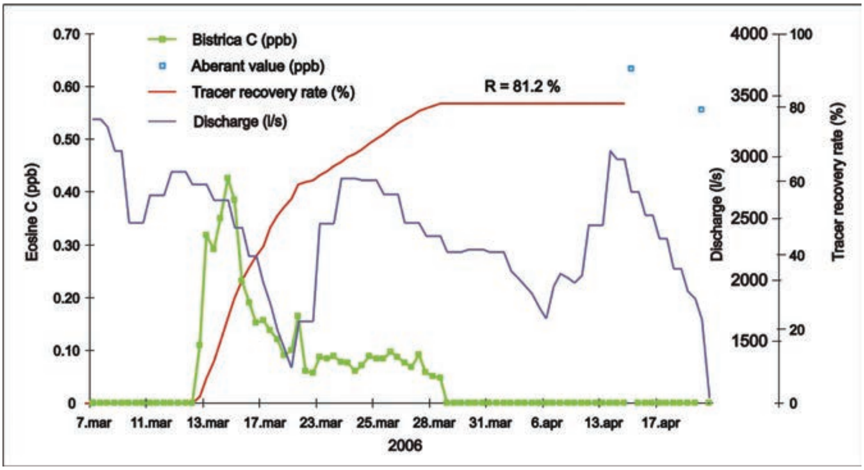


Figure 9.25: Eosine breakthrough curve observed in the Bistrica spring. Bistrica discharge data was gained from the Slovene Environmental Agency (Bistrica ..., 2006).

high. The maximum flow velocities are ranging from 25.7 and 52.7 m/h, the dominant flow velocities are ranging from 21 and 41.5 m/h indicating the presence of moderately developed system characterised by karst conduits of smaller dimensions and moderate connectivity.

Based on these tracer test results we can conclude that in the conditions of high waters the underground water flow from Šembijsko Jezero is directed only to Podstenjšek springs; and from Kamenščina and area below the Milanka mountain is directed mainly towards the Bistrica spring, and in small proportions also to the Podstenjšek springs.

9.7.4 DELINEATION OF THE CATCHMENT AREA

In the studied area the exact positioning of the watershed is, except in the contact area of the carbonate and flysch rocks, practically impossible to define due to its karst nature. Apart from the western and southwestern edge the catchment border is rather like a wider zone.

On the southwest and west, the Podstenjšek springs catchment border goes by the thrust margin from the Tuščak to the Bezgovica hills. On the north it follows the Pivka and Reka watershed presumed already by Melik (1951). The watershed goes from Vrh and Reber on the northwest across Stani hrib to the Milanka mountain and the ridges of Volovja reber on the east.

From there it turns south towards Tuščak mountain crossing southern and southeastern edges of the Kamenščina dry valley. Altogether the Podstenjšek catchment occupies 9.1 km^2. We divided the catchment into an inner and outer zone. The inner zone comprises part of the aquifer system that always contributes to the spring and is directly

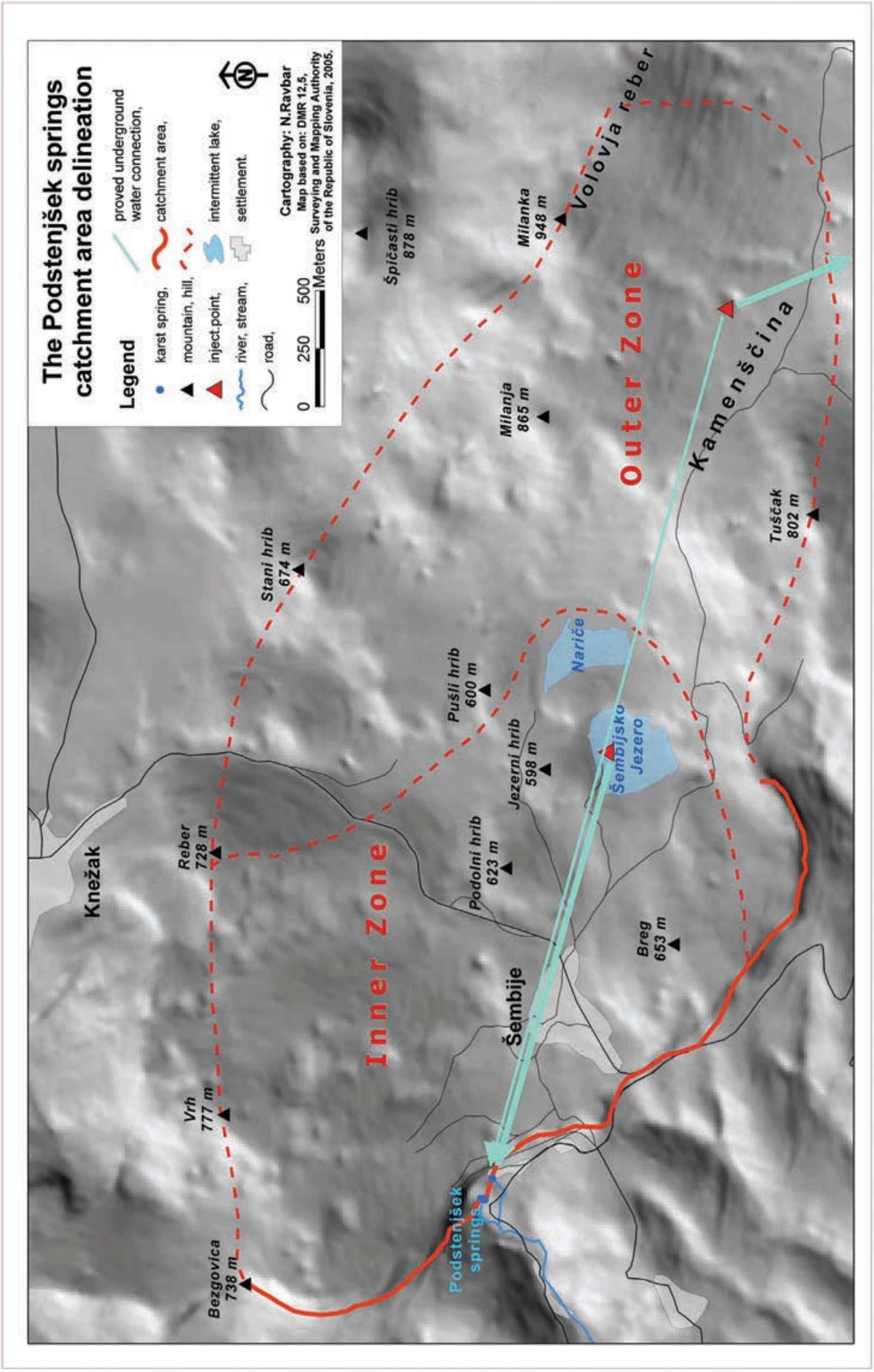


Figure 9.26: The extent of the Podstenjšek springs catchment area.

connected to and drained by the spring. The outer zone comprises the morphologically uplifted part of the aquifer that contributes only a small portion of the total springs' discharge and the parts we are not sure if they contribute to the Podstenjšek springs on the northern and northeastern side (Fig. 9.26). The inner zone embraces 4.3 km^2 and the outer zone 4.8 km^2.

9.8 CHARACTERISTICS OF THE CATCHMENT AREA

In order to get to know geological, geomorphological and speleological characteristics of the area, in addition to the existing literature different research methods have been used. The emphasis was on detailed structural-lithological and geomorphological mapping, as well as geophysical investigation by means of electrical imaging.

9.8.1 DETAILED STRUCTURAL-LITHOLOGICAL AND GEOMORPHOLOGICAL MAPPING

In autumn 2005 the detailed structural-lithological mapping after the method of Čar (1982) was done at a scale of 1:5,000. The purpose was to determine tectonic deformation and lithological juncture of carbonate rocks with either flysch or alluvium more precisely. At the same time we performed detailed geomorphological mapping as well (Fig. 9.28). The resulting information was used for the application of vulnerability maps.

In the studied area the tectonic and lithological contacts between Eocene flysch and carbonate rocks were determined, as well as the position of some other tectonic deformations connected with folding and thrusting were confirmed. However, we discovered that the information provided by the geological map (Šikić *et al.*, 1972; Šikić and Pleničar, 1975) does not completely match the real situation.

First of all, the exact locations regarding thrust or lithological units are different from the existing literature and mapping data. The differences mainly appear due to the interpolation of the regional-scale data to the local scale.

Nevertheless, the extent of the Quaternary alluvial deposits interpreted by the Šikić *et al.* (1972) and Šikić and Pleničar (1975) is oversized. According to our field mapping we only observed alluvial sediments in the bottom of the Šembijsko Jezero (Fig. 9.27). Even though we did not observe any sediment in the Nariče we still admit the possibility that these appear to a smaller extent. Furthermore, we also discovered that the dry valley below the Milanka mountain, named Kamenščina, is in places covered by thicker layers of periglacial material. Detailed further research to these topics is described in section 9.8.2.

Regarding geomorphology the most typical features are dolines of bowl shape that intersect conical hills. Using geomorphological field mapping, topographic maps and aerial photographs we observed 95 dolines. Their density reaches 16 dolines per km^2. In some smaller parts, their density reaches up to 35 or in places even 60 dolines per km^2. The majority of dolines are rather small, their average surface area being around 1,675 m^2. Their bottoms are rather flat and covered by thicker soil. On the west two dry valleys of smaller scale appear. The already mentioned Kamenščina dry valley is much larger and is situated on the uplifted plateau below the Milanka mountain.

In large parts of the area the karstified rocks are covered with very thin soil cover. Only in small patches are there outcrops of highly fractured limestone and individual karren. There have been six caves registered in the studied area (Cadastre of caves, 2006): Uršnja luknja (Cad. No. 1174), Zatrep (Cad. No. 1177), Kozja luknja (Cad. No. 1178), Luknja v gradu (Cad. No. 1179), Jakčeva luknja (Cad. No. 1180) and Brezno pod bregom (Cad. No. 6588).

All except one originate on the limestone and flysch contact and are situated on the thrust front. Brezno pod bregom lies in Šembije village and was opened during construction of a house. Except the cave of Kozja luknja (Fig. 9.29) the caves are very short and dry. The Kozja luknja is an intermittent spring cave where the underground water level with at least 20 m oscillation can be observed. The tracer test has proved the

Figure 9.27: Location of the alluvial sediments at the estavelle, on the bottom of the Šembijsko Jezero and the Kamenščina dry valley at the back (photos: N. Ravbar).

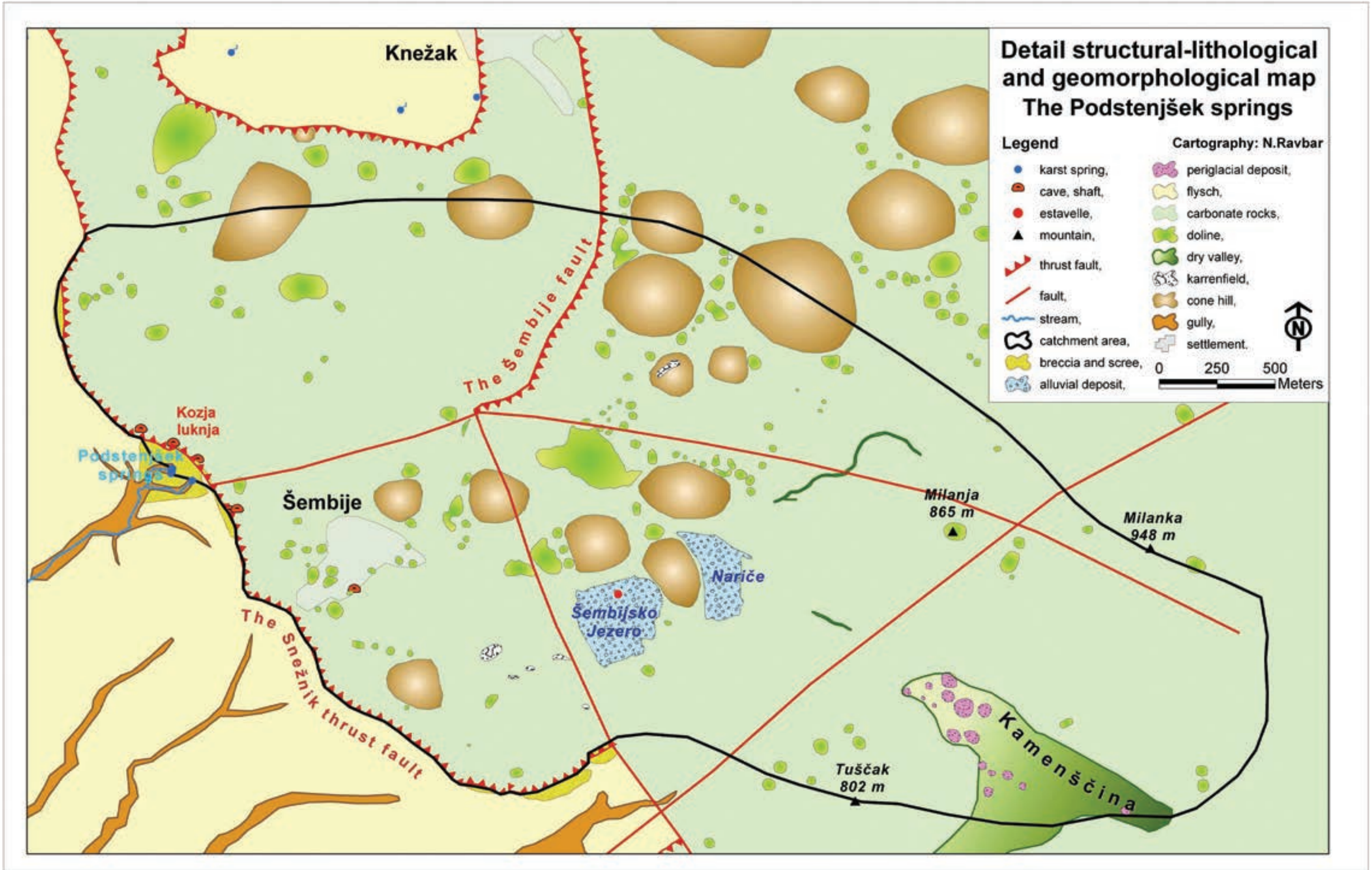


Figure 9.28: Detail structural-lithological and geomorphological map of the Podstenjšek springs catchment area and surroundings.

Figure 9.29: The cave of Kozja luknja (photo: G. Kovačič).

underground water connection to the springs with apparent velocity of 30 m/h (Krivic *et al.*, 1988).

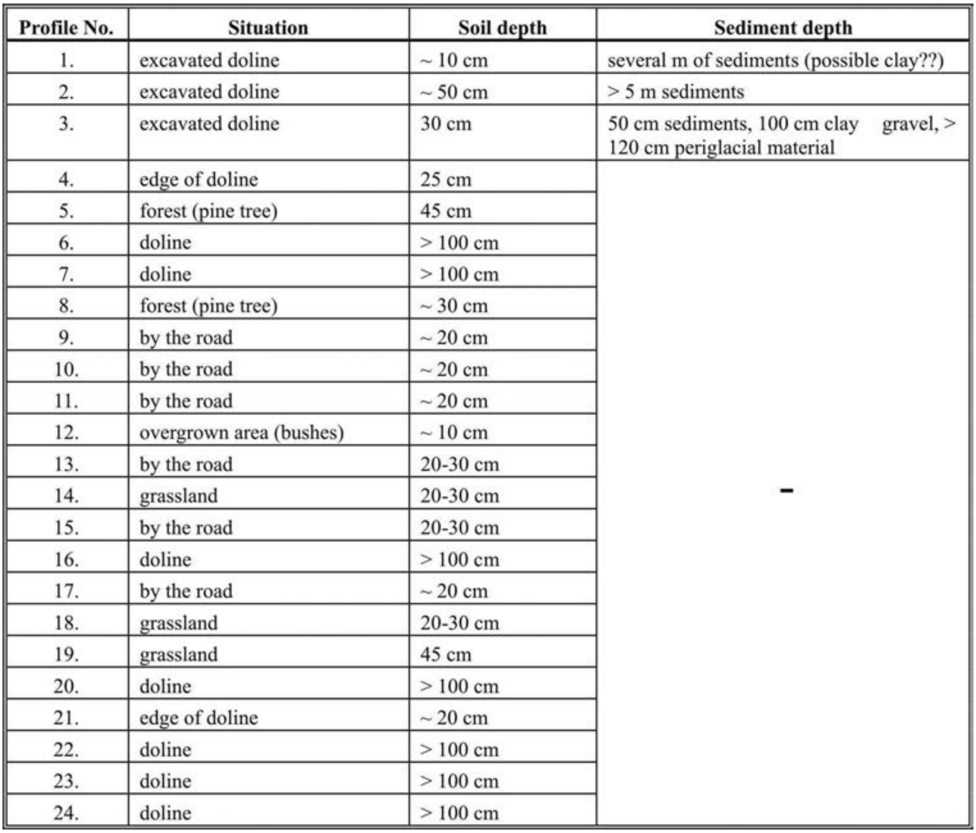
9.8.2 SOIL AND SEDIMENT DEPTH MEASUREMENTS

In summer 2006 several point and line measurements were performed using different techniques in order to gain better information on soil and sediment depth of the studied area that we need for the intrinsic vulnerability assessment.

We made 24 point soil and sediment depth measurements using direct observation of the exposed vertical profiles or by hand auger (Tab. 9.3 and Fig. 9.30). We also performed five line profiles for the indirect insight of the subsurface using Super Sting R1/IP electrical resistivity imaging in order to understand better the soil depth characteristics of the area, as well as to define the extent and depth of the mapped sediments better.

To know what the soil thickness of the area is, we made seven soil depth measurements in the bottom of the dolines and all showed more than 1 m of soil thickness (Fig. 9.32). In two point measurements at the edge of the dolines there was between 20-25 cm of soil and at the rest of the measured points the soil depth ranged between 10-45

Table 9.3: Soil and sediment depth point measurements.



Profile No.	Situation	Soil depth	Sediment depth
1.	excavated doline	~ 10 cm	several m of sediments (possible clay??)
2.	excavated doline	~ 50 cm	> 5 m sediments
3.	excavated doline	30 cm	50 cm sediments, 100 cm clay gravel, > 120 cm periglacial material
4.	edge of doline	25 cm	-
5.	forest (pine tree)	45 cm	
6.	doline	> 100 cm	
7.	doline	> 100 cm	
8.	forest (pine tree)	~ 30 cm	
9.	by the road	~ 20 cm	
10.	by the road	~ 20 cm	
11.	by the road	~ 20 cm	
12.	overgrown area (bushes)	~ 10 cm	
13.	by the road	20-30 cm	
14.	grassland	20-30 cm	
15.	by the road	20-30 cm	
16.	doline	> 100 cm	
17.	by the road	~ 20 cm	
18.	grassland	20-30 cm	
19.	grassland	45 cm	
20.	doline	> 100 cm	
21.	edge of doline	~ 20 cm	
22.	doline	> 100 cm	
23.	doline	> 100 cm	
24.	doline	> 100 cm	

cm (Fig. 9.31). In the Kamenščina dry valley two point measurements in the bottom of the dolines showed more than 1 m of soil depth as well.

Furthermore, in the Kamenščina dry valley three dolines have been recently excavated (Fig. 9.33). The material had been used for repair of the road towards the Milanja mountain. In contrast to the hand auger results obtained from the bottoms of the dry valley dolines, on the profiles in the excavated dolines not more than 50 cm of soil depth could be measured. In the excavated dolines – the profiles no. 1-3, we have also been able to observe that these dolines have been filled with sediment layers several metres thick. Thus the sediment structure and its depth have been measured. Profiles showed around one metre of clay layers and layers of clastic material as described in the tab. 9.3. Note that the structure of sediment profiles and their thickness is not the same in all three profiles.

As a conclusion we can deduce that the dolines in the studied area contain more than 1 m of soil cover, while its depth ranges from 0-50 cm in the rest of the catchment.

Moreover, we carried out five line profiles using electrical resistivity technique (Fig. 9.34) in the Kamenščina dry valley, and of the bottoms of Šembijsko Jezero and Nariče

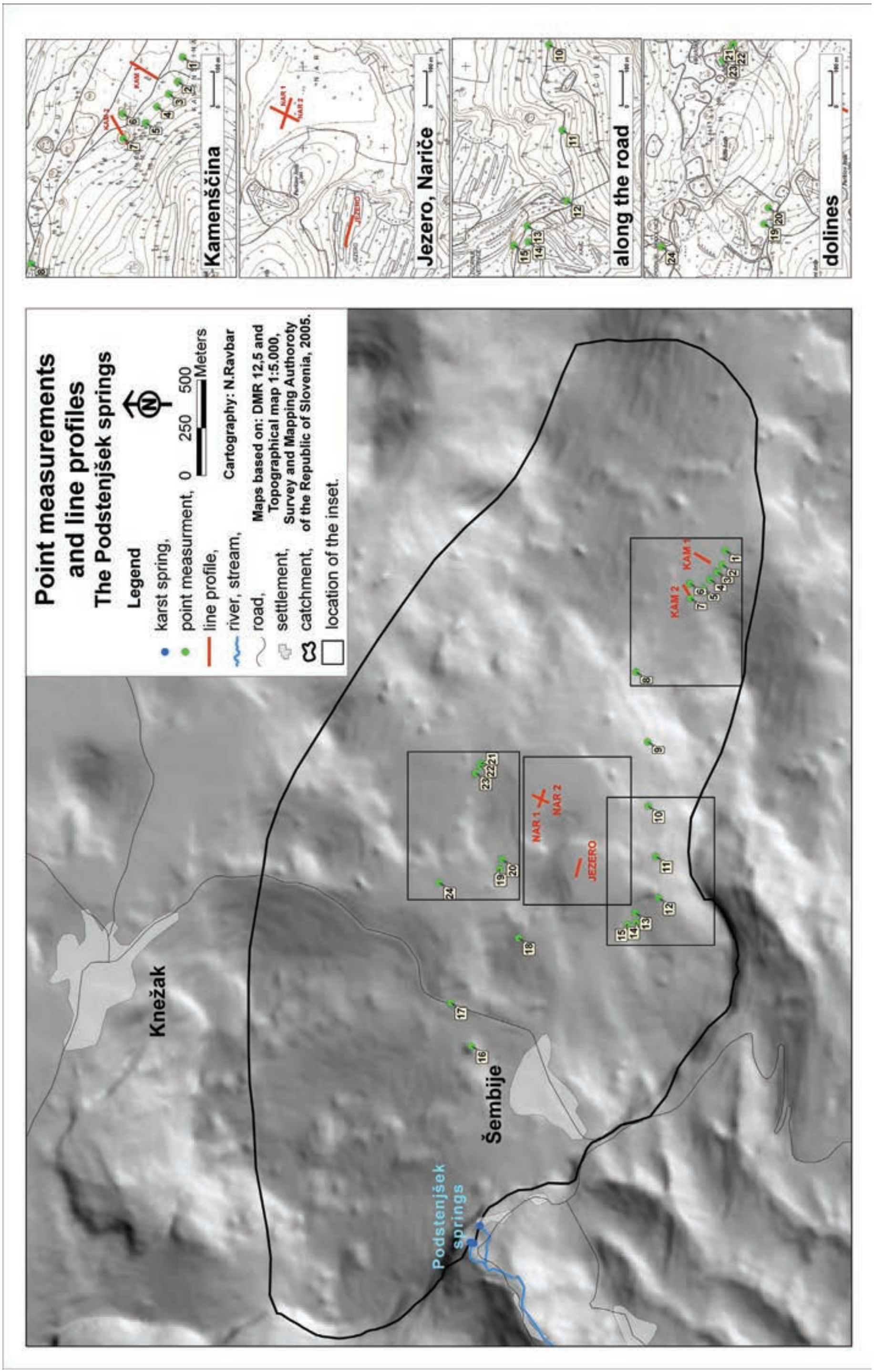


Figure 9.30: Location of the soil and sediment depth point measurements and line profiles with some detailed scale insets.

Figure 9.31: Image of the soil profile no. 13 in the cut along the road (photo: N. Ravbar).

Figure 9.32: Image of the soil profile no. 24 in the excavated doline (photo: N. Ravbar).

(for location see Fig. 9.30). The purposes of the investigation were:

– to confirm or reject whether the periglacial sediments identified in the dolines of the dry valley appear along the whole dry valley or are only locally overlying karst features, while these have probably already been denudated on the rest of the surface,
– to find to what depth does the periglacial material extend,
– to identify the depth of the alluvial deposits on the bottom of the Šembijsko Jezero and
– to confirm or reject the sediment cover in the bottom of the Nariče and to identify its eventual thickness.

The electrical resistance technique involves inputting electrical current into

Figure 9.33: Image of the sediment profile no. 2 in the excavated doline (photos: N. Ravbar).

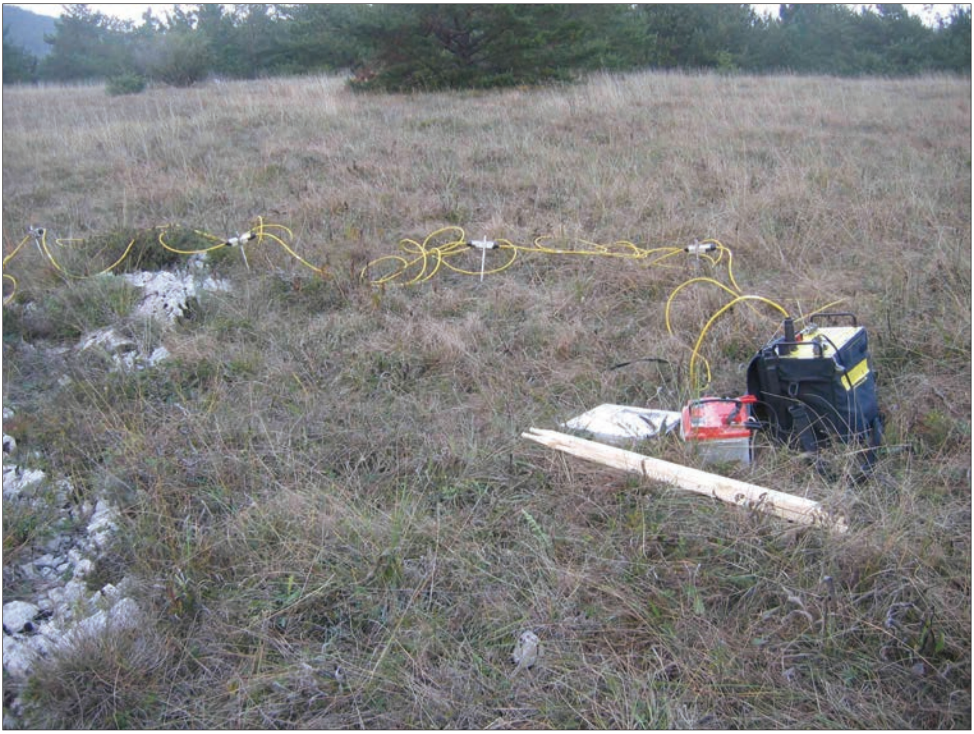


Figure 9.34: The figure is showing the electrical resistivity measurement principle (photo: N. Ravbar).

the ground and measuring the resistivity variations with depth. On the resulting profiles apparent resistivity pseudosections can be observed, providing an indirect insight of the subsurface. The results can be interpreted to provide a geological model of the subsurface (Bechtel *et al.*, 2007).

Using Super Sting R1/IP electrical resistivity imaging we applied the Wenner array in all the profiles with a length of 100 m (5 m electrode spacing) to test the specific predictions. The Wenner array is a relatively robust array, but is rather sensitive to vertical changes in the subsurface sensitivity and less sensitive to horizontal changes. Thus it is good in detecting horizontal structures (Bechtel *et al.*, 2007).

In order to be able to compare obtained results we adopted the same apparent resistivity values to all profiles. To understand the results better we always also had some reference point on the profile providing us cross-examination of the obtained information.

The profile in the Šembijsko Jezero is orientated towards its bottom. The results indicate that the carbonate rocks are covered by lower resistivity layers. At the profile's 10 m distance it approaches the estavelle, which is covered by 50 cm of sediment and a decimetre thick soil cover. According to the highly homogeneous results the depth of sediments and possible clayey soils increases towards the bottom of the lake, where these

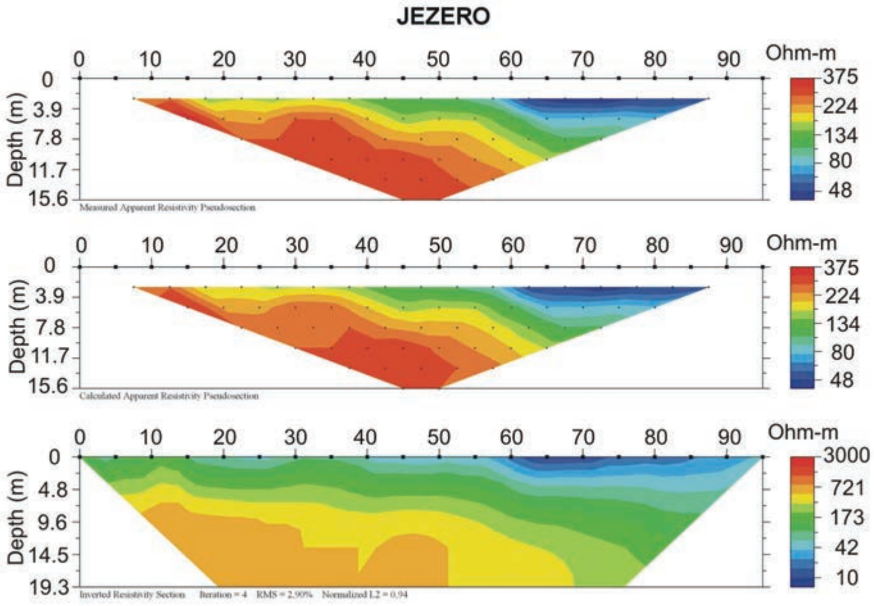


Figure 9.35: The observed apparent resistivity pseudosections for the Šembijsko Jezero (JEZERO) together with inversion models.

reach a depth of more than 10 m. Moreover, the structures are in relatively horizontal layers (Fig. 9.35).

The profiles from the Nariče were placed perpendicular to each other. The results show big heterogeneity of the subsurface characteristics. In the first profile (NAR 1) it is shown that the examined area consists mainly of practically bare carbonate rocks, which are highly fractured or intertwined with zones of higher permeability. From the 65-90 m distance a larger patch of lower resistivity rocks appears, which could consequently be interpreted as gravel-like, fine or detritus material (Fig. 9.36).

Even greater heterogeneity of the subsurface can be observed in the second, NAR 2 profile. The zones of higher permeability and/or fractured rocks are more distinct, while lower resistivity rocks appear in 5-10 m wide pockets between the pinnacle-shaped karst rocks. The initial part of the profile even crosses the morphologically not very distinctive area with a great anomaly in resistivity. We interpret it as a subsurface depression filled with sediments and soil layers more than 10 m deep (Fig. 9.37).

As a conclusion we can deduce that according to direct field observation in combination of the electrical resistivity imaging results, the bottom of the Nariče is highly fractured or intertwined with zones of higher permeability of the carbonate rocks. However, the bottom of the Nariče is only partly covered with 5-10 m wide pockets of

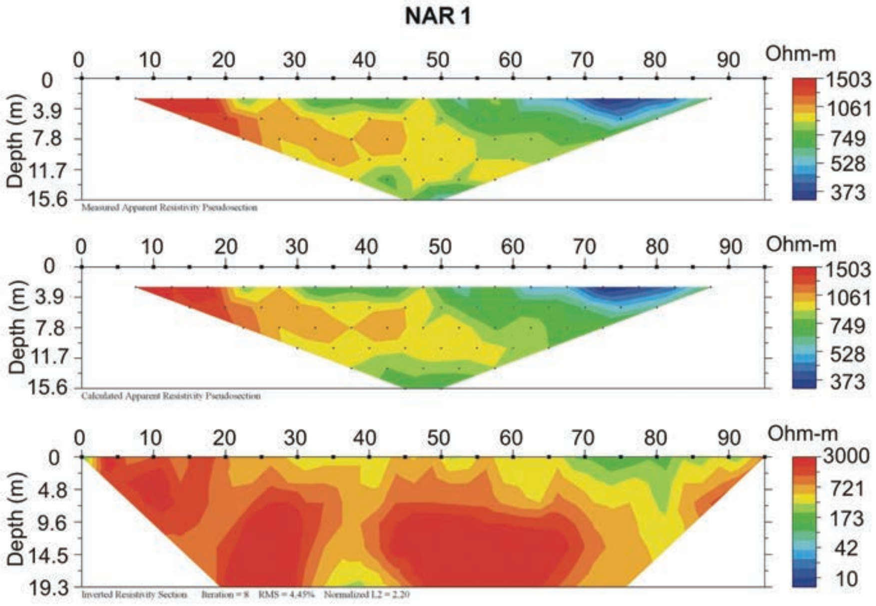


Figure 9.36: The observed apparent resistivity pseudosections for the Nariče (NAR 1) together with inversion models.

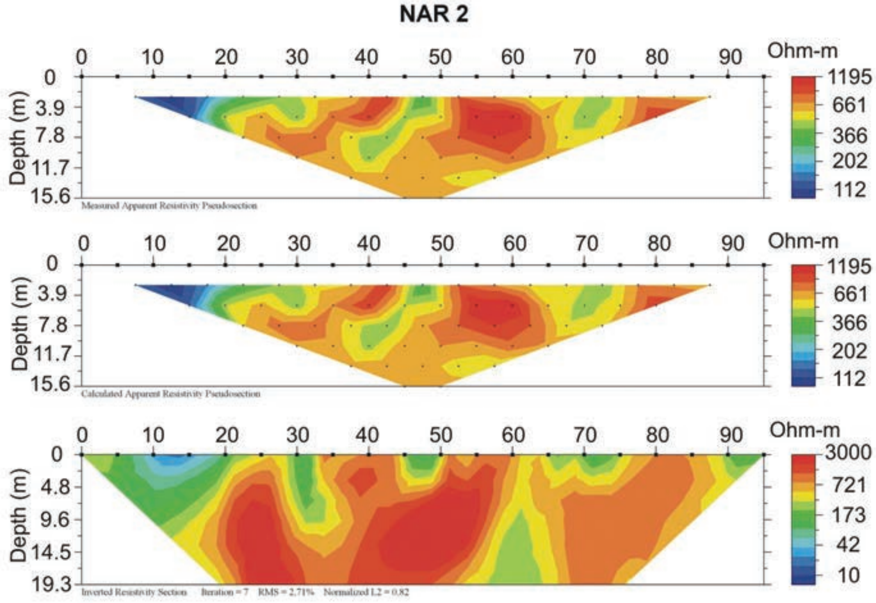


Figure 9.37: The observed apparent resistivity pseudosections for the Nariče (NAR 2) together with inversion models.

soil and sediment layers between the pinnacle-shaped karst rocks that can reach depth up to 10 m or even more.

Contrary to our expectations the profile KAM 1 performed in the upper part of the Kamenščina dry valley, orientated perpendicular to the valley, shows that the bottom of this part of the valley is not covered by soil and sediments layers of significant depth. Practically the entire profile crosses firm and homogeneous limestone rock basis (Fig. 9.38).

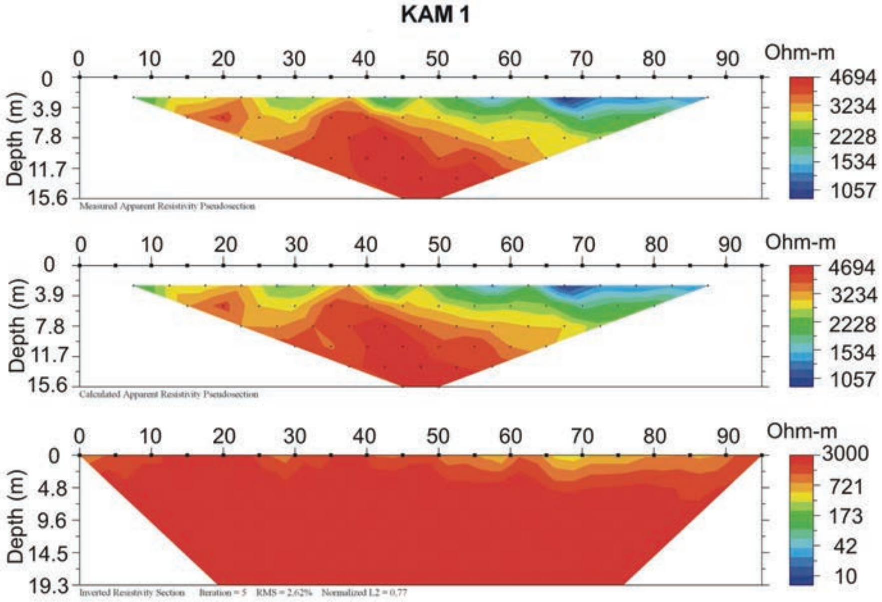


Figure 9.38: The observed apparent resistivity pseudosections for the Kamenščina dry valley (KAM 1) together with inversion models.

On the contrary, the heterogeneity of the second profile KAM 2 has been as expected mainly from the geomorphological observations. The profile has been placed in the lower part of the dry valley and orientated perpendicular to it. It crossed two shallow dolines at the both edges of the profiles. The subsurface of the both dolines are clearly noticeable in the resulting image. The doline in the left corner is presumably filled with several metres deep soil and lower resistivity rocks. In the bottom of this doline a soil depth of more than 1 m has been measured by hand auger. According to the results the doline in the right corner of the profile is also filled with several metres of lower resistivity rocks. In between there is a heterogeneous karst area of wide zones of higher permeability and/or fractured rocks, even a channel presumably filled with low resistivity material. Firm rock only occurs in pinnacle-shape form (Fig. 9.39).

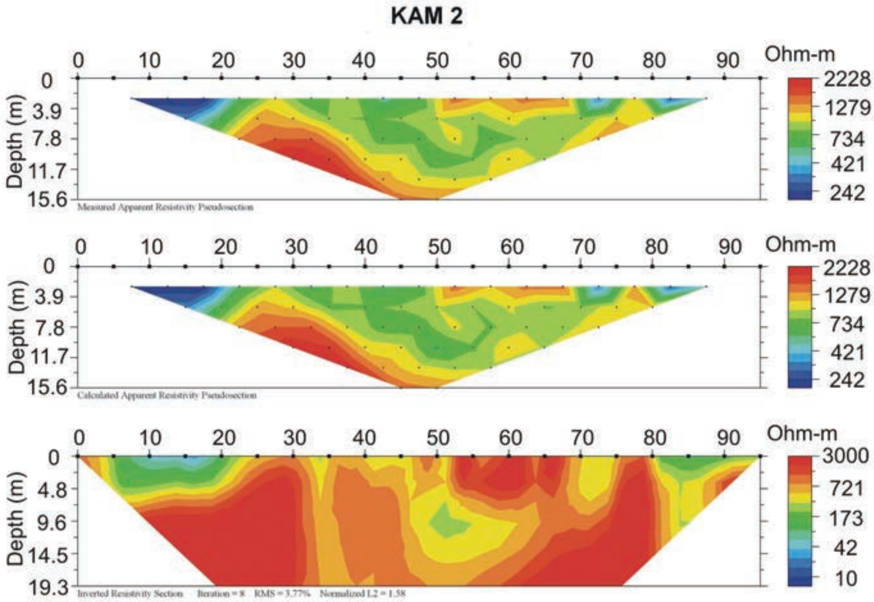


Figure 9.39: The observed apparent resistivity pseudosections for the Kamenščina dry valley (KAM 2) together with inversion models.

According to the direct field observation and electrical resistivity imaging results we suppose that, in general, the bottom of the dry valley is neither covered with soils of significant depth nor with sediment cover. These only fill the depressions e.g. dolines several metres in thickness.

10

APPLICATION OF DIFFERENT VULNERABILITY METHODS

10.1 OVERVIEW

The catchment area of the Podstenjšek springs has been selected as a test site for the application and validation of different intrinsic vulnerability methods. Most vulnerability mapping applications have been in the catchment area of the Podstenjšek springs done so far in Slovenia. Five intrinsic resource and source vulnerability methods (the EPIK method, the PI method, the COP method, the Simplified method and the Slovene Approach) have been applied (described and cited in chapter 5). The latter three methods have been developed on the basis of work accomplished by the European COST Action 620.

For these five methods quantification of the parameters has been done in parallel in order to be consistent for further analyses. The maps have been prepared using the Surfer Mapping System GIS Version 8.0, ArcView GIS Version 3.1 and ArcMap GIS Version 9.1.

The applications are mainly based on:

- Topographic map, 1:5,000, sheets Knežak and Ilirska Bistrica, Surveying and Mapping Authority of the Republic of Slovenia, 2005,
- Digital elevation model, DMR 12.5, Surveying and Mapping Authority of the Republic of Slovenia, 2005,
- Digital orthographic photographs, DOF 5, Surveying and Mapping Authority of the Republic of Slovenia, 1999-2004,
- Geological map Osnovna geološka karta SFRJ, 1:100,000, sheet Ilirska Bistrica, Vojnogeografski inštitut Beograd, 1972,
- Cadastre of caves, Speleological Association of Slovenia, Karst Research Institute SRC SASA, 2006,
- Pedological map, 1:25,000, sheets Ilirska Bistrica-zahod and Ilirska Bistrica-vzhod, Biotechnical Faculty, Center for Soil and Environmental Sciences, 1988,
- Land use data, Ministry of Agriculture, Forestry and Food, 2006,
- Daily and annual precipitation data 1961-2006, Ministry of the Environment and Spatial Planning, Environmental Agency, 2006,
- Field observation by detailed structural-lithological and geomorphological mapping, soil and sediment depth measurements (chapter 9),

– Hydrograph analyses and tracer test interpretation (chapter 9).

The newly proposed Slovene Approach for intrinsic source vulnerability method has been applied for the first time. Its application allowed testing, further development and completion of the proposed approach. Thus, the applications of other intrinsic vulnerability methods have made it possible to compare and validate obtained results.

10.2 APPLICATION OF THE EPIK METHOD AND RESULTS

The application of the EPIK method is quite easy and simple, even though the presence of epikarst and the degree of its development is in general relatively hard to determine. The E parameter has been assessed mainly by the examination of the topographic maps and digital orthographic photographs. Afterwards the data have been supplemented by field observation, detailed geomorphological mapping and information from the Cadastre of caves database.

The E_1 category has been assigned to the dolines, caves, karren, highly fractured areas, the estavelle, karst edge (Fig. 10.1) and outcrops along the roads. The E_2 category

Figure 10.1: Thrust contact of limestone over flysch forms the so-called karst edge (photo: J. Logar).

has been assigned to the dry valleys and the intermediate zones between the clusters of dolines. The E_3 category extends over the rest of the catchment and occupies the largest area.

Evaluation of the P parameter has been based on information from geological and pedological maps in conjunction with verification in the field by means of detailed structural-lithological mapping, as well as soil and sediment depth measurements using hand auger and electrical resistivity technique.

The protective cover in the studied area consists mostly of soil. Therefore the P_1 category has been assigned to the small areas where soil is absent, only occurs in patches or its thickness merely exceeds 20 cm. The karren, highly fractured areas, caves, the estavelle, karst edge, three excavated dolines in the Kamenščina dry valley and outcrops along the roads have consequently been characterised as category P_1. The P_2 category has been assigned to the area with a soil thickness between 20 and 100 cm, which occupies dry valleys and a big part of the studied area. The P_3 category has been assigned to the dolines, where soil thickness exceeds 1 m, to the dolines in the Kamenščina dry valley filled with several metres thick periglacial deposits, clay layer and soil, to the area of the intermittent lakes covered by alluvial sediments and to the areas covered by lateral scree or breccia. A small area of flysch rocks has been classified as category P_4.

Infiltration conditions have been evaluated on the basis of the digital elevation model, topographic maps and land use database. Category I_1 represents the intermittent lake Šembijsko Jezero that occurs more often and the estavelle filling and emptying the lake. On the contrary, the intermittent lake Nariče only occurred twice in the past century. As the EPIK method takes into account temporary or perennial water flow conditions, we have not classified the Nariče as a zone of concentrated infiltration.

The delineation of the Šembijsko Jezero catchment area is problematic, as the water recharges the lake by flowing out through innumerable fissures and voids at the bottoms or edges of the depression. Within this catchment area the I_2 category presents overgrown areas, meadows and pastures with slopes greater than 25% and bare limestone outcrops with slope angle greater than 10%. At the lake's catchment the I_3 category presents meadows and pastures, as well as overgrown areas with slope angle lesser than 25%.

Outside the lake's catchment karren, cultivated and urban areas with slopes greater than 10% and meadows, pastures, forest, scrub and overgrown areas with slopes greater than 25% are characterised as I_3 category. In the rest of the area largest part has been classified as category I_4. It extends over areas with slope angle lesser than 10% and over meadows and pastures, forest, scrub and overgrown areas with slope angle between 10 and 25%.

The K parameter has been obtained on the basis of indirect information as to the degree of karst network development; such as geomorphological and speleological settings of the catchment area, hydrograph analyses of the springs and tracer test interpretation.

Geomorphological characteristics show a typical karst landscape, however, the available speleological information only shows poor cave density with only one accessible

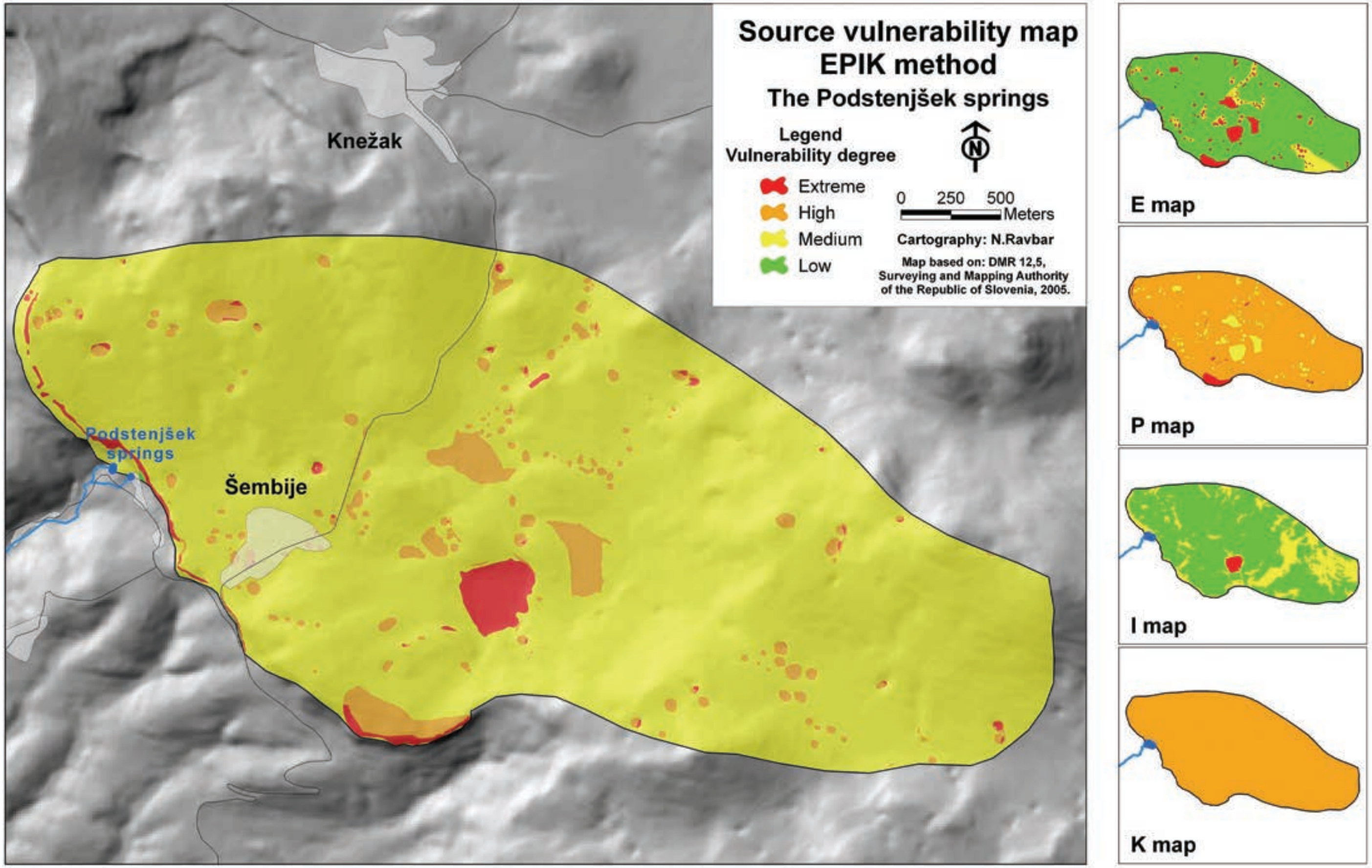


Figure 10.2: Intrinsic source vulnerability map of the Podstenjšek springs – the EPIK method.

active cave network. In addition, the karst water springs in several outlets characterise poorly developed karst network with blocked or poorly developed conduits.

Hydrograph and tracer test analyses provide some evidences of karst character of groundwater flow. Even though the springs' reaction to rainfall results in pointed discharge peaks and their rapid recession, the tracer test showed quite low groundwater flow velocities. Nevertheless, evident groundwater drainage of a part of the catchment into different springs has been proved.

The K parameter has been evaluated for the entire catchment. According to assembled information a compromise appraisal has been done. Consequently the category K_2 has been assigned characterising a not very well developed karst system.

The EPIK vulnerability map (Fig. 10.2) has been obtained by combining the weighted values of all four parameters and calculating the protection index. Large areas, 93%, are classified as moderately vulnerable. High vulnerability is mostly assigned to dolines, karren, fractured areas and outcrops along the roads. Altogether high vulnerability occupies 5% of the total area. Extreme vulnerability is assigned to the estavelle and to Šembijsko Jezero. An interesting result also occurs indicating areas where meadows and pastures, forest, scrub and overgrown areas with slope angles greater than 25% meet geomorphological feature (e.g. doline, karren, karst edge) as extremely vulnerable areas independently from the thickness of the protective cover. Altogether extreme vulnerability occupies 1.9% of the total catchment area; however, low vulnerability occupies only 0.01% or 0.1 ha (Fig. 10.3).

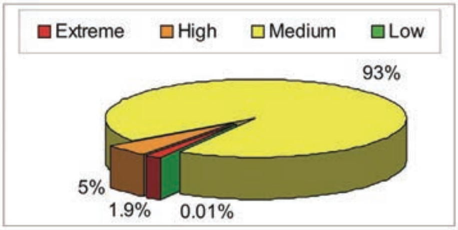


Figure 10.3: Percentage surface area for each vulnerability class in the Podstenjšek catchment area source vulnerability map using the EPIK method.

10.3 APPLICATION OF THE PI METHOD AND RESULTS

In the catchment area of the Podstenjšek springs the PI method has been applied for the first time in Slovenia. Its application required a very large amount of data.

The evaluation for the P factor has been obtained by combining the following subfactors: topsoil, subsoil, lithology, fracturing and recharge. For the information on soil types present in the studied area we relied on the pedological map, but unfortunately there is no available data on soil eFC (effective Field Capacity), required by the PI method. The values have been consequently quantified according to the standard tablets of a German Pedological Textbook (Schachtschabel *et al.*, 1984).

Shallow chromic Cambisol that is interwoven with Rendzina appears in the studied area. Both types are characterised by a low to medium eFC (50-140 mm). Therefore value 250 has been assigned to the bottoms of the dolines, where clayey soil thickness exceeds 1 m. Value 125 has been assigned to the areas, where non-karst rocks outcrop (flysch, breccia, alluvial deposits and periglacial material) as well as in the Kamenščina dry valley. In areas where soil cover rarely exceeds 20-30 cm above the carbonate rocks the value 0 has been assigned. The eFC values have been multiplied by the thickness of the soil horizon, obtained by field observations.

In large parts of the studied area subsoil layers are absent. However, where present, the grain size distribution of the subsoils and their thickness has been assessed on the basis of the geological map in conjunction with verification in the field by means of detailed structural-lithological and geomorphological mapping and electrical resistivity technique.

There are dolines in the Kamenščina dry valley (except for three excavated ones), filled with several metres thick periglacial material, clay layer and soil. In the intermittent lake of Šembijsko Jezero alluvial deposits are laid several metres in thickness and overlaid by thick soil cover. On the other hand alluvial deposits and soil cover in Nariče are unevenly distributed and patchy. Thus the effective soil and sediment thickness has been evaluated.

The thickness and distribution of the unsaturated zone has been determined by subtracting the anticipated groundwater contour lines from the digital elevation model values. The fracturing of the limestone bedrock has been assessed on the basis of the field observation.

The recharge parameter has been quantified on the basis of the average annual amount of precipitation (MOP ARSO, 2007) and the approximate values of this area's evaporation (Kolbezen and Pristov, 1998). A recharge greater than 400 mm/y has been estimated. Therefore the value 0.75 has been assigned to the entire test site.

The application of the I factor requires determination of the dominant flow processes, information on slope gradient, land use and surface waters catchment area delineation. Dominant flow processes of the studied area have been assessed on the basis of geological information and direct field observations. We distinguished between the direct infiltration into the karst aquifer that takes place on outcrops of karstified limestone irrespective of topsoil cover, as well as in areas where limestone is covered by permeable layers. Rare surface flow has been assigned to the area of the Šembijsko Jezero.

The information on dominant flow processes has been intersected with data on slope gradient and land use and afterwards with the surface catchment map. Consequently the I map has been produced reflecting hydrological conditions of the studied area. On the limestone outcrops there is never any lateral surface flow and all the precipitation directly infiltrates into the karst aquifer. On the other hand in the area of the Šembijsko Jezero occasional surface flow and sinking via swallow holes appear causing protective cover to be bypassed.

The PI vulnerability map (Fig. 10.4) has been obtained by intersecting the P and I

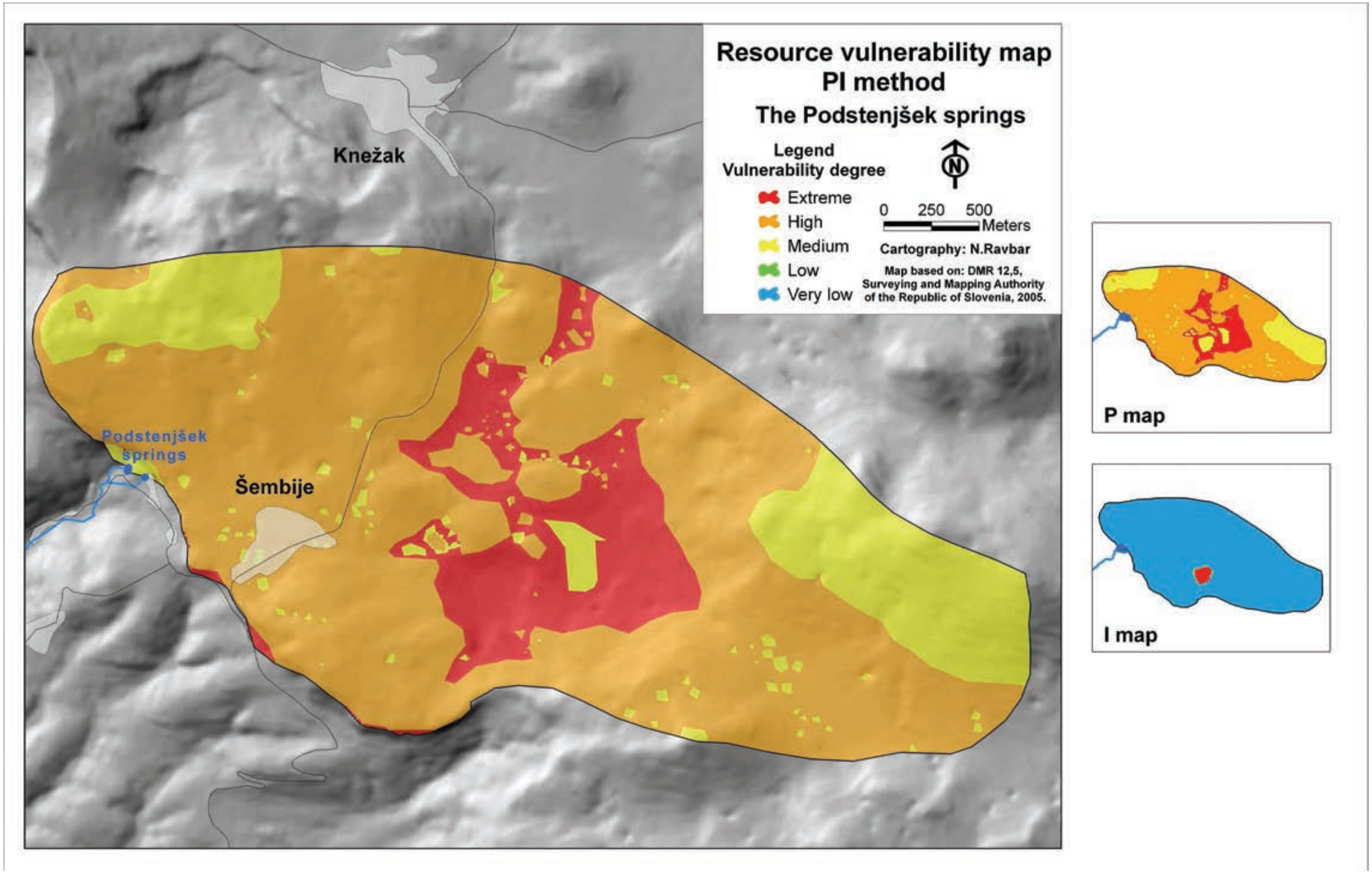


Figure 10.4: Intrinsic resource vulnerability map of the Podstenjšek springs – the PI method.

maps. The protection factor π has been calculated by multiplying the P and the I factors. Most areas range between medium and extreme vulnerability. Nevertheless, the P factor is crucial in determining the resource vulnerability map.

According to the PI method extremely vulnerable parts of the Podstenjšek springs catchment area cover 13.2% of the total area (Fig. 10.5). These embrace large areas where thickness of the unsaturated zone is very shallow and is not protected by sediment or soil cover. The intermittent lake of Šembijsko Jezero and the estavelle are also extremely vulnerable, as well as the karst edge at the southern and southwestern part of the catchment.

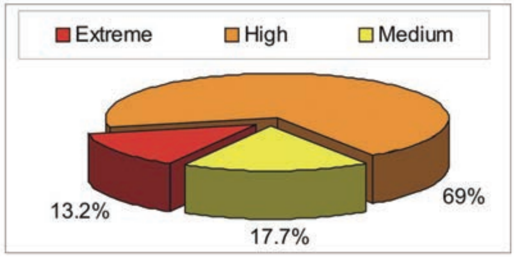


Figure 10.5: Percentage surface area for each vulnerability class in the Podstenjšek catchment area resource vulnerability map using the PI method.

Most of the catchment is highly vulnerable. It covers 69% of the area. Medium vulnerability is assigned to 17.7% of the area, where thickness of the unsaturated zone is higher or where there is thicker soil or sediment protective cover.

The PI vulnerability method provides intrinsic resource vulnerability map of an individual area. Thus, it cannot be used for a source protection scheme. In order to protect a spring or well, according to the European Approach an additional K factor has to be considered.

Therefore we made a first attempt to adopt the PI method to the source vulnerability mapping by intersecting the final PI map with the proposed K factor assessment. In the studied area the distance towards source has been delineated according to the apparent groundwater travel time obtained by the tracer test. Consequently classes for transit time (>1 day, 1-10 days) have been delineated. An immediate area within 980 m distance from the spring has been assumed as though the groundwater reaches the spring within one day. Value 1 for the t sub-factor has been assigned to this part of the studied area. The rest of the area has been characterised assuming that the groundwater reaches the spring within ten days and for the t sub-factor a value 3 has been assigned.

In the studied area only the cave of Kozja luknja provides evident information on groundwater flow. Therefore it has been classified as highly vulnerable and for the n sub-factor a value 1 has been assigned. In the rest of the area the presence of active conduit network has not been identified. Therefore for the n sub-factor there a value 3 has been assigned.

In the catchment area of the Podstenjšek springs we distinguish between an inner and an outer zone. The inner zone comprises part of the aquifer system that always contributes to the spring and is directly connected to and drained by the spring. The outer

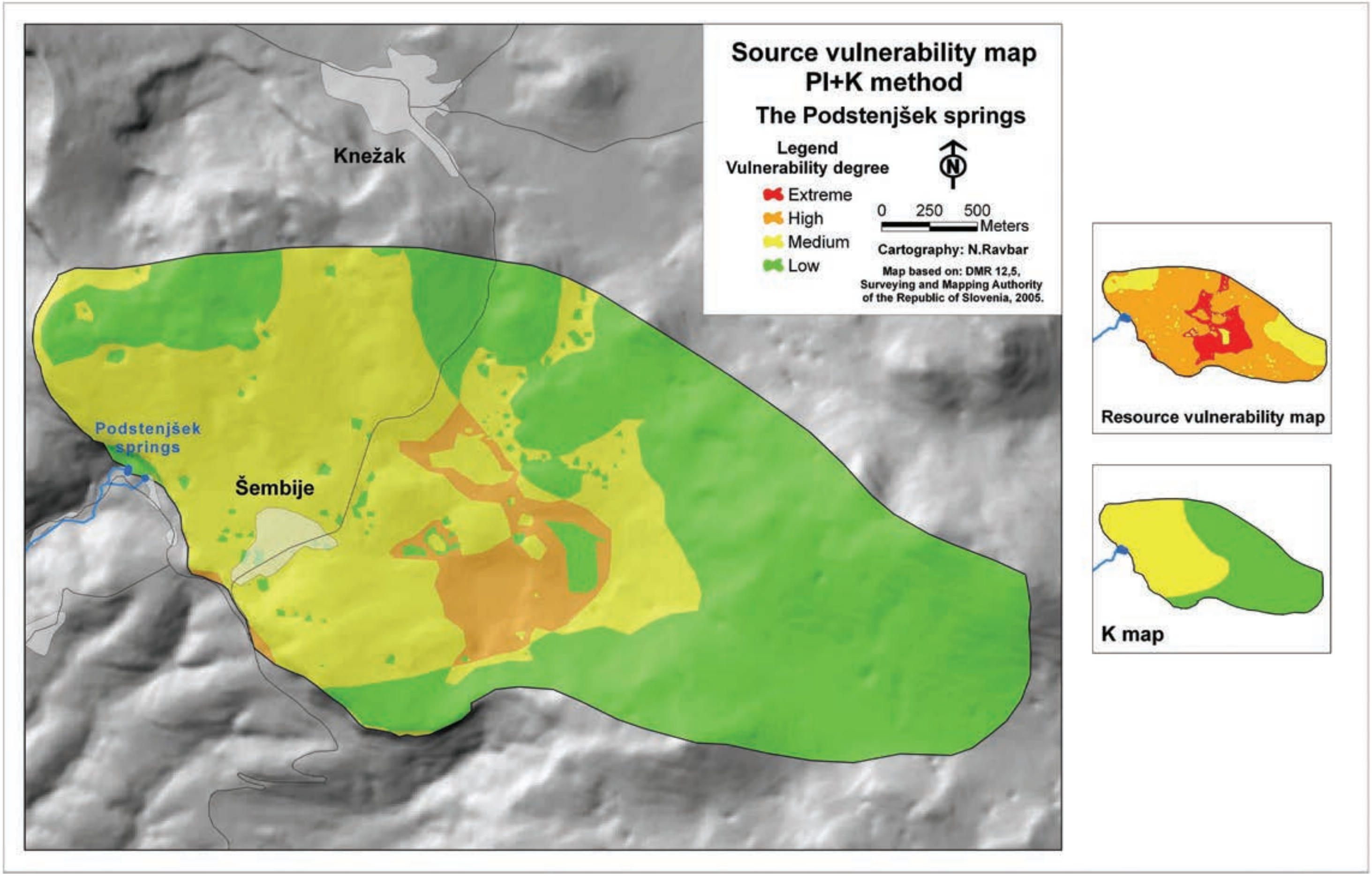


Figure 10.6: *Intrinsic source vulnerability map of the Podstenjšek springs – the PI+K method.*

zone comprises the morphologically uplifted part of the aquifer that contributes only a small portion of the total springs' discharge and the parts on the north and northeast. For these parts it is probable that they contribute to the Podstenjšek springs only during high waters (Fig. 9.26).

The delineation of these zones has been based on the geological, geomorphological, hydrological and speleological information as well as on the information provided by the tracer test. To the inner zone value 1 for the r sub-factor has been assigned and value 5 to the outer zone.

The final K map has been produced by multiplying the three (t, n and r) sub-factors. Consequently three classes of vulnerability have been distinguished. The highest vulnerability has been assigned to the conduit network of the Kozja luknja. The inner zone has been classified as moderately vulnerable and the outer zone as of low vulnerability.

The source vulnerability map (Fig. 10.6) is obtained by intersecting of PI and K maps. To enable both maps combination, primarily K scores have been transformed in the relevant indexes as proposed in the Slovene Approach source vulnerability assessment. The final values have also been classified according to the proposed Slovene Approach assessment scheme (see Fig. 7.12).

Within the inner zone extremely vulnerable areas for groundwater are highly vulnerable for the source. Moreover, regarding the source vulnerability map the area above the Kozja luknja is assigned as highly vulnerable. Within the inner zone highly vulnerable areas for groundwater are moderately vulnerable for source and moderately vulnerable areas for groundwater are of low vulnerability for the source.

Within the outer zone extremely vulnerable areas for groundwater are moderately vulnerable for source. However, highly and moderately vulnerable areas for groundwater have low vulnerability for the source.

Highly vulnerable areas in the source vulnerability map embrace 6.2% of the area, moderately vulnerable areas 40.4% and low vulnerability areas 53.3% (Fig. 10.7).

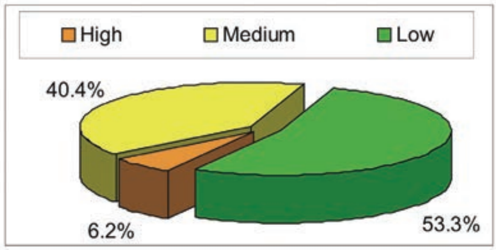


Figure 10.7: Percentage surface area for each vulnerability class in the Podstenjšek catchment area source vulnerability map using the PI+K method.

10.4 APPLICATION OF THE COP METHOD AND RESULTS

In the catchment area of the Podstenjšek springs the COP method has been applied for the first time in Slovenia. For the O factor assessment data on soil texture, lithology fracturing and thickness of each stratum is needed. Evaluation of these data is based on information from pedological and geological maps in conjunction with verification in the field by means of detailed structural-lithological and geomorphological mapping, as well as soil and sediment depth measurements using hand auger and electrical resistivity technique.

To the areas of dolines and intermittent lakes where more than 1 m of soil occurs, soil sub-factor value 5 has been assigned, value 0 to the areas where there is no soil (karren, highly fractured areas, caves, the estavelle, karst edge, three excavated dolines in the Kamenščina dry valley and outcrops along the roads) and value 2 to the dry valleys and the rest of the area where soil cover ranges between 0 and 0.5 m.

Where subsoil occurs (alluvial deposits in the intermittent lakes, periglacial material in the dolines of the Kamenščina dry valley, small areas of breccia at the southern and southwestern edge of the aquifer) an appropriate lithology sub-factor value has been assigned according to the assessment scheme and multiplied by individual layer thickness. The thickness of the unsaturated zone has been determined on the basis of the groundwater table map and the digital elevation model intersection. The fracturing of the limestone bedrock has been assessed on the basis of field observation. The layer index has been calculated and protection values have been obtained based on data collected.

Within the O factor determination very low protection value (high vulnerability) is assigned to the karst morphological features without or with very scarce soil cover. High protection is provided in areas of thicker soil cover and where low permeability layers cover carbonate outcrops. Medium protection corresponds to the rest of the area irrespective of the unsaturated zone thickness.

In order to assess C factor, data on slope gradient and land use has been used together with the topographic and geological maps, digital orthographic photographs, Cadastre of caves database and direct field observation. For scenario 1 the delineation of the catchment area of a sinking water body has been made, whereas the highest possible groundwater level had to be considered (Fig. 10.8). Furthermore, the buffer distance to a swallow hole and the buffer distance to a sinking stream have been classified, as well as the slope gradient and land use data.

In areas where the aquifer is not recharged via a swallow hole, scenario 2 has to be considered. In this situation information on surface karst features and the presence or absence of a permeable or impermeable layer are needed in addition to slope gradient and land use data.

The C factor shows extreme vulnerability explicitly where karst geomorphological features are not covered by permeable or impermeable layers, as well as where there are very small areas within karst geomorphological features with slope angle lesser than 31% independently from vegetation cover. High vulnerability corresponds to areas out-

Figure 10.8: Flooded Šembijsko Jezero and Nariče in November 2000 (photo: M. Ženjko).

side the karst geomorphological features with slope angles less than 8% irrespective of vegetation cover and with slope angles between 8 and 31% covered by denser vegetation cover. Low vulnerability corresponds to small areas of scree and breccia close to the springs, above the limestone formations with slope angles between 8 and 31% covered by scarce or no vegetation. Very low vulnerability corresponds to small areas of scree and breccia close to the springs, above the limestone formations or flysch outcrops with slope angles greater than 31% and covered by denser vegetation.

For the P factor assessment, the yearly and daily amount of precipitation measured at the nearby Ilirska Bistrica precipitation station in the period 1961-2000 has been gained (MOP ARSO, 2007). According to assembled information the P factor value of 0.8 has been estimated and thus the category of low vulnerability has been evaluated. Due to lack of supplementary precipitation stations in the springs' vicinity the P factor value has been assigned for the entire catchment.

The final resource vulnerability index is obtained by multiplying the three factors; however the C factor is crucial in determining the final values of the resource vulnerability map (Fig. 10.9). The final COP vulnerability map of the studied area shows extreme vulnerability in the contributory area to the lakes Šembijsko Jezero and Nariče that drain surface flow towards the estavelle when active. Extreme vulnerability also corresponds to the geomorphological features (karren, highly fractured areas, caves, karst edge, dry valleys), three excavated dolines in the Kamenščina dry valley and outcrops along the

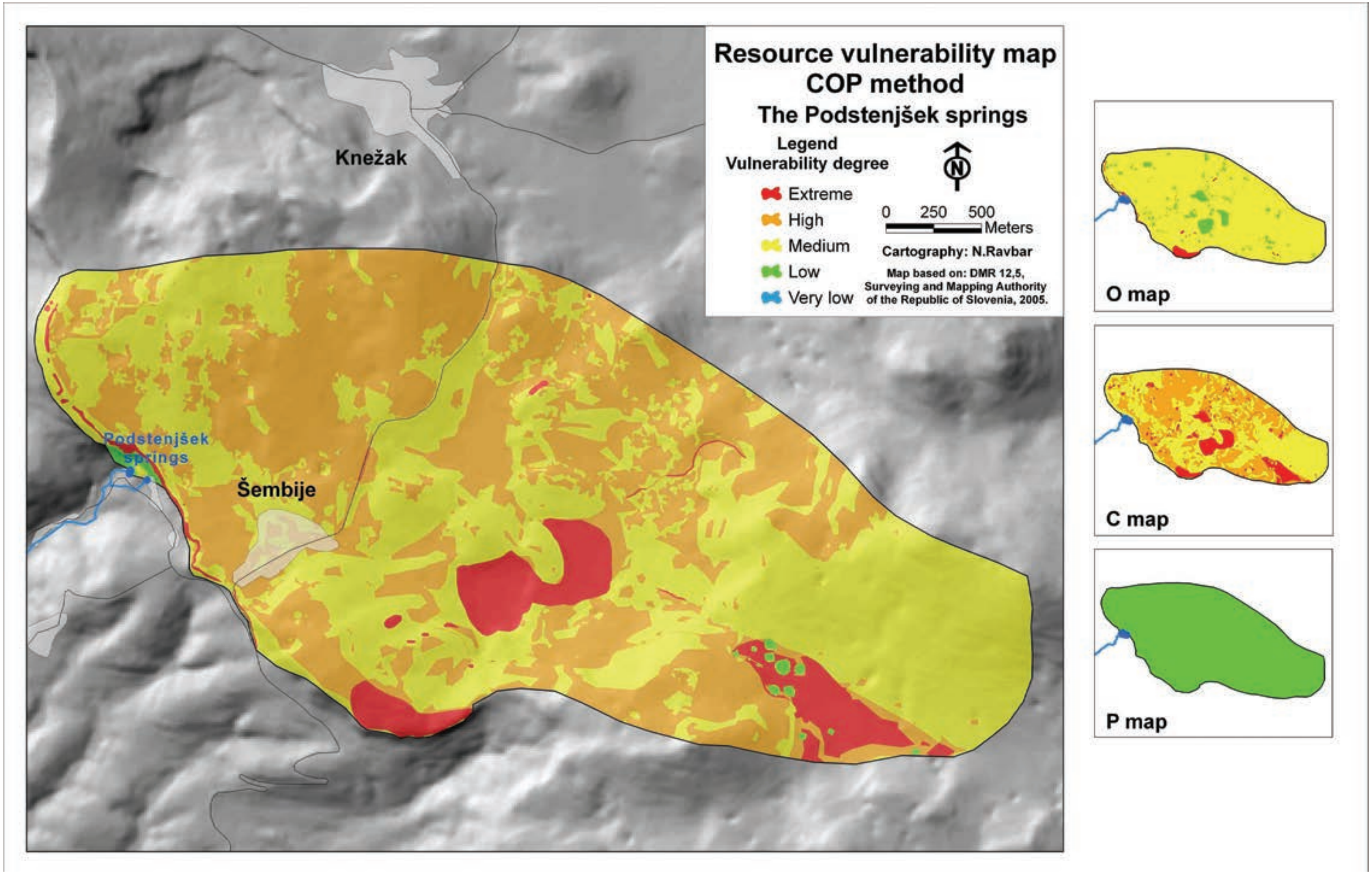


Figure 10.9: Intrinsic resource vulnerability map of the Podstenjšek springs – the COP method.

roads where soil cover is absent or reaches up to 0.5 m in depth. Extreme vulnerability areas cover 6.7% of the total catchment area (Fig. 10.10).

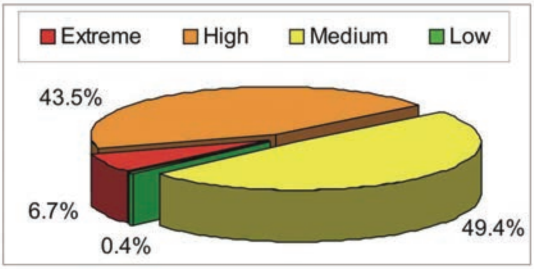


Figure 10.10: Percentage surface area for each vulnerability class in the Podstenjšek catchment area resource vulnerability map using the COP method.

Dolines, which are classified as karst geomorphological features, are not categorised as extremely vulnerable, because they are covered by more than 1 m of soil and hence classified as highly vulnerable. Highly vulnerable also are areas with slope angles lesser than 8% irrespective of vegetation cover and slope angles between 8 and 31% and densely overgrown with the vegetation. Altogether high vulnerability areas cover 43.5% of the total catchment area.

The medium degree of vulnerability extends over the largest part of the studied area, 49.4%. It occupies limestone formations with slope angles between 8 and 31% covered by sparse or no vegetation and with slope angles greater than 31% irrespective of vegetation cover. Medium vulnerability also occupies small areas close to the springs of scree and breccia above the limestone formations with slope angles between 8 and 31% covered by dense vegetation.

Low vulnerability corresponds to the dolines in the Kamenščina dry valley and to small areas close to the springs of scree and breccia above the limestone formations or flysch outcrops with slope angles greater than 31% irrespective of vegetation cover. Low vulnerability extends over only 0.4% of the total catchment area or 4 ha. However, the degree of very low vulnerability is not present at all.

The COP method is developed for mapping groundwater vulnerability. For assessing the karst source intrinsic vulnerability, a factor taking into account the karst network of the saturated aquifer is needed also. The COP method does not provide guidelines for the karst network development factor assessment. A proposed classification system for the K factor assessment has been adapted to the COP method, as proposed by the European Approach. By doing so, the COP method has been implemented for source vulnerability mapping for the first time and first applied to the Podstenjšek catchment area.

The final source vulnerability map has been obtained by intersection of the COP and K maps (for the K map assessment see chapter 10.3). To enable both maps combination, primarily K and COP scores have been transformed in the relevant indexes as proposed in the Slovene Approach source vulnerability assessment. The final values have also been classified according to the proposed Slovene Approach assessment scheme.

Resembling the PI map combined with the K map, the COP map combined with the K map also shows that within the inner zone extremely vulnerable areas for groundwater

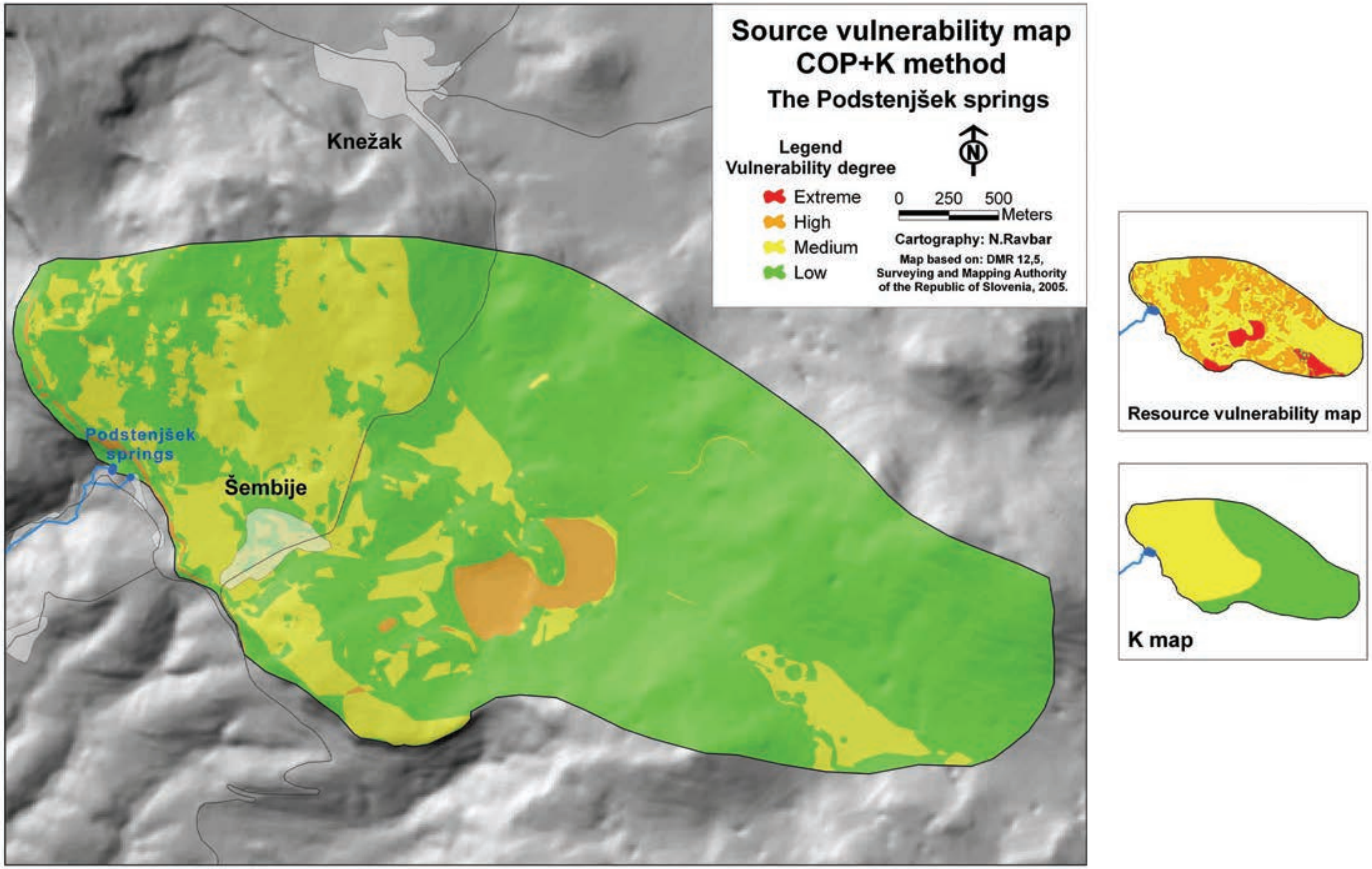


Figure 10.11: Intrinsic source vulnerability map of the Podstenjšek springs – the COP+K method.

are highly vulnerable for the source. However, in contrast to the PI+K map the area above the Kozja luknja is not assigned as highly vulnerable. Similarly highly vulnerable areas for groundwater are moderately vulnerable for the source and moderately vulnerable areas for groundwater have low vulnerability for the source (Fig. 10.11).

Within the outer zone extremely vulnerable areas for groundwater are moderately vulnerable for the source. However, highly and moderately vulnerable areas for groundwater are of low vulnerability for the source. Highly vulnerable areas extend over 3.3% of the area, moderately vulnerable over 24.7% and low vulnerability areas over 71.9% of the area (Fig. 10.12).

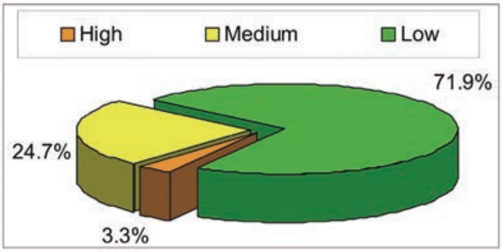


Figure 10.12: Percentage surface area for each vulnerability class in the Podstenjšek catchment area source vulnerability map using the COP+K method.

10.5 APPLICATION OF THE SIMPLIFIED METHOD AND RESULTS

The Simplified method is the easiest method to apply. In the catchment area of the Podstenjšek springs the Simplified method has been applied for the first time in Slovenia and in Europe as well.

Evaluation of the O factor is based on information gained from geological and pedological maps, as well as direct field measurements by means of detailed structural-lithological and geomorphological mapping, soil and sediment depth measurements using hand auger and electrical resistivity technique.

According to the O factor assessment scheme low degree of protection (corresponding to extreme vulnerability) has been assigned to the areas with no or insignificant protective cover, that are caves, karren, dry valleys, highly fractured areas, the estavelle, karst edge, three excavated dolines in the Kamenščina dry valley and outcrops along the roads. Medium vulnerability has been assigned to the rest of the dolines, intermittent lakes and small areas where low permeability scree and breccia appear. Low vulnerability corresponds to patches of flysch and to the rest of the dolines in the Kamenščina dry valley, filled with several metres thick periglacial deposits, clay layers and soil.

The C factor has been assessed on the basis of geological information and direct field observations. Determination of the dominant flow processes reflects extreme vulnerability in the area of occasional point recharge in the area of the Šembijsko Jezero. The rest of the catchment area where direct infiltration predominates, the category of low vulnerability has been assigned.

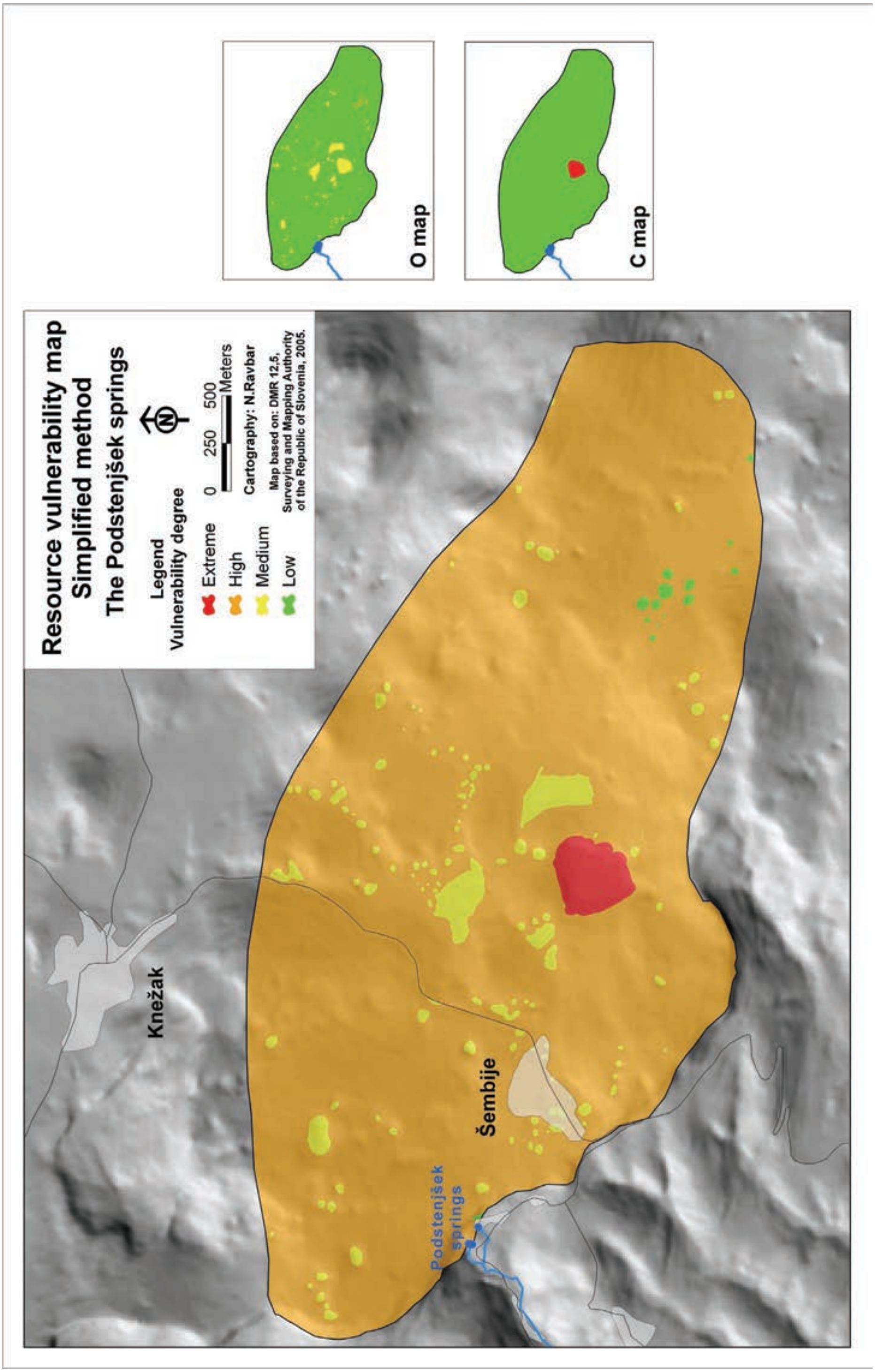


Figure 10.13: Intrinsic resource vulnerability map of the Podstenjšek springs – the Simplified method.

The resource vulnerability map (Fig. 10.13) is obtained by intersection of O and C maps. However, the O factor is decisive in determining the final resource vulnerability values. Areas of extreme vulnerability occupy 1.4% of the catchment and extend over the area of the Šembijsko Jezero. Most of the catchment area, 94.6%, is classified as highly vulnerable and in general correspond to the bare karst landscape or karst covered by shallow soils. Moderate vulnerability has been assigned to dolines and the Nariče and extends over 3.7% of the catchment. Small areas in the Kamenščina dry valley, where several metres thick periglacial deposits and soil fill the dolines, are classified as zones of low vulnerability. Altogether these small patches cover 0.3% of the catchment or 2.6 ha (Fig. 10.14).

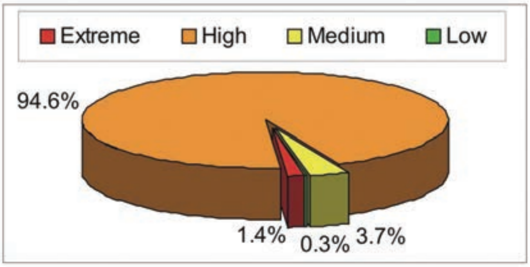


Figure 10.14: Percentage surface area for each vulnerability class in the Podstenjšek catchment area resource vulnerability map using the Simplified method.

The Simplified method can only be used for resource vulnerability mapping. In order to make it applicable for the source vulnerability mapping as well, the authors on this occasion provided a simplified K factor assessment.

According to the simplified K factor scheme the catchment area has been categorised as a karstified carbonate aquifer due to the geological, geomorphological, hydrological and speleological settings of the area.

With regard to tracer test results, geological and geomorphological observations the studied area have been divided to direct and indirect zones. The direct zone has been assigned to the parts of the aquifer that always contribute to the spring and are directly connected to it. The indirect one comprises the morphologically uplifted part of the aquifer that contributes only a small portion of the total springs' discharge and the parts on the north and northeast. For these parts it is probable that they contribute to the Podstenjšek springs only during high waters. The direct zone results in high degree of vulnerability and the indirect one in medium degree of vulnerability forming the final K map.

The K map has been combined with the resource vulnerability map in order to obtain a source vulnerability map (Fig. 10.15). The source vulnerability equals the resource one where the aquifer is karstified and directly connected to the spring. The degree of vulnerability is lower in the source vulnerability map where the catchment is classified as indirect part of an aquifer.

According to the resulting source vulnerability map, only 1.4% of the area is classified as extremely vulnerable. More than a half, 54.6%, of the area is highly vulnerable and 42.7% of the area is moderately vulnerable. Only 1.2% of the area or 11.2 ha is of low vulnerability (Fig. 10.16).

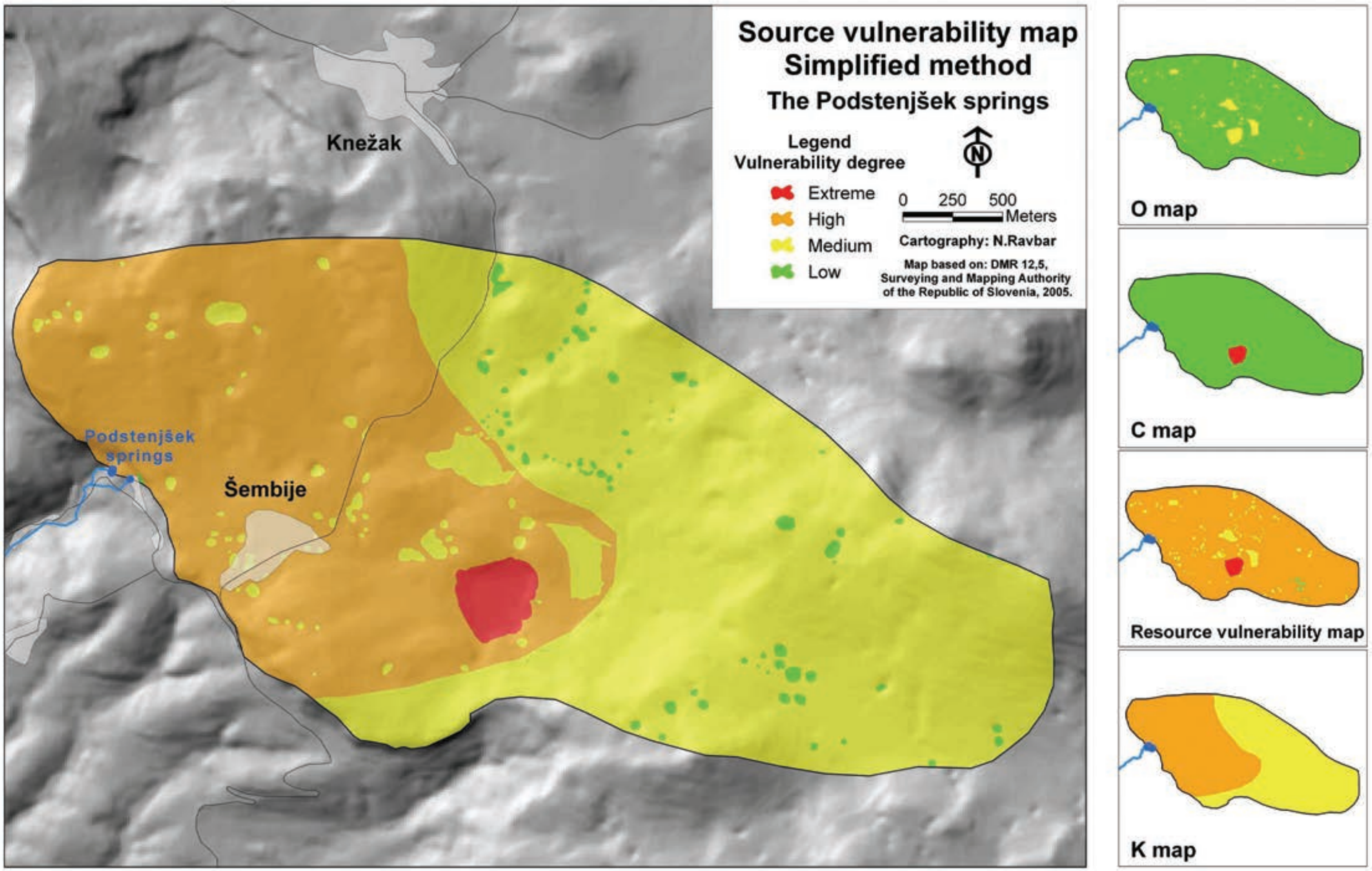


Figure 10.15: Intrinsic source vulnerability map of the Podstenjšek springs – the Simplified method.

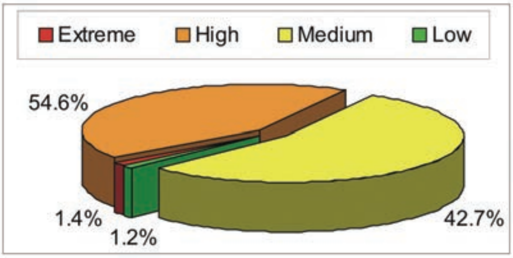


Figure 10.16: Percentage surface area for each vulnerability class in the Podstenjšek catchment area source vulnerability map using the Simplified method.

10.6 APPLICATION OF THE SLOVENE APPROACH AND RESULTS

Within this research a new approach for the vulnerability assessment and mapping for the karst waters protection in Slovenia, the Slovene Approach, has been proposed. It has been applied for the first time in the Podstenjšek springs catchment area in order to test it, complement and adapt it where necessary for particularities of Slovene karst landscapes.

The O factor has been evaluated on the basis of the geological and pedological maps, Cadastre of caves database, as well as direct field measurements by means of detailed structural-lithological and geomorphological mapping, soil and sediment depth measurements using hand auger and electrical resistivity imaging.

In the studied area, thin soil cover is unevenly spread and appears in patches. Its depth changes at short distances. On the basis of filed measurements and existing information, the greatest depth of soil has been recorded in the dolines, bottoms of the intermittent lakes and on top of less permeable layers, where it exceeds 1 m. Therefore soil sub-factor value 5 has been assigned to those areas. On the other hand, to the areas, which are not covered with soil (karren, highly fractured areas, caves, the estavelle, karst edge, three excavated dolines in the Kamenščina dry valley and outcrops along the roads) the soil sub-factor value 0 has been assigned. The rest of the area and the dry valleys where loamy soil cover exceeds 20 cm, the soil sub-factor value 1 has been assigned.

As in the COP method, for the lithology and fracturation sub-factor value has been assigned according to the assessment scheme and multiplied by individual layer thickness. The thickness of the unsaturated zone has been determined by subtracting the anticipated groundwater contour lines from the digital elevation model values. The fracturing of the limestone bedrock has been assessed on the basis of field observation. Based on collected data the layer index has been calculated and protection values have been obtained.

Within the O factor determination very low protection value (high vulnerability) is assigned to the morphological features without soil cover. Low protection is assigned to the rest of the area, except where the unsaturated zone thickness exceeds 250 m. There medium protection is assigned. High protection corresponds to the areas of thicker soil cover and where low permeability layers cover carbonate outcrops (alluvial deposits in the intermittent lakes, periglacial material in the dolines of the Kamenščina dry valley, small areas of breccia at the southern and southwestern edge of the aquifer).

In the test site C factor has been determined on the bases of the slope gradient data and land use, together with the topographical and geological maps information, digital orthographic photographs, Cadastre of caves database and direct field observation. C score of the swallow hole recharge area has been assessed by intersecting the values of the buffer distance to a swallow hole, the area of sinking lakes. Furthermore, values of land use for the relevant slope gradient classified as less permeable surface category have been multiplied. Finally, the temporal variability value 0.25 has been added, since the lakes are full only very occasionally.

In areas where the aquifer is not recharged via a swallow hole classification of the surface karst features and the presence or absence of permeable or impermeable subsoil layers has been considered. In addition, the assigned values have been multiplied by the slope gradient and land use values classified as direct infiltration flow type.

The C factor only shows classes of high, medium and very low vulnerability. High vulnerability corresponds to all karst features irrespective of land use and slope inclination. Only in the dolines of the dry valley, where the less permeable layers occur, areas with slope angles greater than 31% are highly vulnerable, but the rest of the area is moderately vulnerable. Very low vulnerability is assigned to small areas close to the springs of scree and breccia above the limestone formations or flysch outcrops irrespective of land use and slope inclination.

For the P factor assessment, the yearly and daily amount of precipitation measured at the nearby Ilirska Bistrica precipitation station in the period 1961-2000 has been used (MOP ARSO, 2007). According to assembled information, the average annual number of days when rain quantity was between 20 and 80 mm/day and average annual number of days with more than 80 mm/day has been obtained. Thus the average annual number of rainy days in the Podstenjšek catchment is 20.2 and average annual number of storm events is 0.8. The final P factor value of 0.8 has been estimated and thus the category of low vulnerability has been evaluated. Due to lack of supplementary precipitation stations in the springs' vicinity the P factor value has been assigned for the entire catchment.

The final resource vulnerability map has been obtained by multiplying the three factors (Fig. 10.18). The final resource vulnerability map of the studied area shows extreme vulnerability for the geomorphological features (karren, highly fractured areas,

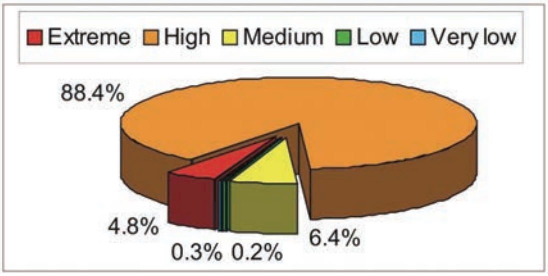


Figure 10.17: Percentage surface area for each vulnerability class in the Podstenjšek catchment area resource vulnerability map using the Slovene Approach.

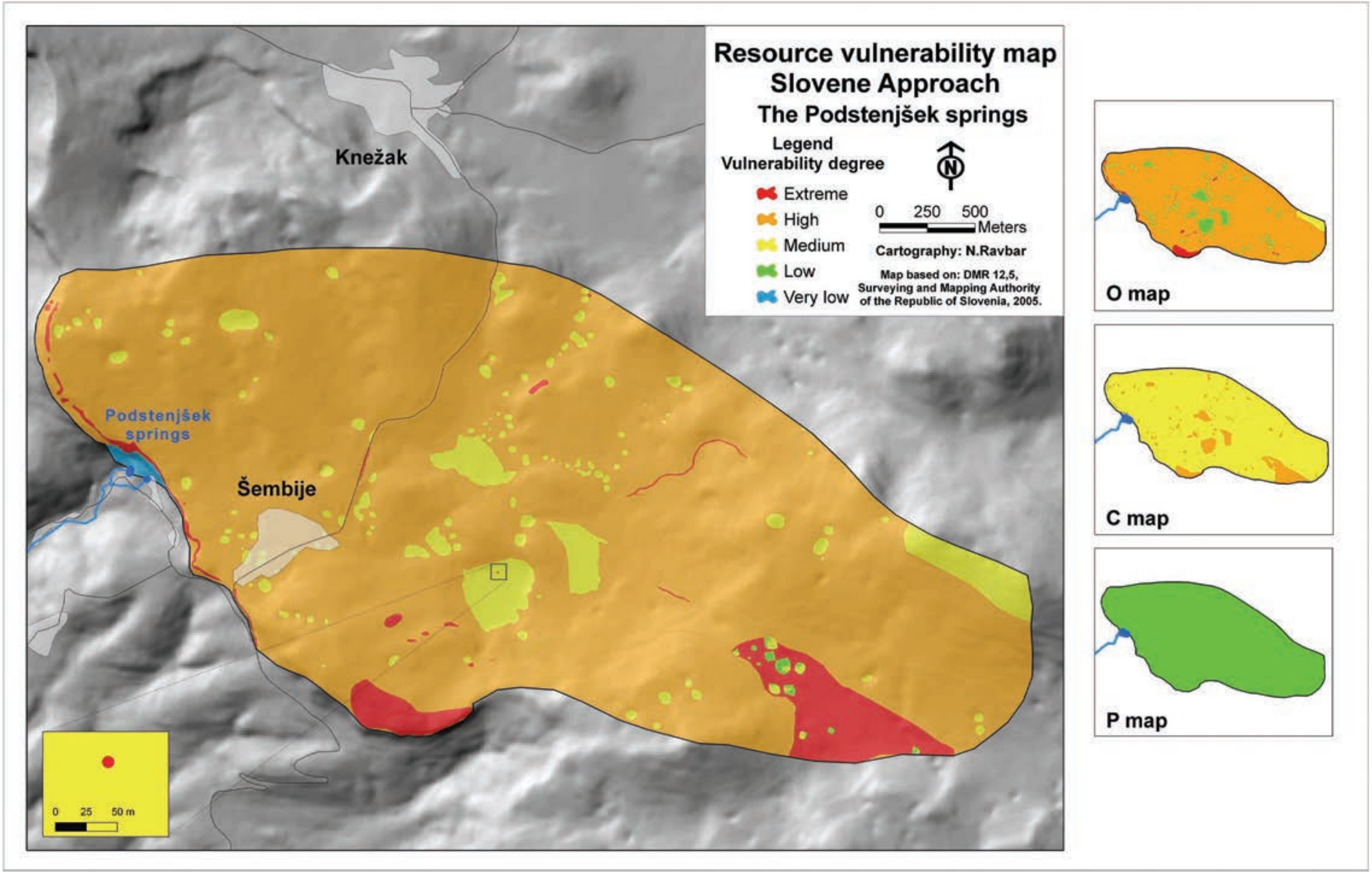


Figure 10.18: Intrinsic resource vulnerability map of the Podstenjšek springs – the Slovene Approach.

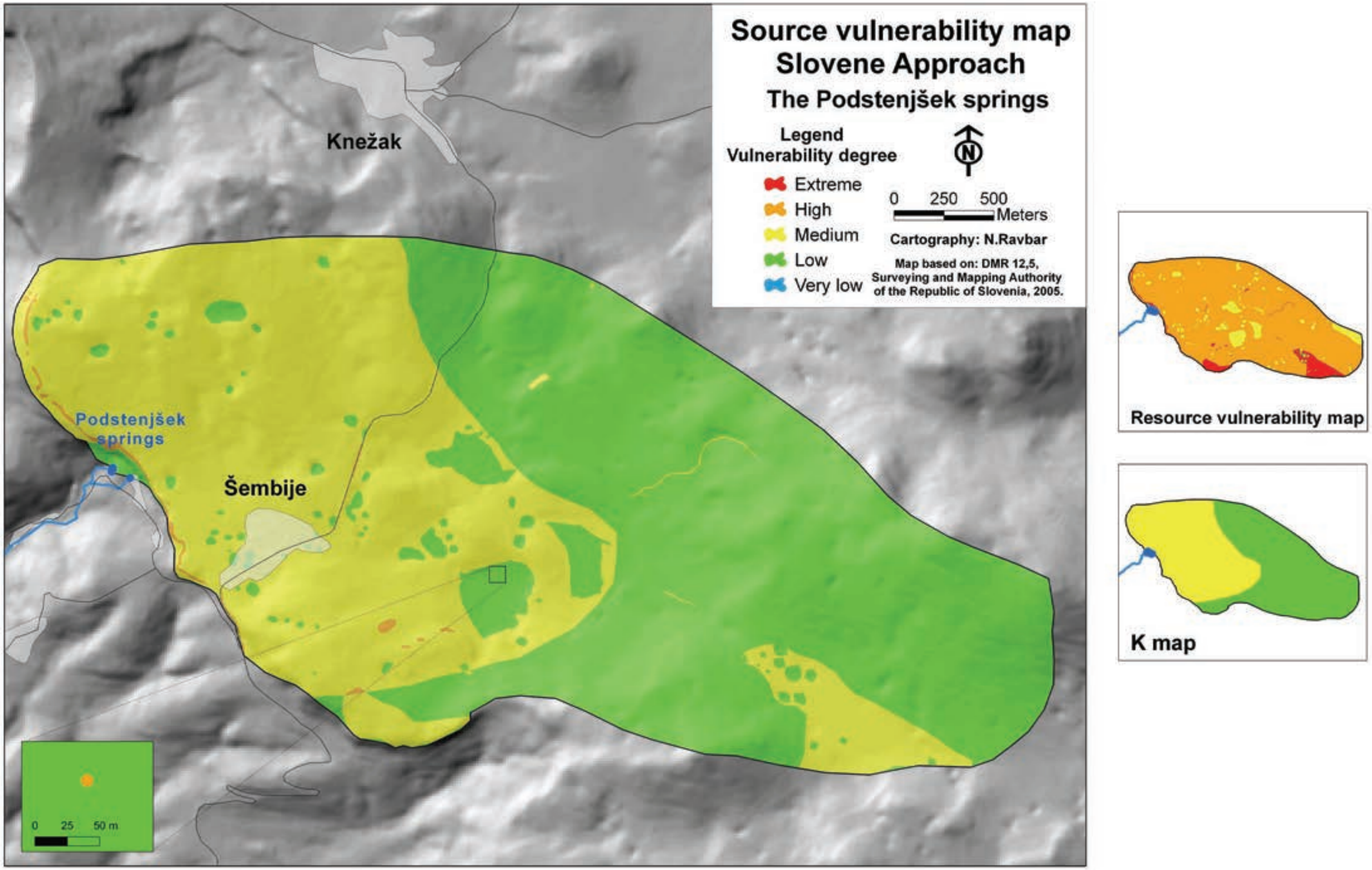


Figure 10.19: Intrinsic source vulnerability map of the Podstenjšek springs – the Slovene Approach.

caves, karst edge, dry valleys), three excavated dolines in the Kamenščina dry valley and outcrops along the roads where soil cover is absent or rarely exceeds 20 cm, as well as the estavelle (shown in the zoomed inset) where occasional indirect infiltration occurs. Extreme vulnerability areas cover 4.8% of the total catchment area (Fig. 10.17).

Most of the catchment area, 88.4%, is classified as highly vulnerable and in general corresponds to the bare karst landscape or karst covered by shallow soils, except in areas where unsaturated zone thickness is greater than 250 m or where limestone is covered by thicker soils. Moderate vulnerability has been assigned to the areas covered by more than 1 m of soil and/or low permeability layers of various depths and to the areas of greater depth to the groundwater. However in the dolines in the Kamenščina dry valley, areas with slope angles greater than 31% are moderately vulnerable, but the rest of the dolines' area is of low vulnerability. Very low vulnerability is assigned to small areas close to the springs of scree and breccia above the limestone formations or flysch outcrops. Small patches of low vulnerability only cover 0.2% or 1.4 ha of the area and very low vulnerability covers 0.3% or 2.5 ha of the catchment.

According to Slovene environmental legislation individual source protection has to be provided. In order to assess source vulnerability map an additional K factor has to be considered and intersected with the intrinsic resource vulnerability map, as proposed by the European Approach.

Therefore we adopted the Slovene Approach to the source vulnerability mapping by overlapping the final resource map with the proposed K factor assessment (for the K map assessment see chapter 10.3). To enable both maps combination, primarily K and resource scores have been transformed in the indexes.

As in the resource maps obtained by the PI and COP methods, the Slovene Approach resource map combined with the K map also shows that within the inner zone extremely vulnerable areas for groundwater are highly vulnerable for the source (Fig. 10.19). As in the PI method source vulnerability map, the Slovene Approach source vulnerability map also shows the area above the Kozja luknja as highly vulnerable. However, the Slovene Approach application does not consider the Šembijsko Jezero and Nariče to be highly vulnerable areas, but only the estavelle.

Furthermore within the inner zone, highly vulnerable areas for groundwater are moderately vulnerable for the source and moderately vulnerable areas for groundwater are of low vulnerability for the source. Within the outer zone extremely vulnerable areas

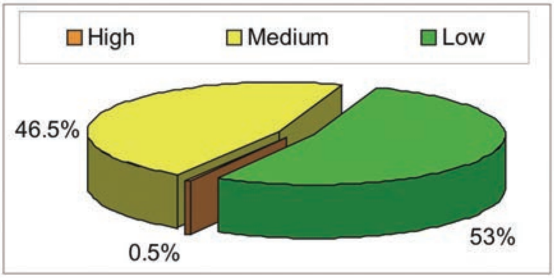


Figure 10.20: Percentage surface area for each vulnerability class in the Podstenjšek catchment area source vulnerability map using the Slovene Approach.

for groundwater are moderately vulnerable for source. However, high, moderate and low vulnerability areas for groundwater are of low vulnerability for the source.

Altogether areas of high vulnerability comprise only 0.5% of the whole catchment or 4.3 ha (Fig. 10.20). Moderate vulnerability extends over 53% of the area and low vulnerability over 46.5% of the area.

10.7 COMPARISON OF THE MAPS AND DISCUSSION

Five different intrinsic vulnerability methods have been applied to the Podstenjšek karst springs catchment area in order to compare and validate the results obtained by different evaluation of definite parameters. These methods are EPIK, PI, COP, the Simplified method and the Slovene Approach. However, comparing these different vulnerability methods using the same database, significantly different and sometimes even contradictory results have been obtained.

Comparing the percentage surface areas for each class of vulnerability using different resource vulnerability methods, the following conclusions can be deduced (Fig. 10.21):

- the most of the area is of extreme vulnerability according to the PI method and the most of the area is of moderate vulnerability according to the COP method,
- largest areas are classified as highly vulnerable by the Simplified method and the Slovene Approach,
- no low and very low classes have been assigned by the PI method,
- only the Slovene Approach considers the very low vulnerability class.

Comparing the percentage surface areas for each class of vulnerability using different source vulnerability methods, the following conclusions can be deduced (Fig. 10.22):

- the most of the area is of extreme and of medium vulnerability according to the EPIK method,
- the most of the area is of high vulnerability according to the Simplified method and of low vulnerability according to the COP+K method,
- the PI+K, COP+K and the Slovene Approach only consider three classes of vulnerability (high, moderate and low),
- the least area is classified as highly vulnerable according to the Slovene Approach.

All intrinsic vulnerability methods, except one, classify the estavelle and the Šembijsko Jezero as extremely or highly vulnerable areas. This is a consequence of the karst specific factors (I respectively C) that assign swallow holes and areas generating runoff towards sinking water bodies as zones of extreme/high vulnerability even though the intermittent lake does not appear very often. Such classification results are because these methods do not have clear guidance for temporal variability.

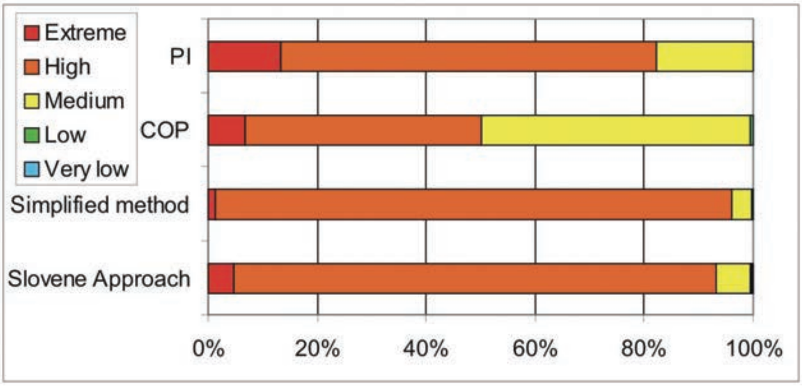


Figure 10.21: Comparison between the classes of vulnerability gained by the resource vulnerability methods application.

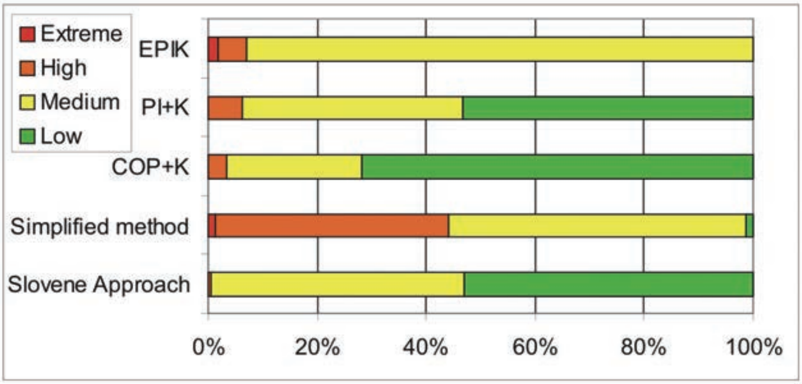


Figure 10.22: Comparison between the classes of vulnerability gained by the source vulnerability methods application.

Unlike other vulnerability maps the Slovene Approach application does not consider the Šembijsko Jezero and Nariče as extremely/highly vulnerable areas due to the hydrological variability integration. The resulting classification justifies this because in case of only occasionally active sinking water a contaminant release might not directly enter the karst groundwater. Nevertheless, the Slovene Approach application does consider the estavelle as extremely/highly vulnerable.

The source vulnerability maps differ in the area above the Kozja luknja classification. The PI+K method and the Slovene Approach classify the area above the Kozja luknja as highly vulnerable, whereas the EPIK, COP+K and the Simplified methods do not.

Furthermore, the differences in the infiltration conditions factor are distinct. Only the COP method considers the lake of Nariče as extremely vulnerable even though it has only been flooded in 1929 and in November 2000 (Kovačič and Habič, 2005; Fig.

10.8). The reason is in groundwater level consideration. In contrast to the methods PI, EPIK and the Simplified method, which take into account average hydrological condition, the COP method considers the most vulnerable situation. However, the question remains, if this classification is justified.

According to the PI map extremely vulnerable areas are enlarged due to the crucial classification of the shallow unsaturated zone thickness. However, it is disputable, if these results are consistent.

The PI and the Simplified method do not classify the limestone edge as extremely vulnerable, because these methods do not take into consideration or only partly take into consideration the karst geomorphological features.

Higher vulnerability values in general correspond to the bare karst landscape or karst covered by shallow soils. Only the EPIK map classifies these areas as moderately vulnerable (and thus less vulnerable than for example the dolines covered with soil of great thickness). On the other hand, differences between high and medium vulnerability according to the COP map appear dependent on slope gradient and land use. Nevertheless, it is doubtful if these evaluations are consistent.

Areas where the aquifer is covered by thick formations of low permeability are classified as moderately vulnerable by the PI and the Simplified method. However, the latter and the COP method classify dolines in the dry valley as of low vulnerability. So does the Slovene Approach, but the vulnerability of the dry valleys' dolines is increased there in respect to slope inclination. Only the EPIK method classifies areas covered by thick formations of low permeability as more vulnerable than the bare karst formations. Furthermore, only the Slovene Approach includes the very low vulnerability class, assigned to the less permeable formations in the vicinity of the springs.

For all source vulnerability maps, except for the EPIK map, the K factor is crucial in determining the final values of the source vulnerability. This is due to the same or similar adaptation procedure applied to the resource vulnerability maps. Thus in general, the source vulnerability equals the resource one where the aquifer is karstified and directly connected to a spring. The degree of vulnerability is lower in the source vulnerability map, where the catchment is classified as indirect part of an aquifer.

Examination of the final maps shows that the EPIK map does not provide consistent results. Besides critical remarks on the method, previously described in the literature, it shows some more discrepancies. Firstly, even dolines, filled with thicker soil and/or sediment layers, are characterised by higher vulnerability as bare or modestly covered karst due to the least importance of protective cover (soil/sediment) influence, which is not justified.

It shows no difference between areas that are characterised by shallow or high depth of the unsaturated zone. Furthermore, even the remotest parts of the catchment are equally vulnerable with the nearby ones. On the other hand, there are many small details that are not justified, i.e. tiny red spots incorporated by the dolines, fractured areas, even far away from the spring. High vulnerability is assigned to the intermittent lake Šembijsko Jezero and its estavelle as well, even though the surface flow on average only appears once per two years.

In addition, the way land use is classified is not satisfactory. The EPIK method mainly focuses on meadows, pastures and arable land, but proposes no guidelines how forest, scrub, overgrown and urban areas as well as bare areas should be considered. Furthermore, we believe that the intrinsic vulnerability does not depend on the intensity of agriculture, but on the density of vegetation cover. Thus, in the present application we distinguish arable, urban and bare areas as more vulnerable than meadows, pastures, forest, scrub and overgrown areas.

In general the PI vulnerability map of the Podstenjšek springs is consistent. However, its application requires a large amount of data and the application of the P and I maps is rather complicated. Especially for the complex structural geological conditions e.g. in the Slovene Alpine karst systems the PI method application would be extremely difficult. An additional reason would be lack of data in such areas.

The application of the PI method to the Podstenjšek springs catchment area shows that majority of groundwater vulnerability values are dependent on P map class boundaries, which may result in overestimation of the protective cover effectiveness. Hence the PI map shows large areas of extreme vulnerability, which is not practical for land use planning. Moreover, the application also manifests soil to be very important in the calculation of the PI map on the whole. In contrast to Cichocki *et al.* (2004) we thus believe that at least the first two classes of the final PI map are too narrow.

Furthermore, as with the EPIK method also in the PI method land use is not satisfactorily classified. There are no guidelines how bare and particularly urban areas should be classified.

In contrast to the PI method, the Simplified method is very easily applicable and its application can in general be done within a short period of time, since it can be done on the basis of general information of the area. No detailed research is needed and thus it is very effective at little cost. However, data shortage can in some cases be misleading as it can lead to incorrect results.

The Simplified method has not been sufficiently tested yet and hence comprehensive critical remarks cannot be given. In the studied area the application of the Simplified method and the comparison with the other methods proves that the results are consistent and the vulnerability classes are generally justified. However, the Simplified source vulnerability map in general shows higher classes of vulnerability than other source vulnerability maps. Thus according to the Simplified method large areas should consequently be highly protected.

However, due to simplification the Simplified method does not consider the depth to groundwater level, as these data are often very hard to obtain especially in karst systems. It has been stressed by many authors that thickness of the unsaturated zone is of major importance (Vrba and Zaporozec, 1994; Gogu and Dassargues, 2000; Magiera, 2000). The results of the Simplified method would therefore show no differences between areas that are characterised by shallow or high depth of the unsaturated zone, which could especially be inconsistent in Slovene high karst plateaux with deep unsaturated zone.

The Simplified method also does not consider several other aspects, which are in general of minor importance for groundwater vulnerability, such as slope, land use and vegetation cover.

Regarding the COP method we disagree with the proposed scheme in some particular aspects, presented on the whole in chapter 7. The application of the method to the case study of the Podstenjšek catchment proves our remarks well founded. The final map shows many details that are not always justifiable. Namely, slope inclination and vegetation cover are one of the most crucial factors in determining the final vulnerability values. Even though it is generally acknowledged that denser vegetation is always favourable for the groundwater protection, the COP vulnerability is categorised in such a way that e.g. forested areas are classified as more vulnerable than areas with less dense vegetation cover. Also greater slopes on highly permeable formations are classified as less vulnerable.

Concerning the unsaturated zone protective cover effectiveness, application of the COP method does not show large areas of extreme vulnerability, in contrast to the PI method. According to the PI method the protective cover effectiveness is divided in classes ranging from 0-10, 10-100 and 100-1000. However, according to the COP method very low values of the protective cover effectiveness have been joined in the intervals 0-250, 250-1000 instead. Such classification is more adequate.

On the other hand, the COP map shows large areas of the Šembijsko Jezero and Nariče as extremely vulnerable areas, which is not practical for land use planning. Moreover, it is questionable if this classification is justified.

The results obtained by the Slovene Approach resource and source vulnerability maps are consistent. The vulnerability classes are generally justified. However, the methodology has only been applied in one test site and therefore it has not been sufficiently tested yet. Hence, critical remarks cannot be given and the verification could show if any results are of doubtful consistency.

11

HAZARD AND RISK ASSESSMENT

11.1 IMPORTANCE OF THE PODSTENJŠEK SPRINGS FOR DRINKING WATER SUPPLY

Since 1992 one of the Podstenjšek springs has been captured for local drinking water supply (Fig. 11.1). It supplies 133 households in four settlements: Šembije, Podstenjšek, Podtabor, Podstenje and Mereče. According to the data of the water supply company that manages the water source, it supplied 379 inhabitants in 2001.

Beside domestic use people use the water also for gardening and animal breeding.

Figure 11.1: The captured Podstenjšek spring (photo: N. Ravbar).

However, the quantities used for these purposes are small. On average 0.5 l/s is captured. According to the water supply company data 13,000 m^3 of water was sold in 2001. In comparison to previous years the consumption has been decreasing.

Even though the water protection zones of a source have been delineated and the necessary provisions defined some years ago (Petauer *et al.*, 2002), the required decrees have not yet been accepted.

11.2 ACTUAL AND POTENTIAL SOURCES OF CONTAMINATION

There are no serious actual and potential sources of contamination to the Podstenjšek karst springs situated in its catchment. The main part of the studied area is uninhabited and infrastructure is poorly represented. Only the village of Šembije is situated in the immediate vicinity of the springs, which does not host any industrial activities. Wide areas are covered by forest or are used for extensive agricultural practice, mainly as meadows and pastures.

Regarding actual and potential sources of contamination, useful and valuable data were compiled from existing databases and gathered by field observation and direct inquiries. During the systematic examination of the studied area in years 2005 and 2006 all hazards to karst water were recorded and mapped. In spite of the relatively precise survey of the area it is possible that some of hazards remained unrecorded.

Hazard classification is based on type of human activities. In addition, a hazard assessment considers the descriptive information of the existent and potential degree of harmfulness.

11.2.1 THE ŠEMBIJE VILLAGE

According to the Census database from the Statistical Office (Popis …, 2002) the Šembije village hosts 209 inhabitants in 74 households with an average of 2.4 members. Even though the number of inhabitants has decreased since 1961 for 0.45% on average per year, many new houses have been built. Almost half of the villagers are new comers and among these two fifths have arrived in the period 1991-2002 (Popis …, 2002).

The function of the once rural settlement has been recently changed into the mainly suburban (Fig. 11.2). The village mainly acts as a residential settlement, as most (more than 91%) of the active inhabitants work outside the village. They drive daily either to Ilirska Bistrica or Pivka to work (Popis …, 2002). There are just three wholly agricultural households.

There are 13 ha of paved surfaces. The houses are linked to the public sewage system since 1998 and connected to the wastewater treatment plant, which is situated below

Figure 11.2: The Šembije village is an example of a nucleated village that acts as a suburban settlement (photo: N. Ravbar).

the karst edge and so the discharge from the treatment plant is drawn off the karst area. The sewage system drains runoff from the main road as well.

Among the potential contaminants there is also a small graveyard in the immediate vicinity of the springs and oil reservoirs that are often built unprofessionally and without control. However, according to the Census these are not numerous. Only one fifth of the households use gas oil for heating, while the rest use solid fuel (Popis …, 2002).

11.2.2 AGRICULTURAL ACTIVITIES

For agricultural activities data we used Census database from the Statistical Office (Popis …, 2002) and for the land use analyses we used Land use data gained from the Ministry of Agriculture, Forestry and Food (Land use data, 2006). Because these data have not been sufficient for our needs, we prepared our own database in order to achieve optimal results of our study, which base exclusively on field observations and inquiries performed in 2005 and 2006.

We tried primarily to point out basic characteristics of the agricultural activity in the studied area and its influence on the karst water. Hence, the inquiry enables direct acquirement of needed information that was in the existing databases marked as confidential.

The data gained thus enable better understanding on the extensiveness of agricultural activities of the area and mutual comparison of the hazards of the same and different types. The inquiry has been prepared on the basis of previous similar researches (Lampič, 2000; Rejec Brancelj, 2001).

In the village of Šembije an inquiry was made of 29 households. Thus, two fifths of all households have been included. The aim of the inquiry was to gain data on household social structure, general intensity of agricultural activities (i.e. annual manure, mineral fertilizers and pesticides consumption, density of livestock) and individuals' attitude towards the environment.

Altogether three wholly agricultural households, where all members are working in agriculture, were included. A quarter of questioned households were only partially agricultural, meaning that at least one member is working in agriculture, and in 65.5% of the households active members were employed outside the farm. However, all households without exception were practising at least some farming or gardening. Additionally, all were harvesting their own supply, but one household has marketing plans in future.

According to the land use data (Fig. 11.3) forest, scrub and overgrown areas cover 52.3% of the catchment, 43.6% is used for agriculture – fields and gardens occupy 0.04% of the catchment or 0.4 ha and orchards 0.27% or 2.5 ha – the rest are meadows and pastures. Only 2.5% of the catchment represents rock outcrops and 1.5% are settled areas (Land use data, 2006).

The size of land properties of those asked shows the suburban way of living. It is relatively small in comparison to Slovene circumstances (Vrišer, 2005). The maximum estate size of studied households was indeed 54.5 ha and the average estate size amounts 9 ha, but half of those asked have only up to 0.5 ha of land. Only one of them has 0.5 to 2 ha of land, 17% of them have 2 to5 ha of land, two of them have 5 to 10 ha of land and three of them have more than 30 ha of land.

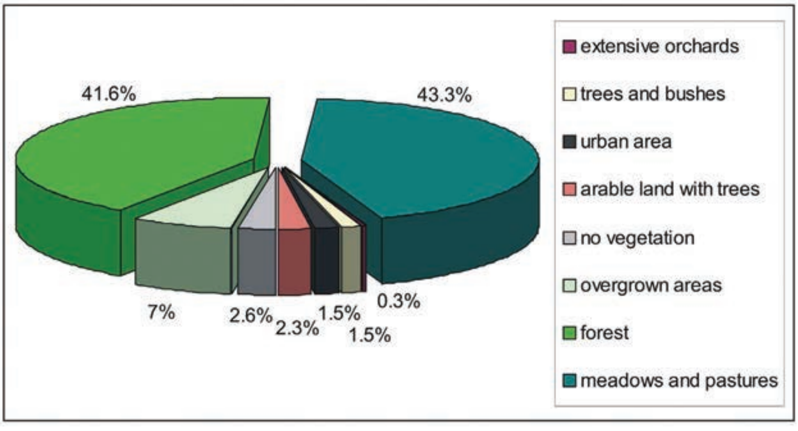


Figure 11.3: Land use distribution in the studied area (source: Land use data, 2006).

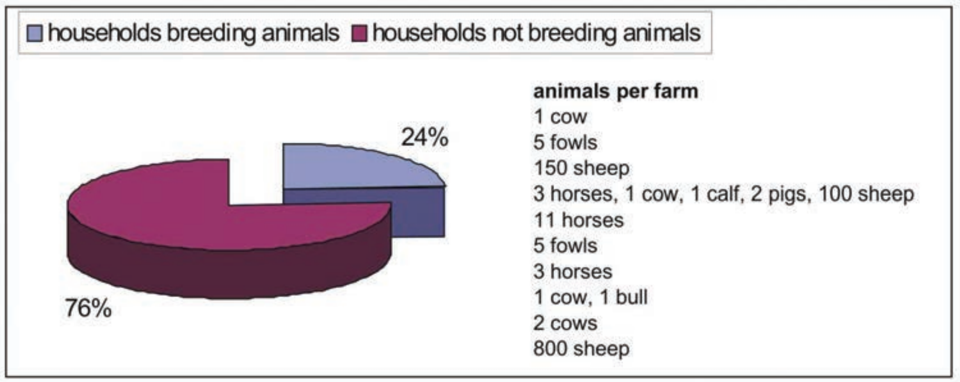


Figure 11.4: Animal breeding in the studied area.

Agriculture in Slovenia is in general no longer an important activity. Furthermore, natural circumstances of the karst landscapes are not the most convenient for agriculture. Thus, the agriculture is in the test site restricted to cultivation of small fields at the bottom of depressions and close to the village. Former vast pastures are becoming increasingly overgrown with pine forests. Today only a few of them are still used, mostly for sheep pasturing. Thus, stockbreeding is negligible in the studied area, and there are no bigger farms. In agriculture one of the biggest contaminants of environment are the nitrogenous compounds that mostly derive from farming and fertilization. Therefore we were especially interested in livestock and fertilizing habits of the questioned.

In general, the questioned households in Šembije do not breed animals (Fig. 11.4). In the time of inquiry there was one little farm that bred 150 sheep and the other one bred 100 sheep, three horses, a cow, a calf and two pigs. Another two farms bred 11 and three horses. One farm had two cows, one had a cow and a bull and one had only one cow. There were also two farms breeding 5 fowls each. In general, the number and structure of cattle does not vary much with time, only one farm replaced cattle breeding by sheep farming within the past few years.

Another farmer from Vrbice pastures around 800 sheep in the warm part of the year at the Kamenščina dry valley. His pastures occupy about 530 ha and he does no manuring in that area.

Among the discussed farms of Šembije all except one use their own manure alone, considering that six of them do not exceed livestock density 0.5 LU/ha cultivated land, one has 0.5 to 1 LU/ha cultivated land and two have more than 2 LU/ha cultivated land. One of the latter gives the surplus of his manure to his fellow villagers. In addition, all claim that they have dung installations built according to the standards, though the reality is distorted.

Regarding manuring of the cultivated land, the results indicate that the questioned are mostly using stable and liquid manure. The biggest annual quantities of the inputs of the manure per hectare are 20 m^3, practised by two farmers. Two of them are annually spreading 10 to 15 m^3/ha cultivated land and four of them 5 to 10 m^3/ha cultivated land. One third of the asked is annually spreading 1 to 5 m^3/ha cultivated land and one third less than 1 m^3/ha cultivated land. The average annual quantities of the inputs of the manure per hectare are thus 5.6 m^3, which is in comparison to other karst areas relatively small (Lampič, 2000; Rejec Brancelj, 2001). The obtained result is due to prevailing husbandry only for the supply of the inhabitants in the test site.

Other ways of manuring and usage of pesticides is negligible in the studied area, which is also comparable to the circumstances in other karst areas (Lampič, 2000; Rejec Brancelj, 2001).

Thus, average annual nitrogen input in the studied area is relatively small and ranges within a few kg/ha of cultivated land. Only two farmers use more, but also they do not exceed 70 N kg/ha cultivated land.

Most of the catchment is covered by forest, overgrown by *Pinus nigra* and *Pinus sylvestri*. The forest is economically not very important and thus at times the only activity there is felling.

Regarding the educational background of the households, determined on the basis of the economically active member of the family with the highest education, elementary and secondary schools prevail and none has agricultural education. Like observed by previous study, the manner of maintaining the landscape is linked to this structure, as well as ecological consciousness and perception of ecological problems (Špes, 1994), it proved to be the case in our test site as well.

Figure 11.5: The agriculture in the test site is not very intensive; however, sheep pasturing is coming to the fore (photo: N. Ravbar).

Manuring and usage of pesticides by most farmers is based upon recommendations of a salesman and others or upon their own experience. Indeed, none of the farmers manures in the time of prohibition and they mostly know what are the restrictions regarding manuring. Majority, 72% of those asked think that usage of fertilizers and pesticides affects vegetation and faunae; however, 20% still think the opposite.

Additionally, 14% of those asked having property inside predicted water protection zones claim that they know what restrictions will be prescribed, but 38% of them do not know. Almost half of those asked, 48%, do not have property inside predicted water protection zones and among these only half know what the restrictions within the water protection zones are.

By means of field observation and results gained by detailed inquiry of households we can conclude that intensity of agricultural activity in the studied area is relatively low (Fig. 11.5). The livestock density, the annual consumption of stable and liquid manure and hence the average annual nitrogen input are low. Therefore major contamination deriving from agricultural activities is not to be expected, except in exceptional cases e.g. accidents and uncontrolled leakages. However, in terms of karst water protection such low agricultural activity is very favourable.

Figure 11.6: An accident on the road Knežak – Ilirska Bistrica. In case of a serious traffic accident it could lead to a spillage of dangerous substances (photo: N. Ravbar).

11.2.3 TRAFFIC

The area is crossed by the local road connecting Knežak village with the municipal centre of Ilirska Bistrica town, as well as several smaller farm and forest tracks. Apart from the local road segment crossing the Šembije village, the roads are not built according to water protection standards.

According to the traffic recording on the state roads of the Republic of Slovenia data the average annual number of vehicles per day that passed the main road Knežak – Ilirska Bistrica amounted to 3,400 in year 2001. Among these 10% were foreigners. Most, more than 90.7% were cars, 6.4% were trucks, 1.9% motorcycles and 1% buses (Promet 2001, 2002). Thus, we can conclude that traffic in the catchment of the Podstenjšek springs is of local importance based upon the everyday migration of inhabitants.

The influence of traffic on the quality of the spring water is negligible, but in case of an accident the contaminants could reach the springs quite quickly (Fig. 11.6). The 4 km section of the Knežak – Ilirska Bistrica road is used for international speedway races ending in the Šembije village that increases the possibilities of accidental spillage of dangerous substances.

Because of mild climate, salting of roads is not intensive, but yet has a certain effect on the karst groundwater. For strewing NaCl and $CaCl_2$ usually is used. The annual amount that is spent for strewing of the road section Knežak-Ilirska Bistrica amounts to around 0.6 m^3/km. Important contamination of the Podstenjšek springs because of strewing has not been yet detected.

11.2.4 WASTE MATERIAL DISPOSAL AND EXCAVATION SITES

In 2005 and 2006 we made a systematic survey of the area in order to precisely record and map illegal waste material disposals and excavation sites in the catchment. For this purpose the location, extent and situation in the field have been identified, and the structure of the waste material in dumps has been determined. Thus a database of the establishment of illegal waste disposal dump and excavation sites properties has been made to allow comparison. All the data have been combined in an interactive database.

Illegal garbage dumps derive from times when collection of waste was not organized. Many of them are, unfortunately, still in use today. On the surface of the studied area there have been seven illegal dumps registered. Due to their remoteness and difficult accessibility the caves in the catchment are not dumping places.

The illegal waste disposal sites are only of local origin. Four of them contain less than 100 m^3 of material, but three contain from 100 to 500 m^3 of material. Among waste material building and excavation material, rural and furniture waste material prevail. There are also dangerous materials (motor vehicles, packaging of cleaning agents, remainders of agrochemical substances). On such dumps we can often find old ironware, insulating material, pneumatic tires, waste from gardens or fields, etc.

All except one are situated 2 km of direct distance from the source (Fig. 11.7). Three disposal sites are up to 500 m from the settlement, three up to 1 km, and one more than 1 km. All, except one are placed by the road, with the possibility to turn round. The waste is placed on the poorly used land, in the bushes or on the land with unsettled property. Characteristic of all of the dumps is location on a slope or in a doline.

Two of the disposal sites are continuously in use. Four of them have only been in use at times, but these have all been equipped with prohibition boards. Only one disposal site has been used once. Nevertheless, none of the waste disposal sites have been sanitized so far. Thus, the dumping sites on the karst terrain may also influence the quality of groundwater by bacterial and chemical load.

Figure 11.7: The illegal garbage dump 2 km distant from the springs and situated by the road to the Kamenščina dry valley (photo: N. Ravbar).

Additionally, three uncontrolled excavation sites appear in the catchment, which are 3.6 km distant from the springs. In the Kamenščina dry valley gravel and detritus material has been removed from the three dolines recently. From each doline more than 100 m^3 of material has been excavated.

11.3 MAPPING OF HAZARDS

In order to be able to evaluate the risk of the karst water contamination posed by human activities all actual and potential sources of contamination to the Podstenjšek karst springs have been identified. The hazard assessment in the catchment of the Podstenjšek springs has largely followed the procedure as proposed by the COST Action 620, supplemented by the authors' proposal of the ranking procedure for each hazard type, presented in chapter 8.

Gathering of the data bases on:

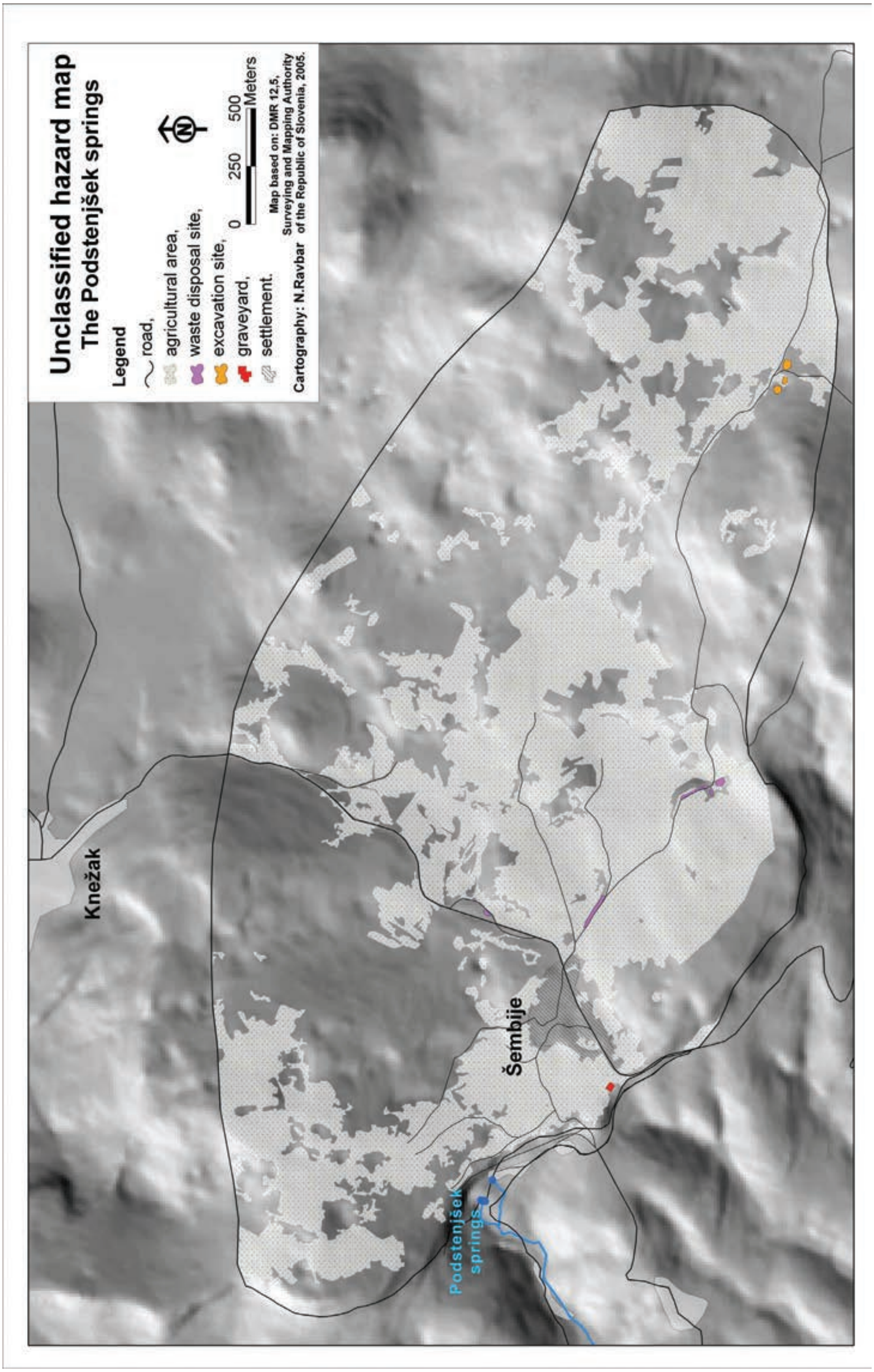


Figure 11.8: Unclassified hazard map of the Podstenjšek springs.

- Topographical map, 1:5,000, sheets Knežak and Ilirska Bistrica, Surveying and Mapping Authority of the Republic of Slovenia, 2005,
- Digital orthographic photographs, DOF 5, Surveying and Mapping Authority of the Republic of Slovenia, 1999-2004,
- Census 2002 database, Statistical Office of the Republic of Slovenia, 2002,
- Traffic numbering data on the state roads of the Republic of Slovenia, 2002,
- Land use data, Ministry of Agriculture, Forestry and Food, 2006,
- Field observation and direct inquiries (chapter 11).

For data handling and graphical processing geographical information systems ArcView GIS Version 3.1 and ArcMap GIS Version 9.1 have been used. Firstly the unclassified hazard map was made, showing the actual and potential sources of contamination (Fig. 11.8) as described in the previous sections.

The classified hazard map depicts the possible impact of the hazards on the source (Fig. 11.9). It has been produced considering a weighting factor for each individual hazard multiplied by the ranking factor. Since there is no available information on the probability of a contamination event occurring, the reduction factor has been classified as 1 for all hazards (no reduction).

The detailed hazard classification and assessment schemes are given in chapter 8 (Fig. 8.1). The weighting factor values have been determined by the COST Action 620. The ranking factors have been determined in the present study with special regard to Slovene circumstances. Thus according to their spatial extension the hazards identified in the test site are of point, line and diffuse type.

Point hazards are dumping and excavation sites that represent permanent sources of contamination due to constant outflow of contaminants into the karst aquifer. Line hazards are unsecured roads. These represent a potential and actual source of contamination by transport, traffic and accidents.

Diffuse hazards are mainly extensive agricultural areas that represent sources of contamination generally due to manuring and potential source of contamination due to accidents and uncontrolled leakages. Urban areas and the graveyard are also diffuse hazards.

The hazards found in the test site are mainly classified as low or very low. We identified urban areas with leaking sewer pipes and assigned weighting value 35 and ranking factor 0.9, since population density in the village reaches 19 inhabitants/km^2.

Farms can only be mapped as one single hazard at the given scale, although they often include several different hazards (e.g. animal barn, manure heap, etc.). Thus, only one hazard, manure heap, has been chosen to represent farms. Consequently a weighting value 45 and ranking factors 0.8 to 1 have been assigned (dependent on the livestock number and structure).

Pastures have been classified with the weighting value 25. This value has been reduced by the ranking factor 0.8, since the intensity of pasturing in the test site is very low. The fields, gardens and orchards have been classified as agricultural areas with the weighting value 30. This value has been reduced by the ranking factor 0.8 as well, since the intensity of agriculture in the test site is very low.

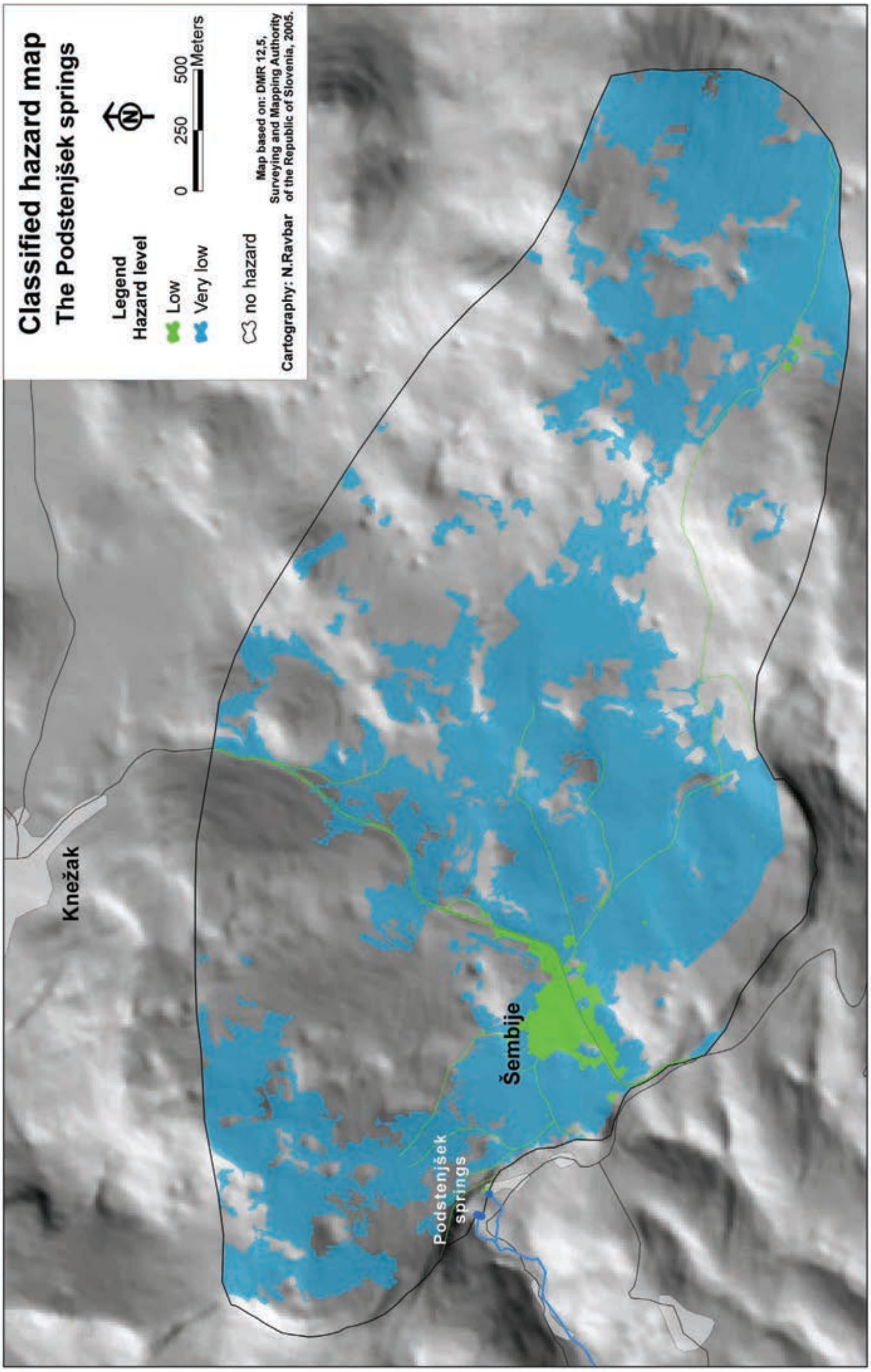


Figure 11.9: Classified hazard map of the Podstenjšek springs.

The roads (except the segment crossing the Šembije village) have been classified as unsecured and a weighting value 40 has been assigned. To the main road ranking factor 1 has been assigned and to the farm and forest tracks a ranking factor 0.8 has been assigned.

To the waste disposal dumps a weighting value 40 and ranking factor 0.8 or 0.9 have been assigned (dependent on waste disposal volume). To the excavation sites a weighting value 30 and a ranking factor 0.9 have been assigned (dependent on volume of excavated material). To the graveyard a weighting value 25 and a ranking factor 0.8 has been assigned.

The classified hazard map shows the actual and potential sources of contamination representing their hazard level (Fig. 11.9). In the case of geographically overlapping hazards, the one with the highest value was chosen to represent the harmfulness at that specific location.

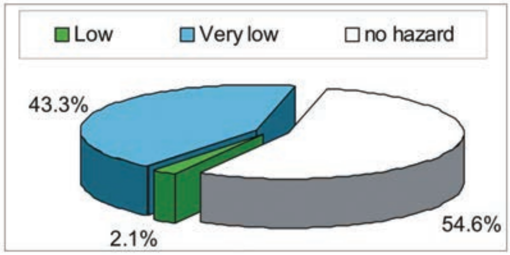


Figure 11.10: Percentage surface area for each class in the Podstenjšek catchment area according to the Slovene Approach hazard map.

More than half of the test site, 54.6%, is not exposed to any hazard (Fig. 11.10). Fields, orchards and pastures are classified as very low hazards. On the other hand settled areas, roads, dumping and excavation sites are classified as low hazards. The area that is exposed to very low hazards occupies 43.3% of the total area, and area that is exposed to low hazards occupies 2.1% of the total area or 19.5 ha.

11.4 RISK MAPPING

The risk assessment has been carried out as proposed by the COST Action 620 and integrated into the Slovene Approach proposal. Following Slovene legislation, the risk map of the Podstenjšek springs has been produced for the risk to source contamination. Considering the source intrinsic vulnerability map using the Slovene Approach and the hazard assessment schemes, firstly the source risk intensity has been obtained.

The hazards occurring in the test site are mostly of the least dangerous type, while source vulnerability of most of the area is classified as moderate or low. The source risk intensity strongly depends on the hazard level and distribution, though.

The risk intensity is low where there is no hazard independently from vulnerability

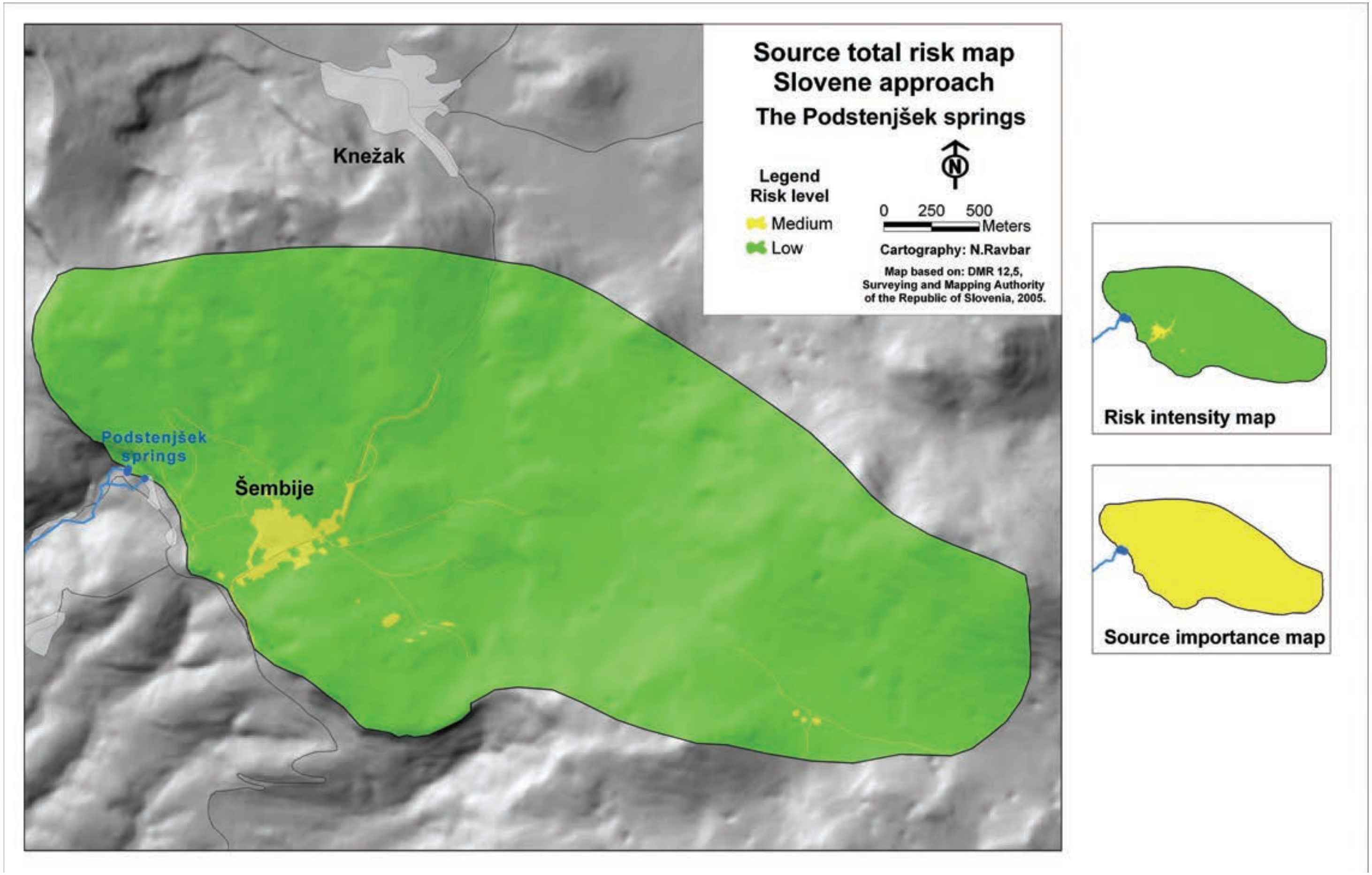


Figure 11.11: Total risk map of the Podstenjšek springs catchment.

degree, where there is very low hazard and source vulnerability is medium or low, as well as where there is low hazard and source vulnerability is low. The risk intensity is medium where there is very low hazard and source vulnerability is high and where there is low hazard and source vulnerability is medium or high.

For the total risk assessment an additional source importance factor has been considered, as proposed by the Slovene Approach. The Podstenjšek spring only supplies 379 inhabitants and is in addition scantily used for animal breeding and gardening. However, it is the only water source. Since there are some reports of *Proteus Anguinus* presence in the Kozja luknja cave (Krivic *et al.*, 1987) and due to cave's immediate vicinity and direct connection to the Podstenjšek springs, we assigned high ecological importance to the springs. Consequently, the medium value of importance has been assigned to the sources and their catchment.

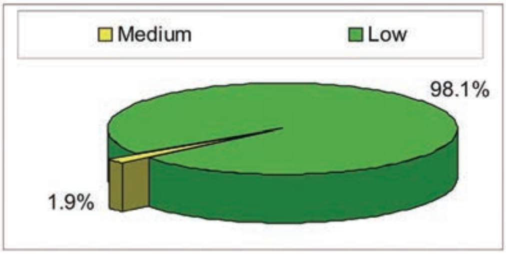


Figure 11.12: Percentage surface area for each class in the Podstenjšek catchment area total risk map.

The total risk map has been obtained by overlying the risk intensity map and the source importance map. The risk map of the Podstenjšek springs catchment shows mainly zones of low and moderate risk and is identical to the risk intensity map (Fig. 11.11). Low risk to the water source occupies majority of the catchment, 98.1% of the total area. Moderate risk occupies only 1.9% of the total catchment (Fig. 11.12) and comprises the urban area, roads, dumps and excavation sites.

11.5 NECESSARY MEASURES FOR THE SPRINGS' PROTECTION

Holistic hydrogeological research including vulnerability and risk mapping were used to develop a strategy for water source protection of the Podstenjšek spring. Consequently, some subsequent suggestions on strategic water source planning and management are given.

The proposals on the Podstenjšek water source protection zones and regimes have already been made some years ago (Petauer *et al.*, 2002). However, the required decrees have not yet been accepted. The water quality at the springs is still relatively high. Nevertheless, for the effective and appropriate protection against contamination the necessary safety measures have to be taken promptly.

First of all, we believe that according to our studies the existing proposals on water protection zones delineation have to be changed. The basis for the new protection zones extension can be the intrinsic vulnerability map, obtained by the newly proposed Slovene Approach to source vulnerability assessment (Fig. 10.19).

By the obtained results from this research the source protection area should be slightly enlarged towards the east, including the Kamenščina dry valley and Milanka mountain as well. Furthermore, the extension of the I. protection zone could significantly be reduced. In contrast to proposed protection zoning, where the I. protection zone extends over the 170 – 400 m distance from the spring, we found the area above the cave Kozja luknja, the karren, highly fractured areas, caves, karst edge above the springs and outcrops along the roads, as well as the estavelle and surrounding area in radius of 10 m, to need the highest protection.

For the protection of the Podstenjšek springs, it is necessary to avoid any contamination within these areas. Thus, these areas should be properly marked and secured as proposed by the *Rules on criteria for the designation of a water protection zone* (Ur.l. RS 64/2004). In addition, as the *Rules* require, also the immediate vicinity of the captured spring should be properly protected, which has so far not been done either. In these areas the appropriate precautionary principles should be adopted (i.e. prohibition of manuring, as well as fertilizers, pesticides usage, prohibition of clear felling and building, prohibition of existing land use change, proper regulation of road sections, etc.).

The extension of the II. protection zone should be reduced towards the north, northeast and east (i.e. to the Inner zone), but extended towards the Kamenščina dry valley exclusive the dolines. The area should also be properly marked (Ur.l. RS 64/2004). The III. protection zone should embrace the parts for which we are not sure if they contribute to the springs or contributes only during high water conditions (i.e. to the Outer zone).

Furthermore, according to the risk map (Fig. 11.11) the existing illegal waste disposals and excavation sites in the Podstenjšek catchment should be sanitized and further dumping or excavation strictly prohibited. The existing roads should be properly regulated, speed limit lowered and racing prohibited in sections crossing the II. protection zone. Further expansion of the settlement should not be allowed; however the adaptation of the existing (empty) houses and their annexation to the sewage system should be encouraged instead.

The present way of agriculture should be preserved and the manure heaps should be regulated according to the existing legislation (Ur.l. SRS 10/1985). Other human activities should be planned in accordance with the *Rules* (Ur.l. RS 64/2004), where certain activities are prohibited or limited regarding the adequate protection zone. Finally, control over the implementation of regulations in certain water protection areas is necessary.

11.6 FUTURE PLANNING PREDICTIONS

Among the vast plans of building wind power plants on several karst ridges in the south-western Slovenia the construction of the wind turbines on the ridge Volovja reber is the closest to its realization. The ridge Volovja reber is situated in the outmost northeastern edge of the Podstenjšek karst springs (for location see Fig. 9.26), where erection of 33 wind turbines is planned. These wind turbines will be of type G52-850 kW with the rotors at a height of 55 m (Gamesa, 2006).

According to the evaluation scheme proposed in the scope of the Slovene Approach the wind turbines would present medium potential degree of harmfulness to karst waters. Besides wind turbines also their foundations construction and construction of the rest of infrastructure, as well as existing roads adaptation and new roads construction towards the Volovja reber would present potential danger to the karst waters. The mentioned activities would remove the already scarce protective cover. In times of construction also the traffic would increase and the existing roads are unprotected (Ravbar and Kovačič, 2006b).

The northern outskirts of the planned wind turbines location border the Podstenjšek source catchment, which in that part is rather like a wider zone than a line drawn on the map. The tracer test results showed that at high water conditions the area below the Milanka mountain is mainly and directly drained towards the Bistrica spring, but in small proportions also to the Podstenjšek springs. However, the injection point is 1 km direct distance and 220 m height difference from the Volovja reber.

Thus, the Volovja reber is situated on a watershed area, however, possible different drainage can also be expected. Nevertheless we assume that the planned wind turbines location entirely lies within the Bistrica water source catchment.

Therefore, further investigation is necessary. When evaluating potential risk of contamination of the groundwater or water sources, research on groundwater drainage from the Volovja reber in different water conditions is needed. Subsequently, in case of a contamination not only from the wind power plants but also from other listed activities, ecological, social and economical consequences should be assessed based on adequate risk mapping.

However it is, above all, necessary to make people acquainted with the importance of sustainable management of karst water sources. Education of various target groups is therefore of exceptional importance.

12
VALIDATION OF VULNERABILITY MAPS

12.1 RELIABILITY OF THE MAPS AND VALIDATION MODE

Groundwater vulnerability is not a characteristic that could be measured or directly obtained in the field (Vrba and Cività, 1994). Many different methods for its assessment have been proposed and tested worldwide. Vulnerability maps are conservative simplifications of natural conditions indeed, but the reliability of the maps is mainly influenced by diverse data sources, their amount and quality, accuracy of data, their interpretation, as well as selection and evaluation of different parameters for the vulnerability assessment.

When different methods are tested in the same area, using the same database, the resulting maps could still be very different and sometimes even contradictory, as shown already by several studies. Therefore it is disputable which of the methods produces the most reliable and consistent results (Gogu and Dassargues, 2000).

Within this research special attention is devoted to the application of different intrinsic vulnerability methods and their validation (for the comparison of the results and comments see chapter 10).

Even though the validation of resulting vulnerability has not become a practice yet, the maps should be tested in order to confirm or reject adequacy of the obtained results in agreement with actual conditions. However, until now no common technique for vulnerability map validation has been accepted. Various different hydrological and statistical methods have been proposed by the European COST Action 620 programme: the hydrographs and chemographs analyses, bacteriology analyses, water balance, tracer techniques, analytical and numerical models (Daly *et al.*, 2002).

Based on three fundamental questions that have been initiated into the groundwater vulnerability mapping concept (Fig. 5.1), the COST Action 620 programme suggests considering the following aspects in order to quantify intrinsic vulnerability (Goldscheider *et al.*, 2001):

- travel time of an (assumed) contaminant from the hazard to the target,
- relative quantity of an (assumed) contaminant that can reach the target,
- physical attenuation (dispersion, dilution) that decreases an (assumed) contaminant concentration.

The required information can most holistically be obtained using tracer techniques.

By monitoring of a tracer breakthrough curve allows observing the (assumed) contamination from the injection point (origin) to a sampling point (target). However, tracer tests allow for validation at certain points only, while large surfaces cannot be validated with this method. Moreover, tracer tests can merely be used to validate source vulnerability, as the springs or wells should be observed. Observation at the base of the unsaturated zone is often not possible (Goldscheider, 2004; Andreo *et al.*, 2006).

For validation, artificial conservative tracers are recommended, since long-term storage may decrease the relative quantity of contaminants that can reach the target (Goldscheider *et al.*, 2001; Goldscheider, 2004).

No general demands on setting up the tracer test results for validation purposes have been established so far. The vulnerability can be evaluated by means of the time of first appearance of a particular tracer, its maximal concentration, the process of its concentration reduction, duration of the particular tracer appearance and its relative quantity (Brouyère *et al.*, 2001).

We suggest tracer test results be evaluated on the basis of two criteria. The first one should be the time of the tracer's first arrival or the time of maximum concentration. In addition, the ratio between the integral of the breakthrough curve and the tracer input quantity should be taken into account (Fig. 12.1). For the latter criteria we introduced the term **normalized tracer recovery R_N**, which is defined as follows (1):

$$(1) \quad R_N = \frac{1}{M}\int C dt = \frac{R}{Q}$$

It is a way of expressing the tracer recovery independent of the spring discharge.

The origin (injection point) presents high vulnerability for the observed target (most commonly a source), if rapid infiltration and fast flow in conduits are the dominant conditions. Resulting travel times are thus very high, minimizing also the sorption, degradation, cation exchange, dispersion and dilution of a solute matter. In such conditions the eventual contamination would reach the water source very rapidly and its concentration at the outlet, as well as relative quantity of the recovered tracer would be high.

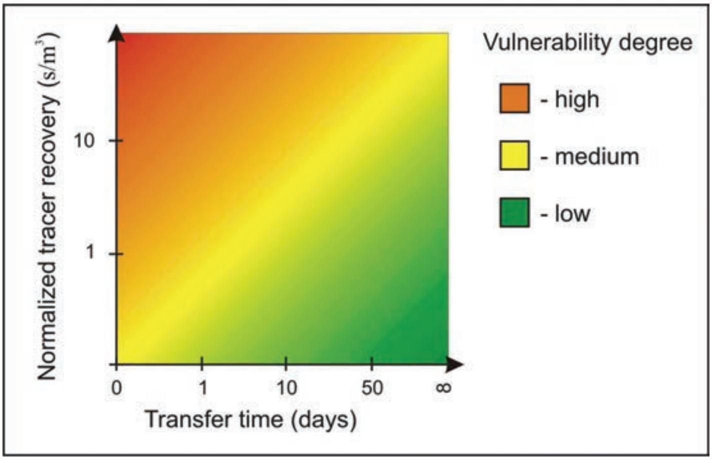


Figure 12.1: Diagram setting up the tracer test results for source vulnerability validation purposes.

In contrast, the origin (injection point) presents low vulnerability for the observed target (most commonly the source), if the tracer is mostly absorbed in the sediments and soil. Consequently, the eventual contaminant arrival is retarded and its concentration significantly reduced or the contaminant does not arrive at all. Intermediate situations correspond to medium vulnerability.

12.2 VALIDATION OF THE OBTAINED MAPS WITH TRACER TESTS

The obtained source vulnerability maps result in zones of low, medium, high and extreme vulnerability. However, the results vary significantly and it is disputable which are the most reliable.

By carrying out the multi-tracer tests we can examine and verify the adequacy of such vulnerability class distribution and gain additional information on the mechanism of the potential contaminant transport. Based on the previously described validation procedure the source vulnerability maps obtained in the studied area have been validated by means of two combined tracer tests in high and low water conditions:

- a multi-tracer test performed in March 2006 during high water conditions (for detailed description and results see section 9.7.3),
- a multi-tracer test in November 2006. The weather conditions of autumn and winter 2006/07 allowed us to observe the response of karst aquifers to contamination during a long-lasting and extremely dry period.

Based on adequate preliminary tracer test preparations we simultaneously injected four different tracers in four polygons of different vulnerability values: the Šembijsko Jezero, the Nariče, the Pušli hrib north of the Nariče and the area northeast from Šembije village. Details on tracer test execution and results are presented in the next sections.

12.2.1 INJECTION SITES INFILTRATION CONDITIONS

Before the injection we made line profiles using electrical resistivity imaging technique. The purposes of the measurements were to enable insight of the subsurface and to study possible infiltration conditions at the particular injection sites. The measurements were also done in order the better to characterise the profiles in detail and to identify possible zones of higher permeability e.g. the soil and sediment depth characteristics, location of the potential high-permeability zones and fracture zones.

Using Super Sting R1/IP electrical resistivity imaging we applied the dipole-dipole array in all the profiles with a length of 20 m. The electrode spacing was 1 m, since we were more interested in higher resolution of the horizontal changes of each injection site and not so much in the depth. The dipole-dipole array is very sensitive to horizontal

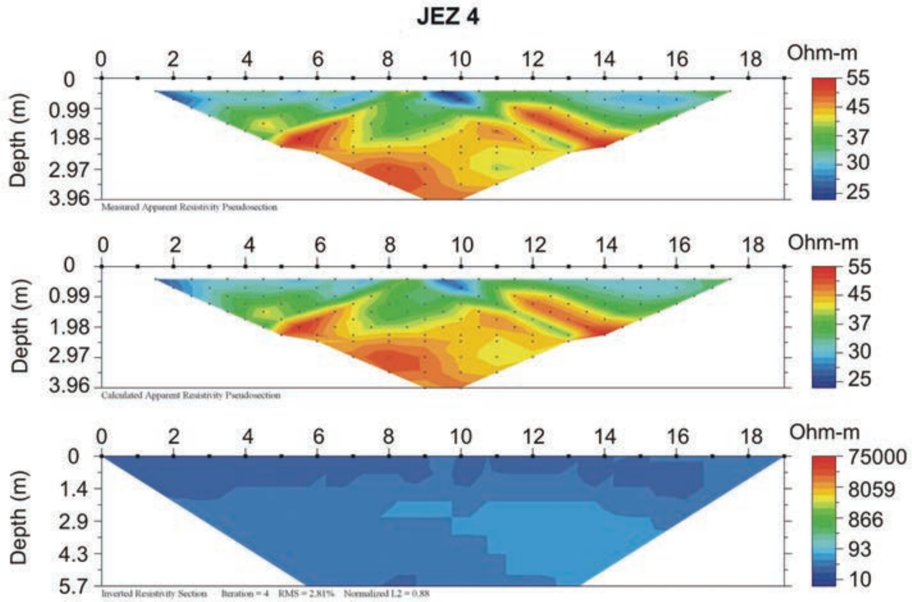


Figure 12.2: The observed apparent resistivity pseudosections for the Šembijsko Jezero (JEZ 4) together with inversion models.

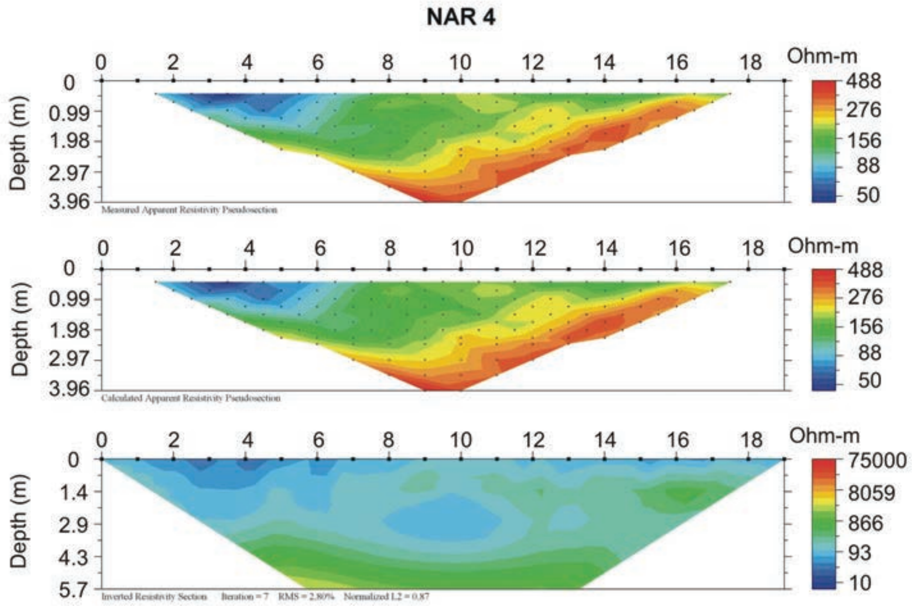


Figure 12.3: The observed apparent resistivity pseudosections for the Nariče (NAR 4) together with inversion models.

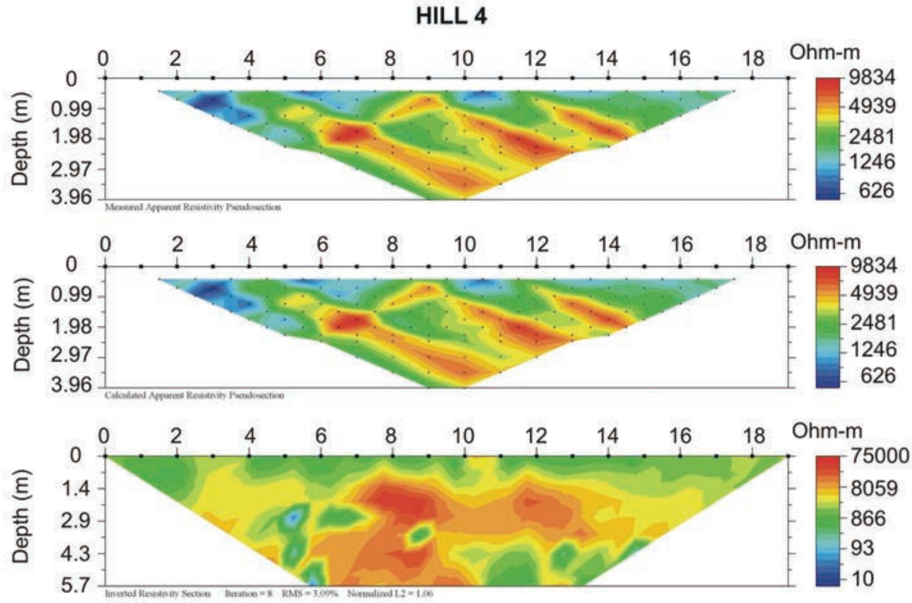


Figure 12.4: The observed apparent resistivity pseudosections for the Pušli hrib (HILL 4) together with inversion models.

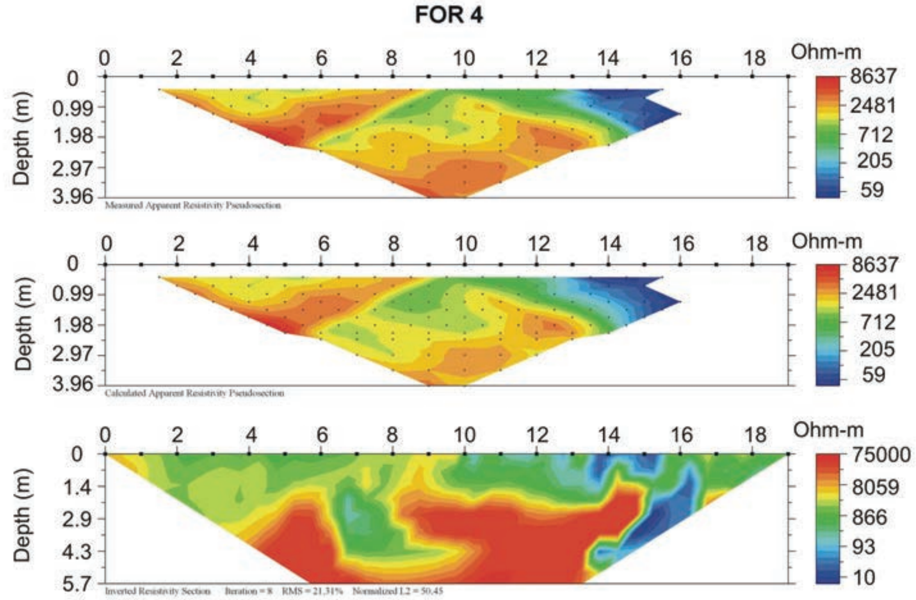


Figure 12.5: The observed apparent resistivity pseudosections for the area northeast of the Šembije village (FOR 4) together with inversion models.

changes in the subsurface sensitivity, but relatively insensitive to vertical changes. Thus it is good in mapping vertical structures (Bechtel *et al.*, 2007).

The first polygon was chosen on the bottom of the Šembijsko Jezero. Previous electrical resistivity imaging carried out there showed that the carbonate rocks are covered by lower resistivity layers of soils and alluvial sediments reaching more than 10 m in depth. Our second resistivity measurement confirmed this (Fig. 12.2).

The second polygon was chosen on the Nariče. The resistivity imaging result shows quite some heterogeneity in infiltration conditions. Even though the site is morphologically homogeneous and completely flat, the left corner of the profile is presumably filled with a soil pocket about 3 m deep. The rest of the polygon is covered by very thin soil. In the middle there is a zone of lower resistivity or fractured rocks that could increase or decrease infiltration (Fig. 12.3).

The third polygon was chosen on the top of the hill north of the Nariče. The mostly firm and in places fractured rocks that appear on the surface emerge as karrenfield covered in places by modest soil cover. The fractures could allow faster infiltration though (Fig. 12.4).

The fourth polygon was chosen at the edge of the forest close to Šembije village. Unfortunately some error occurred during measurement, so the furthest right results cannot be considered. However, the results show that the profile crosses a firm and homogeneous limestone rock base with a probable fracture zone in the middle (Fig. 12.5).

12.2.2 INJECTION MODE

On 23rd November the injection of all four tracers was carried out. Essentially we planned to do the injection in high water conditions in order to simulate an accident and to observe the results in the worst possible scenario. Unfortunately, due to the extremely dry weather conditions in autumn 2006 we actually observed the karst system reaction to imaginary contamination under low water conditions.

According to the data obtained from the Slovene Environmental Agency the precipitation amount measured at the measuring station in Ilirska Bistrica from beginning September to end December reached about 250 mm in total, which was only 39% of the 1961-1990 period average amount for this time of the year (Klimatografija Slovenije, Količina padavin, 1995; MOP ARSO, 2007).

In autumn 2006 larger quantities of rain fell only on 4th October and, except for some occasional drizzle, there was no more rainfall until 22nd November. At that time about 47 mm of rain fell within 20 hours (MOP ARSO, 2007). The water level at the Pivka spring rose for at least 8 m within 12 hours and the spring became active. The discharges of the Bistrica spring rose as well. The discharges of the Podstenjšek springs increased from 50 l/s to 500 l/s within 12 hours after the rain (Fig. 12.6).

All the tracers were injected with a watering can at the land surface on rectangles of 20 m x 5 m in extent (Fig. 12.7 and Tab. 12.1). In the first injection polygon at the

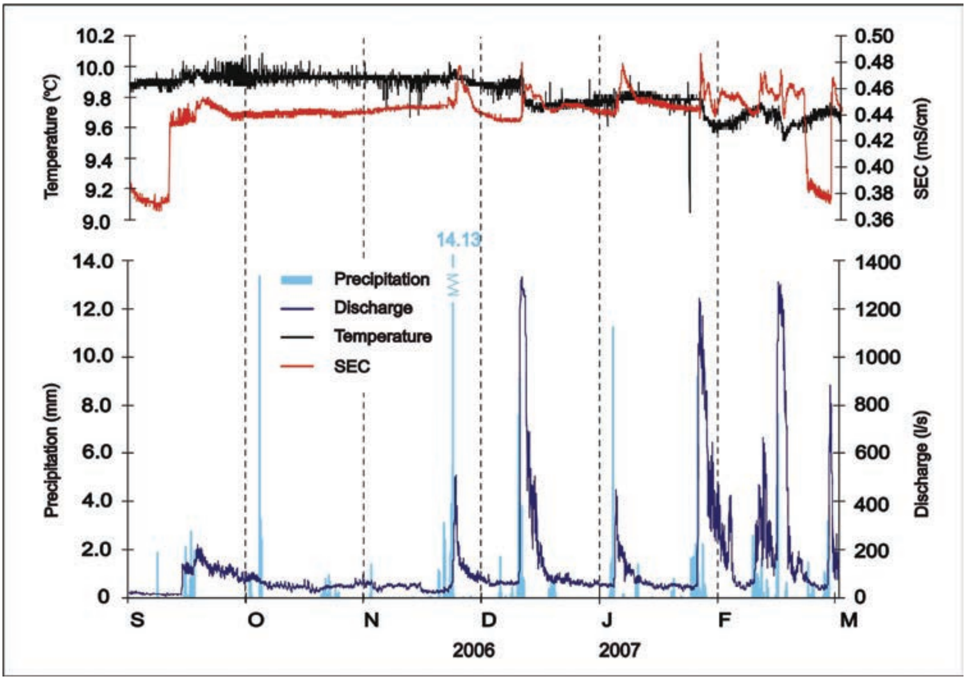


Figure 12.6: Climatic and hydrological conditions of the Podstenjšek springs in autumn and winter 2006/07. Half hour values are displayed on the graph. Precipitation data was gained from the Slovene Environmental Agency (MOP ARSO, 2007).

Table 12.1: Distance and altitude difference between the injection sites and the sampled springs (for location see Fig. 12.9).

Sampling points	**Podstenjšek springs**	**Pivka spring**	**Injection points**
Distance / altitude difference from the injection points	2 km / 34 m	4.5 km / 2 m	1. Šembijsko Jezero
	2.3 km / 45 m	4.5 km / 13 m	2. Nariče
	2.1 km / 75 m	4.2 km / 40 m	3. Pušli hrib
	1 km / 90 m	3.7 km / 57 m	4. Northeast of Šembije

bottom of the Šembijsko Jezero we injected 500 g of uranine. We spread it over the soil and sediment cover of several metres in thickness. Before and after this 0.7 m^3 of irrigation water was used.

The second injection polygon was at the bottom of the Nariče lake where soil and sediments only occur in pockets and are rather unevenly spread. We injected 400 g of sulforhodamine G and irrigated it before and after the injection with the 0.7 m^3 of water.

The other injection polygons were located on the limestone surface. The third injection site was located north of the Nariče, at the top of the hill. The polygon is characterised by karren partly covered by 5-10 cm of soil. A total of 5 kg of Lithium Chloride (LiCl)

was injected. The fourth injection site was located at the edge of the forest, where limestone is covered by vegetation and in places up to 15 cm of soil, but no karren are exposed. A total of 5 kg of Potassium Iodide (KI) was injected. For the third injection polygon 0.6 m^3 of flushing water was used and 1.2 m^3 for the fourth one, before and after the injections.

Figure 12.7: Injection of a tracer at the land surface (photo: S. Guglielmetti).

12.2.3 SAMPLING AND ANALYSING

The Pivka spring was observed for up to 60 days and the Podstenjšek spring for up to 98 days. Fluorescence of the spring water was measured *in situ* with a flow through filed fluorometer FL30 (GGUN) at the Podstenjšek spring and a flow through filed fluorometer FL03 (GGUN) at the Pivka spring.

At the Podstenjšek spring samples were collected through an automatic sampler (ISCO 2900) as frequently as precipitation circumstances required. Control samples were also taken manually in both plastic and dark glass bottles. At the Pivka spring the samples were taken manually in plastic and dark glass bottles. The glass bottles were afterwards stored in a dark and cool place.

The fluorescent dye analyses were carried out at the Karst Research Institute's laboratory using luminescence spectrometer LS 30, Perkin Elmer. Scanning of the emission spectra was done by the method of simultaneously changing excitation and emission wavelengths (E_{ex} = 531 nm, E_{em} = 552 nm for sulforhodamine G with detection limit of 0.04 ppb and E_{ex} = 491 nm, E_{em} = 512 nm for uranine with detection limit of 0.005 ppb) (Käss, 1998; Benischke *et al.*, 2007).

The iodide and lithium were analysed in the laboratory of the Centre of Hydrogeology, University of Neuchâtel. We measured the iodide electrical potential with an iodide-specific probe (detection limit 0.9 ppb) and the lithium using ICP-MS (inductively-coupled plasma - mass spectroscopy; detection limit 0.03 ppb) (Benischke *et al.*, 2007).

12.3 RESULTS

The tracer test, carried out in November 2006, was done under low water conditions. In autumn and winter 2006/07 an extraordinarily dry period lasted for a few months. Not until 15 days after the injection a more abundant rainy event occurred. Moreover, in the three months period after the injection only three efficacious rain events were followed, that in our opinion were not sufficient for the adequate mobilization of some of the tracers towards the spring (Fig. 12.6 and Fig. 12.8).

Three months after the injection only two tracers have been detected in two observed springs. Two days after the injection iodide that was injected in the site no. 4 appeared in the Podstenjšek spring and lithium that was injected in the site no. 3 appeared in the Pivka spring (Fig. 12.9). Iodide was detected in the Podstenjšek spring for additional two days with maximal concentration of 3.2 ppb. Altogether 0.63% of the injected iodide

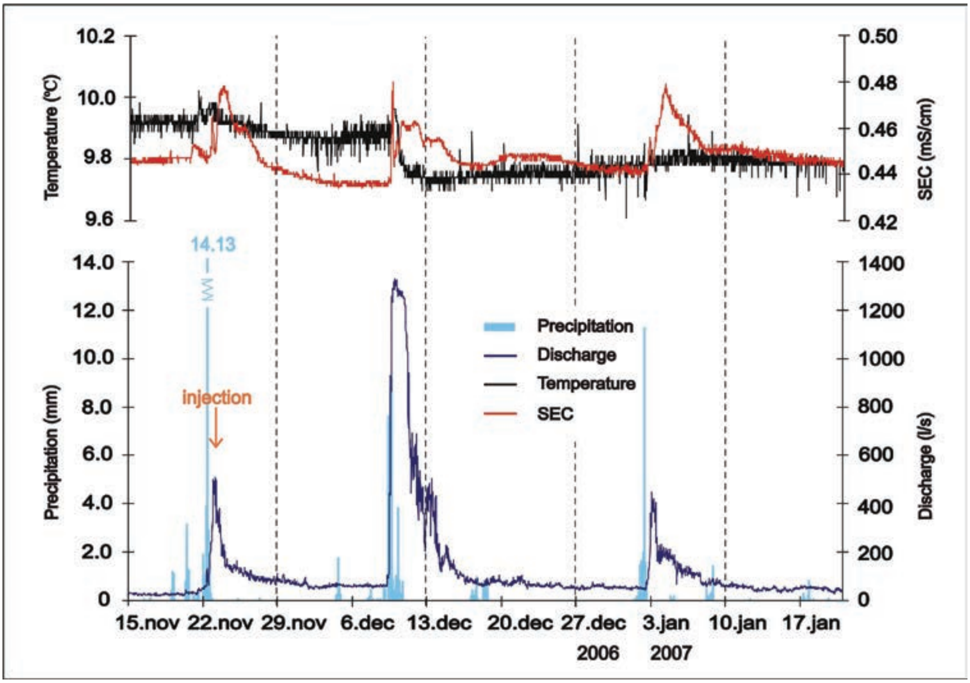


Figure 12.8: Hydrological conditions of the Podstenjšek springs in the time of the second tracing test. Half hour values are displayed on the graph. Precipitation data was gained from the Slovene Environmental Agency (MOP ARSO, 2007).

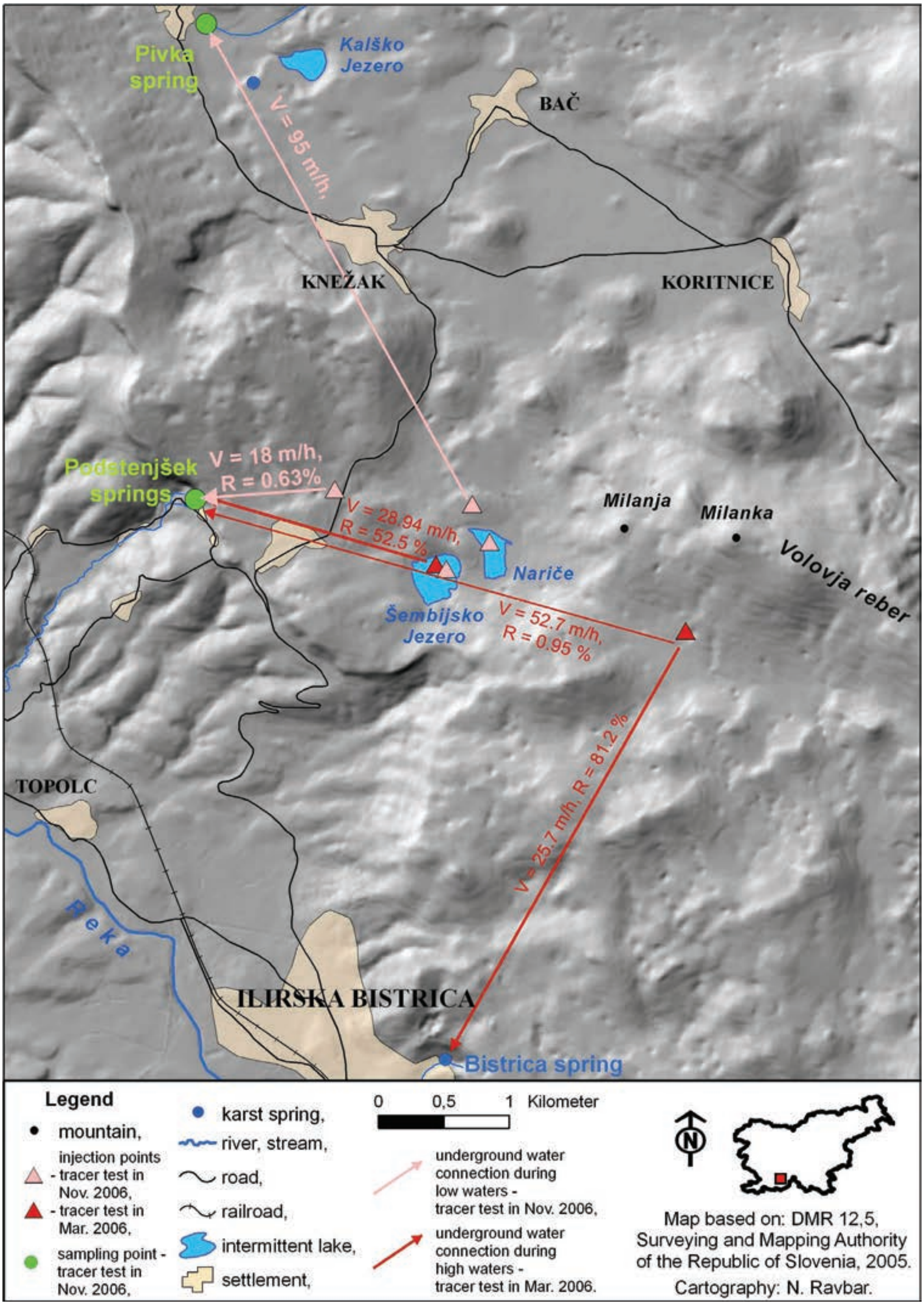


Figure 12.9: Overview of two tracer test results performed in the Bistrica, Pivka and Podstenjšek catchment during high and low water conditions.

was recovered. The apparent groundwater velocity to the Podstenjšek spring was 18 m/h at low waters (Fig. 12.10).

On the other hand lithium was in the Pivka spring detected for additional 16 days, until 10th December with maximal concentration of 2.6 ppb. The apparent groundwater velocity to the Pivka spring was 95 m/h at low waters (Fig. 12.11).

Even after 130 days of sampling no fluorescent tracers have been detected in either Podstenjšek or Pivka springs. They were presumably completely absorbed in the soil, sediments and epikarst.

The tracer test results proved the underground connection between the area north-east of Šembije and the Podstenjšek springs. It also proved that at low water conditions northern part of the studied area drains to the Pivka spring (Fig. 12.9). However, due to the supposed overflow characteristic of the Podstenjšek springs, it is possible that the area is drained by the Podstenjšek springs during high waters.

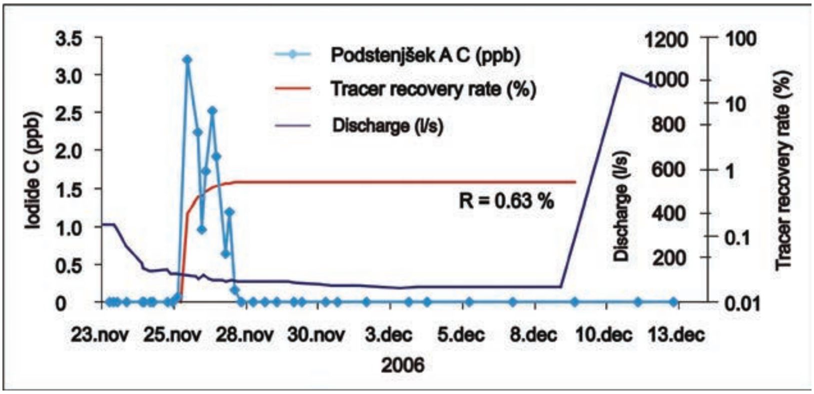


Figure 12.10: Iodide breakthrough curve observed in the Podstenjšek spring.

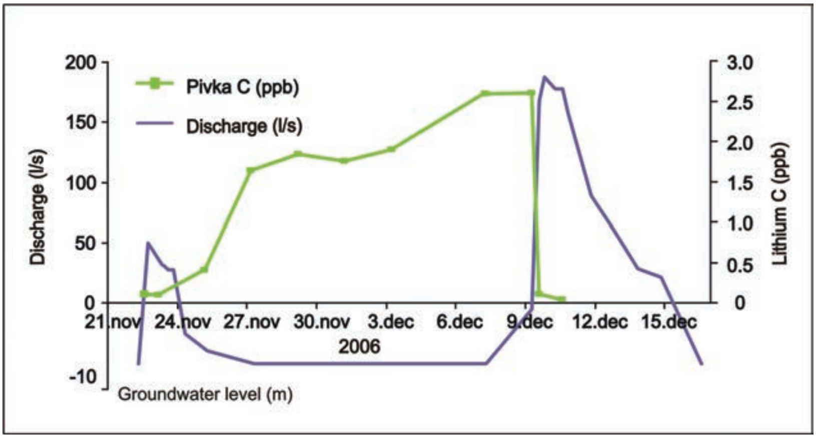


Figure 12.11: Lithium breakthrough curve observed in the Pivka spring.

12.4 CONCLUDING COMMENT

The performance of an artificial tracer test can be used as simulation of a contamination event. It can most straightforwardly demonstrate the contaminant infiltration and transport mechanisms from origin to target.

Tracer test results indeed depend on the injection mode and tracer properties but, besides the aquifer's properties, they depend mainly on the hydrological conditions at the time of testing. The tracer infiltration is significantly controlled by the soil and epikarst water saturation, as well as the pre-stored water volume, and subsequent rainy events are of considerable importance.

The first experiment, carried out in March 2006, was made under high water conditions and was followed by frequent strong and efficacious precipitation events so that immediate infiltration of tracers took place. Two tracers were injected in two locations. Sulforhodamine B was injected in an estavelle that was empty at the time of injection (injection site A) and eosine was injected in karren (injection site B).

The estavelle is characterised as highly vulnerable in all the source vulnerability maps. However, the vulnerability of the area below the Milanka mountain varies notably due to the particular method application. It is characterised as moderately vulnerable by the EPIK and the Simplified method, but as of low vulnerability by the PI+K, COP+K methods and the Slovene Approach (Fig. 12.12 and Fig. 12.13).

Focusing on particular tracer appearance at the observed spring (the Podstenjšek spring) the tracer breakthrough curves have been evaluated based on the proposed validation concept (Fig. 12.1). Thus the injection site A has been evaluated as highly vulnerable and the injection site B as of low vulnerability. The tracer test results fully justify the PI+K, COP+K methods and Slovene Approach source vulnerability maps. The EPIK and the Simplified method show higher degree of vulnerability for the injection site B.

The second experiment, carried out in November 2006, was made under low water conditions. Not until 15 days after the injection a more efficacious rain event occurred. Four tracers were injected in four locations (Fig. 12.12 and Fig. 12.13). One tracer was spread over the bottom of the Šembijsko Jezero over several metres thick soil and sediment cover (injection site 1). This area is in all source vulnerability maps indicated as extremely or highly vulnerable due to the occasional lake that appears according to the hydrological conditions and sinks via the estavelle. Only the Slovene Approach, which satisfactorily takes into account hydrological variability, classified the Šembijsko Jezero as of low vulnerability.

Another tracer was spread over the Nariče where soil and sediments occur in pockets; however, in places the limestone rock base outcrops as well (injection site 2). For the Nariče vulnerability, significantly different results have been obtained. The COP+K and the EPIK method classify it as highly vulnerable and the Simplified method as moderately vulnerable, whereas the PI+K method and the Slovene Approach classify it as of low vulnerability.

Two tracers were spread over the limestone surface, partially covered by scarce soil and vegetation cover, and mostly classified as moderately vulnerable areas. Only the EPIK method classifies both areas as moderately vulnerable. The PI+K, the COP+K methods and the Slovene Approach classify the Pušli hrib as of low vulnerability (injection site 3) and the area close to the Šembije village as moderately vulnerable (injection site 4). The Simplified method classifies the Pušli hrib as of moderate vulnerability and the area close to the Šembije village as highly vulnerable.

In the Podstenjšek springs only the tracer, injected in the injection site 4 was detected. Thus, according to the characteristics of the tracer appearance at the springs, the

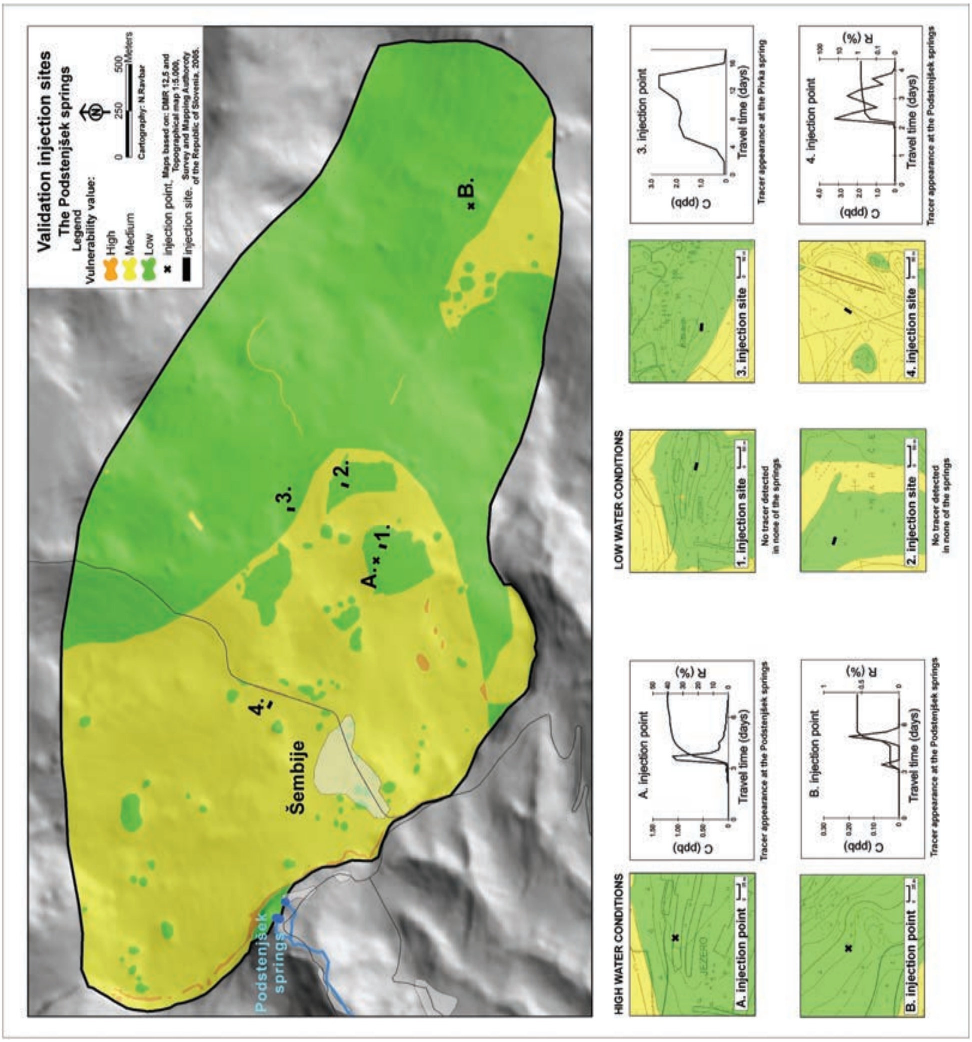


Figure 12.12: Slovene Approach source vulnerability of the test site detailed scale insets of the validation points under different hydrological conditions and obtained results.

injection site has been evaluated as of moderate vulnerability. Since the other tracers have not been detected in the Podstenjšek springs, the injections sites have been evaluated as of low vulnerability.

The executed tracer tests, carried out in different hydrological conditions, illustrate that a karst system could be highly vulnerable in high water conditions, but of low vulnerability or even not vulnerable at all in dry periods, which also justifies integration of hydrological variability into vulnerability mapping. All methods, except the Slovene Approach classify the Šembijsko Jezero as extremely or highly vulnerable due to insufficient guidance for temporal variability, but the tracer injected there was not detected in none of the springs.

In general, the results obtained by the EPIK and the Simplified method are proved to suggest higher degrees of vulnerability. The PI+K method does not give satisfactorily results only at the Šembijsko Jezero, whereas the COP+K method does not give satisfactorily results at the Nariče as well. The newly proposed Slovene Approach gives most plausible results, whereas shows the same degree of vulnerability at all the injection sites as validated (Fig. 12.13).

However, in order to validate better the vulnerability of the system, the multiple irrigation-tracer test should be repeated during high water conditions and other validation techniques should also be applied.

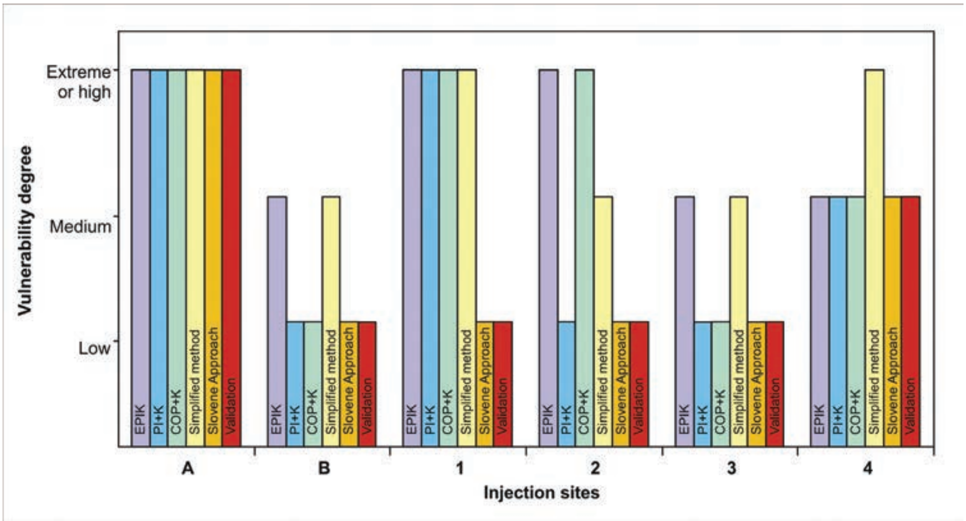


Figure 12.13: Vulnerability classes for six sites predicted by the different methods compared to the validation results.

13

GENERAL CONCLUSIONS AND OUTLOOK

13.1 SIGNIFICANCE OF THE RESULTS

Karst water sources in Slovenia are in the long term the most promising drinking water source, because of good water quality and sufficient amount. Therefore these are of great national, even strategic importance.

Even though the quality of karst waters is still relatively high, individual examples of contamination illustrate the shortcomings of water management even in the uninhabited alpine karst areas, which are ordinarily very favourable for water protection.

In some countries, the concept of groundwater vulnerability and risk mapping has been successfully used for protection zoning and land use planning in karst. Thus, different methods have already been developed and implemented in different test sites worldwide. Moreover, in some European countries the concept of groundwater vulnerability has been successfully integrated in the state protection legislation.

Unfortunately, in Slovenia we do not have many experiences in vulnerability and risk mapping of karst aquifers. Nationally the present research is thus the most holistic contribution to this subject. Before our study only two karst spring vulnerability studies had been done, and hazard and risk mapping had only been applied in a few projects. In the present research special attention is devoted to the application of different vulnerability mapping methods and their validation, as well as to perfection of the existing hazard and risk assessment.

Consequently, the Slovene Approach to vulnerability and risk mapping has been developed taking into account peculiarities of Slovene karst. It is, in addition, compatible with European and Slovene legislation. Its application was successful and validation proved it to give satisfactory results. Thus, it could be proposed as the basis for the karst source protection zones and regimes establishment, and be added to the state protection schemes as well.

Moreover, for the national and local socio-political agencies responsible for the land use planning and decision making, the vulnerability and risk maps could be an advantageous basis for their decisions. The vulnerability maps can help to improve water protection by identifying areas with high or extreme vulnerability and the risk maps can help to avoid contamination by highlighting areas under highest risk. Both, however, provide compromise between land use practices on the one hand and protection on the other.

The final vulnerability and risk maps thus offer a suitable management for karst water sources and consequently may be used for a variety of purposes:

– to optimise and reduce source protection zones,
– to evaluate human activities holistically and thus enable
– identification of land mismanagement, reorganisation and better practices for future planning,
– to better predict possible scenarios in cases of contamination.

By proposing a comprehensive approach for vulnerability and risk assessment for karst water protection and land use planning in Slovene karst areas, we believe that we have opened new perspectives for future development on this topic. We highlighted the impact of drastic temporal variations to contaminant transport and groundwater vulnerability. In the study it is outlined how hydrological variability with time could be considered in karst groundwater vulnerability assessment and land use planning.

Furthermore, when considering source vulnerability assessment, a significant achievement has been made concerning an evaluation proposal for the water (and contaminant) flow in the saturated zone towards spring(s) and its integration into the existing resource vulnerability assessment schemes. The proposed source vulnerability assessment using different methodologies has been first tested and implemented in the Slovene test site.

The existing European and Slovene legislation emphasise that all groundwater is valuable and has to be protected from contamination. However, in order to enable prioritisation procedure for protection and remediation, the Slovene Approach additionally proposes valuation of water resource or source assessment scheme. It also provides its integration into the existing risk analysis.

We hope that with the presented work we have contributed to the stimulation of the vulnerability and risk mapping in Slovene karst areas and that we have made a significant contribution to protecting karst water qualities and quantities for future generations.

Slovenia has a unique opportunity to preserve large quantity of karst groundwater good quality for exploitation in the future. In order to ensure appropriate quality of this unique natural resource it is necessary to establish adequate protection, which consists of the determination of optimum water protection zones with respective regimes. The existing legislation is not sufficient; however, satisfactory results can be obtained by the proposed Slovene Approach. For this, good co-operation between scientists, legislators, planners and decision makers is needed to avoid land use conflicts and to work together in a framework of integral karst protection.

Additionally, it is above all necessary to educate the population of the significance of sustainable water management in karst regions. Finally, control over the implementation of regulations in certain water protection areas is essential.

The holistic hydrogeological research of the test site (the Podstenjšek springs catchment) in this study has contributed greatly to the pure scientific knowledge of the area as well. Before our investigation no detailed geological and hydrological research of the wider area had been done. In the present research we determined some underground water flow connections and located the Adriatic–Black Sea watershed more precisely. We also delineated the catchment area of the Podstenjšek, studied the geological and geomorphological properties of the catchment and its surroundings, as well as analysed springs' hydraulic properties and the hydrodynamic behaviour of the aquifer.

13.2 APPLICABILITY OF THE SLOVENE APPROACH

The application of the proposed Slovene Approach to the Podstenjšek water source catchment was successful and the results are justified. The vulnerability, hazard and risk maps are satisfactory and the validation with tracer tests proved the Slovene Approach to give plausible results. Although the Slovene Approach considers karst-specific infiltration conditions, it is not restricted solely to karst aquifer applications, but can be used in non-karst areas as well. Moreover, since we believe the vulnerability methods should not be restricted to the individual countries' borders the Approach could be applied to other aquifers worldwide.

The Approach considers a great number of aspects having a major impact on the vulnerability of groundwater/source to contamination. Consequently, it requires a large input of data, which is in most cases not yet available. Thus it satisfies the scientists' demand for thorough research and at the same time it calls for further investigation. Once the required database is gained, using GIS technology facilitates quite simple creation of the maps. The results are user-friendly also for land use planners and decision makers.

The application of the Slovene Approach to the Podstejšek water source catchment illustrates the importance of comprehensive knowledge of groundwater hydraulic connections, as well as hydrodynamic behaviour and hydrogeological properties of the aquifer to identify the most vulnerable areas, which should consequently be highly protected. On the other hand, the hazard and risk maps show that the quality of the source's water is not highly endangered. The few water quality analyses confirm the corresponding degree of human activities (un)harmfulness.

The Slovene Approach will be applied to other test sites in Slovenia and appears to be well adapted to be used as the scientific basis, as well as a comprehensive tool for resource and source protection zoning, sustainable management and land use planning.

However, while vulnerability maps are static and generally do not change drastically with time, hazard and risk maps need to be updated and adapted to changes in land use with time in order to obtain accurate results. In the studied area and its surroundings it is a future challenge to develop a holistic evaluation of the planned activities in the karst ridge of Volovja reber and to determine what potential risk would the wind turbines pose to the groundwater and especially to the internationally important Bistrica water source.

13.3 MAPPING SCALE

Often the eventual scale of the output map is determined dependent on the size of the area under investigation. The vulnerability and risk maps are thematic maps, where the information must be presented in a concise and clear manner. Thus, the selection of a suitable mapping scale must primarily be decided according to the map's purpose.

General maps at a scale 1:100,000 or 1:50,000 should be prepared for land use planning on a national or administrative unit's scale. The data entry should be generalized, wherever several different information become associated with the same location. It is recommended that the most critical situation is shown (i.e. extreme vulnerability, very high hazard or risk). Such maps should be used for land use planning on a national and/or regional basis or when integrating water protection into the land use planning processes.

Detailed maps at scales 1:5,000, 1:10,000 or 1:25,000 should be prepared for land use planning and resource or source protection zoning on a catchment scale. Since also some catchments can extend over many square kilometres, detailed maps could only be produced for the highly vulnerable areas, areas under high risk or areas of special interest e.g. where new infrastructure is planned. Depending on the purpose of mapping, only the maps for the inner catchment zones or for the main recharge areas of groundwater could be produced (Fig. 13.1).

Since the preparation of vulnerability and risk maps can be a relatively costly and time-consuming task, a priority list of the regions to be mapped should be established, starting with the areas under highest necessity for action, where rapid expansion threatens the drinking water sources or for (re)sources of prime importance.

However, in some cases the actual size of some, generally physical features or more commonly hazards of the study area cannot be presented due to their small dimensions. In such instances the existing shape as spatial information could be lost. Furthermore, the data coordinate information is mainly determined by the scale at which the information was collected. Therefore, the accuracy of the maps greatly depends on the quality of the original sources, which often have different origins.

Clearly, the scale of the mapped objects should be the same, or better and more detailed, as the eventual scale of the output map. However, due to the above-mentioned scale issues the individual users are in some cases forced to generalization. Dependent on the size of the area under investigation and consequently on the eventual scale of the output map, generalization of the final maps is necessary in order to make them useful.

However, while the small non-vulnerable areas within the highly vulnerable ones could be eliminated in the maps, the most vulnerable areas must not be. Such areas must be enlarged and made adequate at a definite mapping scale (e.g. a buffer around a small swallow hole) to make them noticeable. Zoomed insets of such areas should be included in the final map as well, enabling the end user immediate understanding of the situation. The same applies for hazard and risk mapping (Fig. 13.2).

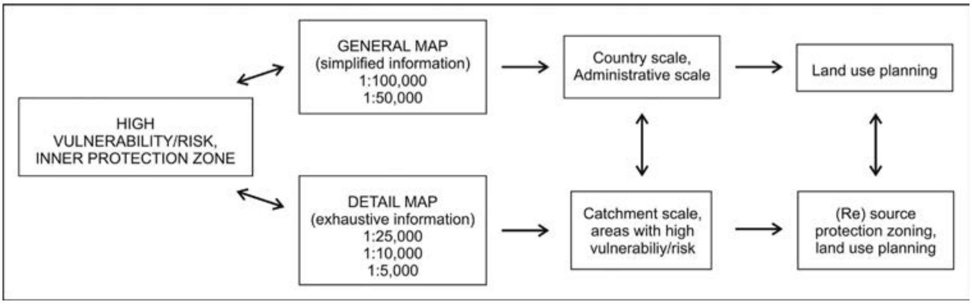


Figure 13.1: Mapping scale should depend on the purpose of maps.

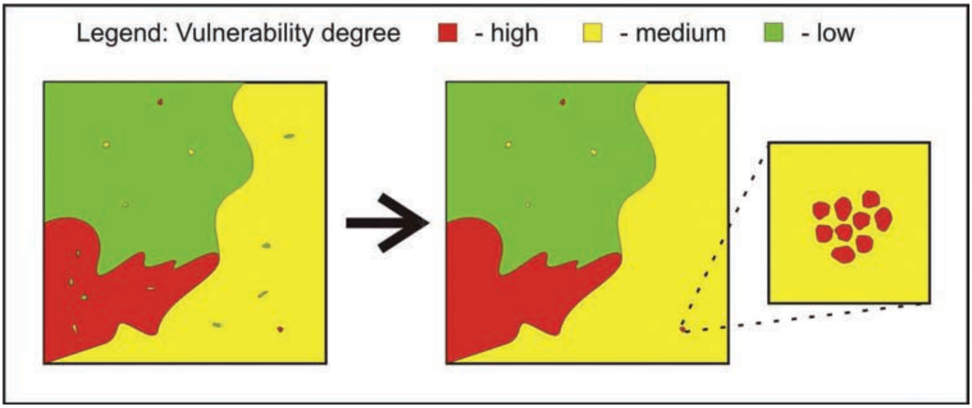


Figure 13.2: Generalization of the maps allows elimination of the non-vulnerable/non-risk areas and emphasis on the highly vulnerable/high-risk areas.

13.4 NEW RESEARCH CHALLENGES

13.4.1 DEPENDENCE OF KARST AQUIFER'S VULNERABILITY ON THE HYDROLOGICAL CONDITIONS

In some aquifer systems the released contaminant might quickly and/or completely reach the target in high water conditions, but can reach it with a long delay, in small proportions and with low concentrations when there is no media to transport contaminants towards the target. The vulnerability of karst aquifer systems is consequently greatly dependent on particular hydrological conditions.

Where such hydrological variations are of great significance and have a major impact on the groundwater and source vulnerability, we provided an approach for addressing this issue. However, the evaluated vulnerability degree of a karst environment cannot give answers as to how a system would react in possible different hydrological situations.

For efficient protection of karst waters against contamination it is primarily essential to understand and consider the characteristics of flow and transport of soluble substances within the aquifer in different hydrological conditions. More detailed results about the dynamics of groundwater flow within different zones of a karst aquifer and about the role of the differences in the mode of this flow on the transport of harmful substances could be achieved by promoting research (e.g. natural tracers' observation, analytic and numeric modelling).

Based on existing knowledge of transport and retardation characteristics in a particular karst aquifer, seasonally adapted land use practices and groundwater quality monitoring guidelines could be prepared in addition to an assessed vulnerability situation.

13.4.2 A HOLISTIC VALIDATION TECHNIQUE DEVELOPMENT

So far the reliability of gained data has generally not been practiced. Therefore, no specific procedure on vulnerability and risk mapping validation has been accepted either. Further research work in vulnerability and risk mapping should thus mainly focus on validation issues.

In the present research the maps have been directly validated by means of tracer tests. However, carrying out a tracer test also draws some uncertainties, because the results also depend on respective hydrological conditions, the injection mode and tracer properties.

Thus, it is a future challenge to develop a holistic validation technique to evaluate the reliability of the vulnerability and risk maps. It should include various spectra of physical testing of the map in a direct or indirect way, such as tracer tests using artificial or natural tracers, as well as mathematical and statistical methods. However, the validation schemes should not be based on one single validation tool only. They should follow main concepts of vulnerability, but should still be developed independently from the map making processes.

Thus, in future, global catchment validation can be done by means of other natural tracers (e.g. environmental isotopes, dissolved gases, turbidity, etc.) in a way to seek for the (in)consistency of their response at the outlet from the karst aquifer system with the spatial statistics of vulnerability classes. Several other indirect parameters, such as a spring's hydrograph and chemograph analyses could be combined in a hydrogeological validation model. Similarly, real contaminant events can be used to validate risk maps.

13.4.3 INTEGRATING EXPLOITATION ISSUES

Since the public and economic supply of drinking water has been expanding, its consumption is constantly increasing. In general the vulnerability and risk assessment does not consider any aspects of over-utilization problems. However, to prevent over-exploitation the states should have a reasonable strategy of capture and usage of drinking water.

An economical and ecological solution for the assurance of adequate quality and quantity of drinking water (in drought periods also) is in the first place based on economical consumption. Even though this issue is well addressed in existing European and also in Slovene legislation, the protection mechanisms should be integrated in the existing vulnerability and risk concept and applied as the future drinking water supply strategy basis.

14

VAROVANJE KRAŠKIH VODA

OBŠIREN SLOVENSKI PRISTOP H KARTIRANJU RANLJIVOSTI IN TVEGANJA ZA ONESNAŽENJE

(POVZETEK)

14.1 PREDSTAVITEV PROBLEMATIKE

V številnih delih sveta kraška podzemna voda že predstavlja zelo pomemben, ponekod pa celo edini vir pitne vode. Tudi v Sloveniji so kraški vodonosniki izjemnega pomena za vodooskrbo, saj skoraj polovico potreb pokrivamo s črpanjem iz kraških vodnih virov, ob suši pa celo dve tretjini (Brečko Grubar in Plut, 2001). Zaradi izjemne kakovosti voda in ekonomsko zadostnih količin so kraški vodonosniki pri nas dolgoročno obetajoč vir in jim lahko pripišemo status strateške surovine.

Vendar pa so kraški vodonosniki v primerjavi z nekraškimi še posebej občutljivi na onesnaženje. Na krasu je zaradi dobre prepustnosti in običajno odsotnega ali zelo tankega zaščitnega pokrova prsti in sedimentov infiltracija v podzemlje izredno hitra. Skozi dobro prepustne razpoke in kraške kanale se voda in v njej raztopljene snovi hitro prenašajo tudi na zelo velikih razdaljah.

Pomembnejši kraški izviri imajo običajno veliko napajalno zaledje in potencialno onesnaženje kjerkoli v zaledju lahko zelo hitro doseže izvir in ogroža oziroma zmanjšuje njegovo kakovost. Visoke hitrosti vode v krasu (tudi do več sto metrov na uro) ne morejo zagotavljati zadostne razgradnje onesnaževal in večja oddaljenost od vodnega vira ne pomeni nujno tudi večje varnosti pred onesnaženjem.

Zaradi posebnih lastnosti pretakanja voda imajo kraški vodonosniki v celoti izredno nizke samočistilne sposobnosti. Zato jih je potrebno ustrezno zaščititi, dolgoročni načrt varovanja pa mora temeljiti na dobrem poznavanju značilnosti pretakanja in prenosa snovi v krasu. Načrtna in dolgoročna zaščita tega pomembnega naravnega bogastva mora temeljiti na kakovostnih strokovnih podlagah.

Ker so hidrografska zaledja posameznih kraških izvirov pogosto zelo obsežna, je maksimalno zaščito za celotno območje nemogoče zahtevati in izvajati. To bi bilo sicer primerno za zaščito kraške podzemne vode, vendar bi bile omejitve posameznih dejavnosti zaradi navzkrižnih interesov drugih uporabnikov prostora nesprejemljive.

V Sloveniji so obširne kraške pokrajine, predvsem visoke kraške planote, praviloma odročna območja, ki so zaradi reliefne razgibanosti in neugodnih klimatskih razmer manj privlačna za intenzivnejšo poselitev ter koncentracijo industrijskih, kmetijskih in drugih dejavnosti. To so navadno gozdnata območja ali območja, kjer prevladuje ekstenzivno kmetovanje.

Čeprav je kakovost kraških voda pri nas še razmeroma visoka, pa posamezni primeri onesnaženja kažejo na pomanjkljivosti upravljanja s pitno vodo tudi na območjih alpskega in dinarskega krasa. Takšna redko poseljena ali neposeljena območja so sicer z vidika varovanja zelo primerna, pomanjkljiva pa je predvsem zakonodaja na področju varovanja vodnih virov.

V primerjavi z razmerami na krasu po svetu in gosto naseljenimi nižinskimi območji Slovenije, kjer imamo pomembne zaloge podzemne vode v medzrnskih vodonosnikih, je mnogo kraških vodnih virov še vedno pomanjkljivo zaščitenih. Razlogi za to so kljub relativno ugodnim razmeram za varovanje v pomanjkanju znanja o trajnostnem ravnanju z vodnimi viri, navzkrižnih interesih različnih uporabnikov prostora in pogosto v neučinkovitem nadzoru nad kršitelji določil.

Izdelavo vodovarstvenih območij in režimov varovanja vodnih virov, ki se uporabljajo za javno oskrbo s pitno vodo, predvideva *Zakon o vodah* (Ur.l. RS 67/2002). Vodovarstvena območja v zaledju vodnega vira zahtevajo določene omejitve razvoja urbanizacije in dejavnosti, in predpisujejo primerno komunalno ureditev naselij, razvoj čiste obrti in industrije ter zmerno uporabo gnojil in drugih sredstev v kmetijstvu. Bližje izviru praviloma veljajo strožji varnostni ukrepi, kar pa za zaščito kraških vodonosnikov z drugačnim pretakanjem ni primerno.

Posebne značilnosti pretakanja voda v krasu v slovenski zakonodaji na splošno niso zadovoljivo upoštevane. Pogosto se vodovarstvena območja določajo na podlagi skopih hidroloških in geoloških podatkov, redko pa so bile v te namene opravljene raziskave načina napajanja, pretakanja, skladiščenja in praznjenja kraških vodonosnikov ter izvedeni sledilni poizkusi v zaledju vodnih virov, ker jih obstoječa zakonodaja ne predvideva. Neučinkovitost in nezadostnost zaščite kraških vodnih virov tako izhaja predvsem iz nepoznavanja specifičnih hidrogeoloških in drugih značilnosti heterogenih kraških vodonosnikov. Določanje obsega posameznih varstvenih pasov kraških vodnih virov največkrat ne upošteva občutljivosti krasa na onesnaženje (vloga zaščitnih slojev, razvitost kraške mreže, spreminjanje zaledja v različnih hidroloških situacijah, ipd.).

Poleg tega je trenutno stanje v Sloveniji na področju varovanja vodnih virov v precejšnji meri odraz prejšnje zakonodaje, ko so bili za določanje vodovarstvenih pasov zadolženi lokalni upravni organi. Zaradi navzkrižnih interesov so bila varstvena območja vodnih virov, katerih zaledja se raztezajo preko več občin ali celo preko državnih meja, pogosto omejena le na administrativna območja občin (primeri Rižane, Globočca idr.) ali pa odloki sploh niso bili sprejeti (primeri Malenščice, Hublja, Mrzleka idr.).

Dejstvo je, da imajo pomembnejši kraški vodni viri običajno veliko napajalno zaledje in je visoko stopnjo zaščite za celotno območje težko zahtevati. Takšno prostorsko načrtovanje tudi ne bi bilo praktično. Še več, na območjih z veliko tržno vrednostjo zemljišč, bi strogo omejevanje dejavnosti pripeljalo do kolizije interesov.

Zato v ospredje vse bolj stopa kartiranje in ocenjevanje naravne ranljivosti[*] kraških vodonosnikov oziroma vodnih virov in ocenjevanje tveganja za onesnaženje, ki se ponekod po svetu že uspešno uporablja pri določevanju vodovarstvenih pasov in načrtovanju rabe prostora na krasu. Na osnovi kart ranljivosti lahko pred pretiranim obremenjevanjem smiselno zavarujemo predvsem tista območja vodonosnikov, ki so najbolj občutljiva. Karte tveganja, ki izpostavljajo najvišjo doseženo stopnjo dosedanjih človeških vplivov na najbolj ranljivih območjih, preprečujejo postavitev novih onesnaževalcev v območja, kjer bi obremenjevanje preseglo naravne samočistilne sposobnosti.

14.2 NAMEN IN PRAKTIČNA VREDNOST RAZISKAVE

Koncept ocenjevanja ranljivosti in tveganja ponuja ravnotežje med varovanjem na eni strani ter prostorskim planiranjem in ekonomskimi interesi na drugi. Ocenjevanje naravne ranljivosti kraških vodonosnikov upošteva naravne značilnosti vodonosnika in je neodvisno od lastnosti in obnašanja posameznih onesnaževal. Temelji na oceni varovalne funkcije zaščitnih pokrovov, torej debeline in značilnosti prsti, sedimentov nad kraškimi kamninami ter nezasičene kraške cone. Za oceno naravne ranljivosti so ključnega pomena še stopnja koncentracije odtoka v podzemlje, razvitosti kraškega sistema in značilnosti infiltracije padavin (Vrba in Zaporozec, 1994; Zwahlen, 2004).

Končni rezultat ocenjevanja naravne ranljivosti kraške podzemne vode je karta, kjer so različne stopnje ranljivosti kraških voda na onesnaženje simbolično prikazane z različnimi barvami. Z identifikacijo najbolj ranljivih območij karte naravne ranljivosti ponujajo

- optimizacijo in zmanjšanje vodovarstvenih pasov,
- primerno in previdno upravljanje vodnih virov,
- podlago za načrtovanje monitoringa kakovosti podzemne vode.

Na najbolj ranljivih območjih naj bi veljali najstrožji ukrepi varovanja, najbolj škodljive človekove dejavnosti bi bile prepovedane.

Če takšne karte dopolnimo še s kartami, na katerih prikažemo potencialne in dejanske onesnaževalce kraške podzemne vode, lahko ocenimo tveganje posameznih človekovih aktivnosti, ki ga predstavljajo bodisi za podzemno vodo ali vodne vire (De Ketelaere in sod., 2004; Hötzl, 2004). Na ta način nam omogočajo

- celostno ovrednotenje dosedanjih človekovih vplivov in s tem
- identifikacijo območij z neustreznim upravljanjem, reorganizacijo rabe prostora in boljšo prakso v prihodnjem načrtovanju,
- podlago za različne presoje vplivov na okolje,
- lažje predvidevanje posledic in škode (ekološke in materialne) ob različnih onesnaženjih.

Tak koncept varovanja se zdi smiseln, saj preprečuje postavitev potencialnih ob-

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[*] v uporabi je tudi pojem **občutljivost kraškega vodonosnika**, ki označuje samočistilne sposobnosti kraškega okolja, neodvisne od lastnosti in obnašanja posameznih onesnaževal.

časnih in stalnih onesnaževalcev kraške podzemne vode v območja, kjer obremenjevanje že presega naravne samočistilne sposobnosti. Ocenimo lahko tudi tveganje posameznih človekovih aktivnosti v zaledju, ki ga predstavljajo za onesnaženje posameznega izvira ali vrtine. Območja z najvišjo stopnjo tveganja je potrebno nemudoma odstraniti in sanirati.

Predvsem za ocenjevanje in kartiranje naravne ranljivosti kraške podzemne vode so bile izdelane številne metode, ki so bile tudi večkrat uporabljene in preizkušene na različnih testnih poligonih po svetu.

Čeprav se zaledja posameznih vodnih virov močno razlikujejo med seboj celo v slovenskem prostoru, je z vidika načrtovanja in primerjave na državni ravni priporočljivo, da so za vse kraške vodne vire predpisana ista osnovna merila za določanje vodovarstvenih območij in rabe tal. Upoštevajoč razlike med posameznimi kraškimi vodonosnimi sistemi, razlike v dostopnosti podatkov in v ekonomskih zmožnostih, je namen raziskave izdelati metodo za ocenjevanje naravne ranljivosti in tveganja kraških vodnih virov za onesnaženje, prilagojeno slovenskim razmeram.

Predlagana metoda, tako imenovani Slovenski pristop, temelji na posebnostih slovenskega krasa in sledi tako evropski kot slovenski zakonodaji. Metodo smo uporabili na izbranem testnem območju, v zaledju kraških izvirov Podstenjška. Dobljene rezultate smo preverili s pomočjo dveh kombiniranih sledilnih poizkusov z različnimi umetnimi sledili. Izkazalo se je, da je bila aplikacija uspešna in rezultati kart naravne ranljivosti, obremenjevalcev in tveganja za onesnaženje v izbranem zaledju verodostojni.

Takšne karte imajo zelo veliko uporabno vrednost, saj odgovornim za odločanje o izrabi prostora hitro in jasno pokažejo, katera območja znotraj zaledja posameznega kraškega vodnega vira so primerna za določene človekove dejavnosti in katera območja so potrebna zaščite in do kakšne mere oziroma kako strogo, kar pa lahko pomeni tudi prepoved opravljanja določene dejavnosti. Nenazadnje lahko iz omenjenih kart predvidimo sanacijske ukrepe dejanskih onesnaževalcev ter skladno s tveganjem tudi določimo časovni načrt njihove izvedbe.

Karte ranljivosti in tveganja za onesnaženje podzemne vode so tako za državne in krajevne organe, odgovorne pri načrtovanju in odločanju o rabi prostora na kraških območjih koristna osnova pri njihovih odločitvah. Ker se je pokazalo, da Slovenski pristop podaja verodostojne izsledke, ker je celovito zasnovan in kot edina izmed obstoječih metod za ocenjevanje ranljivosti in tveganja upošteva posebnosti slovenskega krasa ter pretakanje voda v različnih hidroloških situacijah, bi lahko bil kot dopolnilo vključen v obstoječo slovensko zakonodajo na področju varovanja kraških vodnih virov in načrtovanju rabe prostora na krasu.

14.3 IZHODIŠČE ZA RAZVOJ SLOVENSKEGA PRISTOPA

Izdelane so bile že številne metode za kartiranja ranljivosti in tveganja podzemne vode za onesnaženje. Razlike med njimi se pojavljajo predvsem v izbiri ključnih parametrov, načinu uteževanja in izračunu končne ocene. Med različnimi metodami lahko izbiramo glede na želeni namen prikazovanja stanja, različnih možnosti dostopanja do podatkov in ekonomskih zmožnosti ter razlik med posameznimi kraškimi vodonosnimi sistemi. Številne raziskave, med njimi tudi ta študija (poglavje 10), pa so pokazale, da so rezultati različnih metod za kartiranje naravne ranljivosti, apliciranih na istem območju, z uporabo iste podatkovne baze, lahko drugačni ali so si celo nasprotujoči. Tako se postavlja vprašanje, katera od metod da najbolj zanesljive rezultate.

Iz teh razlogov se je pokazala potreba po pripravi enotnega teoretičnega okvira, t.i. Evropskega pristopa h kartiranju ranljivosti, obremenjevalcev in tveganja podzemne vode na onesnaženje. Osnovne smernice so bile predlagane v okviru evropskega projekta *COST 620-Vulnerability and risk mapping for the protection of carbonate (karst) aquifers* (Zwahlen, 2004).

V Sloveniji so izkušnje pri aplikaciji različnih metod kartiranja ranljivosti kraških vodonosnikov zelo skromne. Do sedaj sta bili opravljeni le dve študiji kartiranja naravne ranljivosti v zaledjih kraških vodnih virov, medtem ko so bile študije dejanskih in potencialnih onesnaževalcev ter tveganja opravljene le v nekaterih projektih. V zaledju izvira Rižane je bilo s pomočjo metode SINTACS določenih šest različnih območij naravne ranljivosti (Janža in Prestor, 2002). Karte naravne ranljivosti so bile na območju občine Postojna določene s pomočjo metode EPIK, dopolnjene s kartami obremenjenosti in tveganja na onesnaženje ter strokovnimi podlagami za varovanje lokalnih kraških vodnih virov (Petrič, 2002b; Petrič in Šebela, 2004). Pregled dejanskih in potencialnih obremenjevalcev kraške vode na različnih vodonosnikih sta pripravila Kovačič in Ravbar (2005a).

Vendar pa bi pri neposredni aplikaciji posameznih metod ocenjevanja naravne ranljivosti na slovenski kras lahko naleteli na številne metodološke težave, ki izhajajo predvsem iz posebnosti slovenskega krasa, izbire in uteževanja ključnih parametrov ter načina izračunavanja končne ocene ranljivosti posameznih metod.

Težave pri kartiranju ranljivosti in tveganja pri nas povzroča tudi pomanjkanje ustreznih in reprezentativnih podatkov, ki so osnova za relevantno oceno samočistilnih sposobnosti kraških voda in dejansko onesnaževanje.

Na slovenskem krasu je zaščitna plast prsti, sedimentov in vegetacije zelo tanka, ponekod pa je sploh ni. Odsotnost debelejšega zaščitnega sloja pospešuje odtok vode v podzemlje. Zato onesnaževala ob prenikanju nimajo nobenega naravnega filtra, da bi se kemično, biološko in fizikalno očistila.

Pri aplikaciji mnogih metod za ocenjevanje naravne ranljivosti bi zaradi splošne odsotnosti zaščitnih slojev na končno vrednost varovalne funkcije vodonosnika vplivala predvsem debelina nezasičene cone. Ta pa še posebej na območju visokih kraških planot in alpskega krasa sega več sto metrov in je lahko celo debelejša od 1500 m. Pri uporabi nekaterih v Evropi večkrat uporabljenih metod bi bila na takšnih območjih stopnja ranljivosti ocenjena kot »zmerna«, ne da bi odrazila razlike v ranljivosti znotraj samega vodonosnika.

Različne metode kartiranja notranje ranljivosti tudi ne ponujajo zadovoljivih rešitev v primerih ogromnega nihanja gladine podzemne vode, ki so v nekaterih slovenskih kraških pokrajinah zelo izrazite. V odvisnosti od trenutnih hidroloških pogojev se lahko stopnja ranljivosti močno razlikuje, saj prihaja do več deset ali celo stometrskih razlik v debelini nezasičene cone. Na takšnih območjih pa je pogosto spreminjanje obsega prispevnih zaledij, menjavanje podzemnega in površinskega odtekanja, pojavljajo se občasni izviri, vodotoki in ponori ter presihajoča jezera (Sl. 6.1 in 6.2).

Obstoječe metode nezadovoljivo obravnavajo vprašanje ovrednotenja stopnje ranljivosti ponikajočih vodnih teles (rek ali jezer) in njihovih prispevnih območij. Več kilometrov dolge reke ponikalnice oziroma velika presihajoča jezera imajo namreč obsežna hidrografska zaledja (Sl. 7.7). Ker gre za neposredno infiltracijo površinske tekoče vode v kraški vodonosnik večina metod celotna zaledja razvršča v razred najvišje ranljivosti. Pri tem pa ni zadovoljivo upoštevano, da imajo površinski vodotoki dosti višjo stopnjo samoočiščenja in da je v nekaterih primerih onesnaženja onesnaževalom mogoče tudi preprečiti odtok v podzemlje.

V nasprotju z evropskimi smernicami, ki si prizadevajo predvsem za zaščito podzemne vode, slovenska zakonodaja predvideva varovanje vodnih virov (izvira ali vrtine). Po priporočilih Evropskega pristopa v prvem primeru upoštevamo izključno vertikalno pot prenikajoče vode do gladine podzemne vode, medtem ko v primeru varovanja posameznega vodnega vira upoštevamo dodatni parameter, ki opisuje način pretakanja voda in v njej topnih snovi v zasičeni coni vse do cilja (Goldscheider in Popescu, 2004). Večina metod kartiranja ranljivosti ni prilagojena za ocenjevanje ranljivosti vodnih virov.

Na obsežnih kraških območjih, ki so hidravlično povezana na dolge razdalje, in kjer pogosto prihaja do križanja poti kraške podzemne vode, se lahko prekrivajo tudi prispevna zaledja več kraških izvirov (Sl. 2.8). Da bi vzpostavili prednostne ukrepe pri varovanju in odpravljanju morebitnega onesnaženja, je potrebno ovrednotiti posamezne vodne vire glede na njihovo ekonomsko, socialno in ekološko vrednost ter pripraviti možnost integracije v obstoječo shemo ocenjevanja tveganja.

V okviru Evropskega pristopa so navodila za celovito oceno dosežene stopnje onesnaženja pomanjkljiva, neizdelan pa je tudi končni izračun tveganja za onesnaženje ter proces validacije končnih rezultatov.

V okviru te raziskave smo predlagali izpopolnjeno metodo za ocenjevanje naravne ranljivosti in tveganja za onesnaženje, prilagojeno posebnostim slovenskega krasa. Tako imenovani Slovenski pristop ustreza slovenski okoljski zakonodaji in omogoča primerjavo z razmerami v Evropi. Zasnova Slovenskega pristopa v veliki meri sledi smernicam, predstavljenim v Evropskem pristopu.

Vključuje močno spremenjeno metodo COP za kartiranje naravne ranljivosti podzemne vode, ki po novem ponuja možnost upoštevanja časovne hidrološke spremenljivosti, povezovanja zaščite površinskih in podzemnih voda ter je prilagojena za kartiranje ranljivosti vodnih virov. Slovenski pristop predvideva tudi obširno analizo tveganja, ki temelji na oceni naravne ranljivosti, dejanskih in potencialnih obremenjevalcev ter pomembnosti vodnega vira oziroma podzemne vode.

14.4 OCENJEVANJE NARAVNE RANLJIVOSTI

Med številnimi v Evropi uveljavljenimi in mnogokrat preizkušenimi metodami kartiranja naravne ranljivosti smo izbrali najbolj primerno za razmere na slovenskem krasu, metodo COP. V določenih podrobnostih ovrednotenja posameznih parametrov smo jo spremenili, dopolnili ali prilagodili razmeram pri nas. Pri tem smo se v veliki meri osredotočili na posebne značilnosti slovenskega krasa in slovenske zakonodaje na področju varovanja voda. Spremembe posameznih faktorjev se nanašajo na Sl. 5.7 in 7.12.

14.4.1 *Vrednotenje zaščitne funkcije*

Medtem ko se infiltrirana voda in onesnaževala precejajo skozi prsteni pokrov in kamnino v nezasičeni coni, so onesnaževala izpostavljena mehaničnim, fizikalno-kemičnim in mikrobiološkim procesom, ki močno vplivajo na njihovo degradacijo. Učinkovitost teh procesov pa je v veliki meri pogojena z zadrževalnim časom prenikajoče vode v prsti in kamnini. Daljši kot je zadrževalni čas, dlje so onesnaževala izpostavljena razgradnji in absorpcijskim procesom. V najbolj ugodnih razmerah onesnaženje niti v daljšem časovnem obdobju ne doseže podzemne vode.

Ocenjevanje zaščitne vloge prsti po metodi COP temelji na teksturi in debelini prsti. Toda na zadrževalni čas prenikajoče vode (in onesnaževal) v prsti pomembno vpliva tudi struktura prsti, to je prisotnost razpok, agregatov, mišjih lukenj, idr. Posledično lahko te makro-pore odločilno vplivajo na infiltracijo padavinske vode in tako omogočijo obitje prstenega pokrova. Zato menimo, da je potrebno zaščitno vlogo prsti oceniti na osnovi njene debeline, teksture in strukture.

Zaradi majhne velikosti delcev imajo glinene prsti nizko poroznost, kar je ugodno za zaščito spodaj ležečih plasti. Vendar so predvsem suhe glinene prsti lahko visoko prepustne zaradi razpok in prednostnih vodnih poti in imajo tako nizko eFC (efektivna poljska kapaciteta), kar pa ni ugodno z vidika varovanja.

Nasprotno pa so meljaste in ilovnate prsti bolj porozne, vendar imajo višjo eFC, kar nudi višjo zaščito. Peščene prsti so zelo prepustne, vendar imajo nizek eFC, kar ni ugodno za zaščito. Končno smo različne vrste prsti razporedili v dva razreda; ilovnate in meljaste kot bolj varovalne ter glinaste in peščene kot manj varovalne.

Vprašanje pa se postavlja pri vrednotenju debeline prsti na krasu, saj se te lahko pojavljajo le mestoma in v žepih različnih debelin. V takšnih primerih je interpolacija podatkov lahko zavajajoča in celo napačna. Zato priporočamo ocenitev efektivne debeline prsti, ki nam pove, koliko časa bo deževnica potovala skozi prst, preden se infiltrira v matično kamnino (Sl. 7.3). Kjer se pojavljajo globoki žepi prsti med vmesnimi stožci škrapelj, se deževnica verjetno ne bo infiltrirala v kamnino takoj na površju, v nasprotju z obsežnim škrapljiščem, kjer je stik deževnice s kamnino praktično takojšen.

Zaradi splošne odsotnosti prsti in sedimentnega pokrova na slovenskem krasu bi bila vrednost parametra O v veliki meri odvisna od zakraselosti nezasičene cone. Vendar bi zaradi njene razmeroma velike debeline aplikacija metode COP na slovenskem krasu pogosto izražala nizke oziroma zmerne zaščitne vrednosti območij, celo na zelo zakraselih območjih škrapelj, povezanih z globokimi brezni (na primer Kaninski podi, Kriški podi, Rombonski podi v Alpah in Ždrocle na Snežniku, idr., sl. 7.4), kar verjetno ni upravičeno.

Predlagamo manjšo spremembo pod-faktorja ly, v katerega bi uvedli dodatno vrednost za opisana zelo zakrasela območja. Metoda PI za takšna območja predvideva vrednost nič, kar pa vodi v ogromna območja nizkih zaščitnih vrednosti (Andreo s sod., 2006). To se je izkazalo za slabo rešitev predvsem z vidika načrtovanja. Kot kompromisno vrednost zato predlagamo vrednost 0,2, da bodo takšna območja označena z zelo visoko ali visoko stopnjo ranljivosti.

14.4.2 *Vključitev hidrološke spremenljivosti ter zaščita površinskih voda*

V Sloveniji so za nekatera kraška območja značilna pogosta in velika nihanja podzemne vode ter menjavanje površinskega in podzemnega odtoka. Nihanje podzemne vode se lahko spreminja za več deset in celo več sto metrov v zelo kratkem času. Toda, periodičnost takšnih nihanj je neznačilna, saj je močno odvisno od trenutnih meteoroloških dejavnikov (tipa, količine, intenzivnosti in razporeditve padavin ter dejavnikov, ki vplivajo na taljenje snega, kot sta temperatura in veter) ter drugih hidrogeoloških dejavnikov (velikost in povezanost kraških kanalov). Posledično na kraških poljih ali območjih plitvega krasa prihaja do spreminjanja podzemnih vodnih poti, presihajočih rek in jezer, občasno delujočih izvirov, ponorov in estavel (Ravbar in Goldscheider, 2006).

Metoda COP označuje ponore in ponikalnice kot območja zelo visoke ranljivosti. Vendar pa mnogi primeri iz slovenskega krasa in drugod kažejo, da so nekateri ponori pogosto ali stalno aktivni, medtem ko drugi funkcionirajo le občasno (Sl. 7.5), ob izrednih hidroloških dogodkih, včasih tudi manj kot enkrat na leto.

Opisana hidrološka spremenljivost pa lahko izrazito vpliva na transport onesnaževal in na ocenjevanje ranljivosti podzemne vode. Le v primeru stalnega odtoka v podzemlje bo onesnaženje vedno in hitro doseglo podzemno vodo brez efektivnejše razgradnje. Nasprotno, v primeru občasno ponikajočih vodnih teles in ponorov ni nujno, da onesnaženje vedno doseže kraško podzemno vodo. Tako se lahko stopnja ranljivosti tudi drastično spreminja v odvisnosti od posameznih hidroloških pogojev.

Čeprav je splošno priznano, da opisane hidrološke spremembe vplivajo na transport onesnaževal, pa obstoječa metoda COP in druge metode ne predvidevajo zadovoljive rešitve in vključevanje hidrološke spremenljivosti pri ocenjevanju ranljivosti.

V okviru Slovenskega pristopa smo prvi ponudili možnost upoštevanja časovne hidrološke spremenljivosti in v kartiranje ranljivosti vpeljali nov pod-faktor, ki opisuje aktivnost ponorov in ponikajočih vodnih teles (pogostnost in trajanje). Vodotoki in ponori, ki so aktivni bolj pogosto (≥ 100 dni/leto) so označeni kot bolj ranljivi kot tisti, ki so aktivni le občasno (< 10 dni/leto).

Velika hidrološka spremenljivost se kaže tudi v spremenljivi debelini nezasičene cone. Dvigajoča se gladina podzemne vode pomeni tanjšanje nezasičene cone, torej zmanjševanje zaščite oziroma naraščanje stopnje ranljivosti. Spreminjajoča se gladina podzemne vode pa v nekaterih primerih pomeni tudi razlike v načinu pretakanja, spreminjanje položaja razvodnice ter drugačne pogoje površinskega in podzemnega pretakanja.

Večina obstoječih metod prednostno upošteva »povprečne neugodne razmere« hidrološkega leta in nezadostno rešuje to vprašanje. Seveda so podatki o nihanju gladine podzemne vode znotraj kraškega sistema zelo težko dostopni in največkrat niso na razpolago. Poleg tega na splošno velja, da je stopnja zaščite nezasičene cone v izredno zakraselih območjih precej nizka. Spremenljivost njene debeline bi posledično imela omejen vpliv na ranljivost.

Zato je v večini primerov za ocenjevanje ranljivosti podzemne vode priporočljivo upoštevati povprečno višino podzemne vode. Po drugi strani pa spreminjanje gladine podzemne vode lahko pomeni spreminjanje razsežnosti zaledja, kar pa je ključnega pomena pri kartiranju ranljivosti vodnega vira. Predloge rešitev smo predstavili v poglavjih 7.5 oziroma 14.4.5.

Če hočemo obravnavati ranljivost kraškega hidrološkega sistema v celoti, moramo upoštevati tudi ranljivost ponikajočih vodotokov in njihovih zaledij. V nasprotju z razpršeno infiltracijo padavin imajo alogeni dotoki vode v podzemlje navadno neposreden stik s podzemno vodo in na svoji poti obidejo zaščitno plast prsti in sedimentov. Zato onesnažene ponikalnice še posebej ogrožajo kakovost podzemne vode.

Po priporočilih metode COP (in mnogih drugih metod) je celotna mreža vodotokov, ki ponikajo v kras, ocenjena kot ekstremno ranljiva. Vendar se postavlja vprašanje, kako ovrednotiti vodna telesa večjih razsežnosti (na primer več kilometrov dolge ponikalnice in njihove pritoke, velika jezera), ki se pogosto pojavljajo v slovenskih kraških pokrajinah (Temenica, Reka, Cerkniško jezero).

Sledeč konceptu, v okviru katerega so ponori in ponikajoči vodotoki najbolj ranljiva območja, bi bilo potrebno v opisanih primerih ogromna območja zaščititi po najstrožjih standardih. Toda, ali so res vsa ta območja zelo ranljiva? Upoštevati je namreč potrebno, da imajo površinski vodotoki na splošno višjo samočistilno sposobnost od podzemnih voda in preden poniknejo, je na razpolago tudi čas za intervencijo in morebitno sanacijo onesnaženja.

Zato priporočamo, da se pri kartiranju ranljivosti združi smernice za varovanje površinske in podzemne vode in se 5 km od ponora gorvodno pripiše vodotokom in njihovim zaledjem nižjo stopnjo ranljivosti. Poleg tega pa se nam zdijo razredi rangiranja oddaljenosti od ponora v okviru obstoječe metode COP preveliki. Ponori so tako obkroženi z ogromnimi območji zelo visoke ranljivosti, kar pa ni vedno upravičeno. Predlagamo radikalnejšo rešitev in razdelitev razredov na 10, 100, 500, 1000 in 5000 m razdalje od ponora.

14.4.3 *Vrednotenje nagnjenosti površja in vegetacijskega pokrova*

Na intenzivnost, koncentracijo in hitrost infiltracije vode v podzemlje, poleg nagnjenosti površja in vegetacijskega pokrova bistveno vpliva način odtoka. Zato Slovenski pristop v nasprotju z metodo COP pri ocenjevanju ranljivosti poleg nagnjenosti površja in vegetacijskega pokrova upošteva tudi način odtoka v podzemlje. Še več, ta odločilno vpliva na končno vrednotenje ranljivosti.

Vključitev procesov pretakanja temelji na prepustnosti površinskih plasti. Neposredna infiltracija je pričakovana na visoko prepustnih plasteh, medtem ko je (pod)površinsko odtekanje pričakovati na območju manj prepustnih in nepropustnih plasti. Poleg tega je na območju (pod)površinskega odtoka tok bolj koncentriran, kar posledično zmanjšuje naravno zaščito.

Kar se tiče metode COP, se ne strinjamo z načinom vrednotenja nagnjenosti površja in zaščitne vloge vegetacijskega pokrova. V okviru 2. scenarija so območja s strmejšimi pobočji in z redko vegetacijo ovrednotena kot bolj varovalna. Nasprotno pa Slovenski pristop ocenjuje, da strmejša pobočja in redkejši vegetacijski pokrov pomenita višjo stopnjo ranljivosti ne glede na način odtoka. Razlika v vrednotenju nagnjenosti površja in zaščitni vlogi vegetacije je pri direktni infiltraciji nepomembna, medtem ko pomembno vpliva na končno ranljivost na območjih s (pod)površinskim odtokom. Zmanjšali smo tudi število razredov nagnjenosti površja.

Poleg tega smo izpopolnili definicijo vegetacijskega pokrova, ki je v obstoječi COP metodi nezadovoljiva. Ločimo med redkejšim in gostejšim vegetacijskim pokrovom. Prva obsega gola območja, območja z malo vegetacije, obdelana območja (njive, sadovnjaki, travniki in pašniki) in pozidana območja, kjer je zaščitna plast zelo redka ali celo odsotna ali jih človek izkorišča za svoje dejavnosti. Območja z gosto vegetacijo so gozdnata in grmovnata območja ter območja v zaraščanju, kjer vegetacija nudi zaščito podzemni vodi pred onesnaženjem, saj pripomore k počasnejši infiltraciji in počasnejšemu površinskemu odtoku.

14.4.4 *Padavinski režim*

Način ocenjevanja faktorja P je bil v celoti preoblikovan iz različnih razlogov. Predvsem se ne strinjamo s trditvijo avtorjev (Vías in sod., 2002), da naraščanje padavin do meje 1200 mm/leto pomeni krajše zadrževalne čase v podzemlju, kar naj bi povečevalo stopnjo ranljivosti. Vías in sod. (2002) še trdijo, da količina padavin, večja od 1200 mm/leto, pomeni večjo stopnjo redčenja in tako nižjo stopnjo ranljivosti. Trditev, da je omenjena količina meja, nad katero je redčenje dominanten proces, ni zadovoljivo teoretično podprta.

Vprašanje je, ali je omenjena meja 800-1200 mm/leto res najbolj nevarna količina padavin, medtem ko sta nižja in višja količina bolj ugodni za zaščito podzemne vode. Namreč, višja kot je količina padavin, višje so hitrosti pretakanja voda, krajši so zadrževalni časi, podzemni tok je bolj turbulenten in zato transport in mobilizacija netopnih snovi in bakterij bolj efektivna, več je površinskega odtoka in koncentrirane infiltracije.

Kot alternativo predlagamo nov P faktor, ki upošteva količino in intenzivnost padavin. Na podlagi 30-letnega obdobja ovrednotimo deževne dni in nevihtne dogodke. Za vrednotenje prvih upoštevamo število dni, ko je količina dežja med 20 in 80 mm/dan, za druge pa število dni, ko količina dežja presega 80 mm/dan. Končna vrednost je zmnožek obeh pod-faktorjev.

14.5 OCENJEVANJE RANLJIVOSTI VODNIH VIROV

Da bi prilagodili obstoječe metode za ocenjevanje naravne ranljivosti podzemne vode za ocenjevanje ranljivosti vodnih virov, je po priporočilih Evropskega pristopa (Goldscheider in Popescu, 2004) poleg poti skozi nezasičeno cono potrebno upoštevati dodatni parameter, ki opisuje način pretakanja voda in v njej topnih snovi v zasičeni coni vse do vodnega vira (izvira ali vrtine; Sl. 5.6).

14.5.1 *Razvoj kraškega sistema (K faktor)*

Ker kraški drenažni sistemi in podzemne vodne poti v zasičeni coni pogosto niso znane, je njihovo detajlno kartiranje nemogoče. Klasifikacija stopnje zakraselosti nekega vodonosnika, upoštevajoč posredne kazalce, pa je lahko pogosto zelo subjektivna, saj je zakraselost težko izmeriti.

Zelo pomemben element pri ocenjevanju ranljivosti vodnega vira je razmejitev zaledja, saj so ta pogosto zelo razsežna in hidravlično povezana na dolge razdalje. Razvodnice je zaradi velike spremenljivosti s časom zelo težko določiti in navadno se prekrivajo (Sl. 7.11).

Če želimo ovrednotiti razvitost in razsežnost kraškega sistema, moramo najti odgovore na vprašanja (Brouyère, 2004; Daly in sod., 2004; Sl. 5.1):

- po kolikšnem času bo onesnaževalo prispelo do izvira (v dnevih, tednih ali mesecih),
- kolikšen delež onesnaževala bo prispel do izvira (le nekaj sledov, 1%, 10% ali vse) in
- koliko časa bo trajalo onesnaženje.

Tako predlagamo, da za ocenitev faktorja K upoštevamo navidezne podzemne hitrosti pretakanja voda, povezave, prispevnost ter zanesljive informacije o mreži kanalov z aktivnim vodnim pretakanjem. Vrednotenje naj temelji na ocenjevanju treh pod-faktorjev:

Pod-faktor t izraža hitrosti pretakanja voda in posredno hidravlično obnašanje vodonosnika. Ekstenzivno razvita mreža kraških kanalov, ki ni najbolj efektivna v prevajanju vode proti izvirom, se odraža v daljših zadrževalnih časih in zato manjšem območju visoke ranljivosti in obratno.

Pod-faktor n označuje prisotnost aktivnih vodnih kanalov. Kjer je zanesljiva informacija na razpolago, je potrebno območju nad podzemnim odtokom pripisati višjo stopnjo ranljivosti (Sl. 7.9).

Pod-faktor r označuje povezavo in prispevnost določenih območij z izvirom. Tako imenovano notranje območje predstavlja dele vodonosnika, ki vedno in v veliki večini prispevajo k izviru, hitrosti pretakanja voda pa so visoke. Zato so takšna območja označena kot visoko ranljiva. Po drugi strani pa zunanje območje obsega dele vodonosnika, ki prispevajo k izviru v majhnih deležih, območja, ki so oddaljena in kjer so potovalni časi do izvira nizki. Zunanje območje lahko obsegajo tudi deli vodonosnika, ki se le občasno drenirajo k proučevanim izvirom, območja, ki so posredno povezana z izvirom ali za katere nismo prepričani, da prispevajo k izvirom (Sl. 7.10).

Končna vrednost je zmnožek vseh treh pod-faktorjev, razdeljena v tri razrede ranljivosti.

14.5.2 *Določevanje vodovarstvenih območij*

V okviru predlaganega Slovenskega pristopa dobimo ranljivost vodnih virov z združitvijo ranljivosti podzemne vode in faktorja K (Sl. 7.12). Končne vrednosti so razdeljene v tri razrede ranljivosti, ki jih lahko pretvorimo v vodovarstvena območja. Na najbolj ranljivih območjih naj veljajo najbolj strogi režimi varovanja.

14.6 ANALIZA TVEGANJA

V nekaterih državah predstavlja koncept ocenjevanja ranljivosti temelj za ohranjevanje zadovoljive kakovosti voda. Vendar pa ranljivost ni vedno zadovoljiv kriterij za primerno načrtovanje rabe tal na krasu, saj karte naravne ranljivosti navadno izražajo značilnosti vodonosnih sistemov ne glede na lastnosti onesnaževal. Hkrati tudi ne prikazujejo, do kolikšne mere je vodonosnik že pod pritiskom antropogenih dejavnosti.

Zato so potrebne informacije o dejanskih in potencialnih onesnaževalcih, verjetnosti, da bo prišlo do onesnaženja in pomembnosti oziroma vrednosti podzemne vode ali vodnega vira, da bi lahko omogočili primerno upravljanje in varovanje. V veljavo vse bolj stopa kartiranje specifične ranljivosti, obremenjevalcev in tveganja.

Evropski pristop predlaga celostno ocenjevanje tveganja, ki temelji na ocenjevanju naravne ali specifične ranljivosti in obremenjevalcev. Hkrati pa poudarja, da bi bilo potrebno upoštevati tudi pomembnost podzemne vode ali vodnega vira (Hötzl, 2004).

14.6.1 *Ocenjevanje dejanskih in potencialnih obremenjevalcev*

V predlaganem Slovenskem pristopu se pri ocenjevanju dejanskih in potencialnih obremenjevalcev opiramo predvsem na Evropski pristop, ki za vsako antropogeno dejavnost upošteva njeno stopnjo škodljivosti za vode. Vsakemu onesnaževalcu je pripisana določena vrednost glede na kvalitativno primerjavo potencialne škode (Sl. 8.1). Glavni kriterij za vrednotenje predstavlja toksičnost substanc, povezanih z vsako vrsto obremenjevalcev, ter njihova topnost in mobilnost. Za primerjavo znotraj ene vrste obremenjevalcev pa se predvideva proces rangiranja (De Ketelaere in sod., 2004).

Za slovenske razmere smo v okviru Slovenskega pristopa pripravili proces rangiranja najbolj pogostih dejavnosti (Sl. 8.2). Predlagani razredi so v glavnem razporejeni glede na stopnjo strupenosti substanc, povezanih z vsako vrsto obremenjevalcev, časom izpostavljanja obremenjevanju ali glede na količino oziroma velikost onesnaževalca.

Pri ocenjevanju obremenjevalcev se po priporočilih Evropskega pristopa upošteva še verjetnost onesnaženja, na kar vpliva tehnični status, stopnja vzdrževanja, varnostne razmere in druge okoliščine. Končna ocena obremenjevanja je zmnožek vseh treh pod-faktorjev, razdeljenih v šest razredov.

14.6.2 *Pomembnost podzemne vode ali vodnega vira*

Glede na priporočila Evropskega pristopa je za celovito oceno tveganja poleg značilnosti vodonosnika in onesnaževalcev ob morebitnih nesrečah potrebno izdelati tudi stroškovno oceno škode z ekološkega, socialnega in ekonomskega vidika (Hötzl in sod., 2004), ki je v največji meri odvisna od pomena vodnega telesa. Na podlagi ocene pomembnosti podzemne vode oziroma vodnega vira lahko ob različnih onesnaženjih lažje predvidimo ekološko in materialno škodo ter posledice, izdelamo prednostno listo preprečevalnih in varnostnih ukrepov ter postopkov v primeru onesnaženja.

Upoštevajoč slovenske razmere smo v okviru Slovenskega pristopa pripravili načrt ocenjevanja pomena podzemne vode ali vodnega vira, ki vključuje družbeni pomen (javna korist), gospodarski pomen bodisi za kmetijstvo ali druge dejavnosti ter ekološki pomen. Ocena pomembnosti vključuje štiri pod-faktorje.

Družbeni pomen izraža **pod-faktor si** in je ovrednoten na podlagi števila ljudi, ki jih vodni vir oskrbuje. Gospodarski pomen izraža **pod-faktor agri**, ki ga ovrednotimo na podlagi kmetijske intenzivnosti na območju, ki ga vodni vir oskrbuje (GVŽ/ha obdelane zemlje ali intenzivnost namakanja). Gospodarski pomen pa se odraža tudi v **pod-faktorju acti**, ki ga ovrednotimo na podlagi povprečne letne porabe vode. Ekološki pomen vrednotimo s **pod-faktorjem bi,** na podlagi biotske raznovrstnosti oziroma na podlagi ocene vodnega vira kot posebej dragocenega ekosistema.

Vrednosti pod-faktorjev, razen ekološkega, razlikujemo s funkcijo vodnega vira, glede na to, ali je:

- edini in nenadomestljiv vodni vir – ni gospodarnih ali tehnoloških možnosti pridobitve alternativnega vodnega vira,
- dodaten, dopolnilen vodni vir – vodni vir občasno v uporabi ali vodni vir, ki pokriva le del potreb po vodooskrbi,
- vodni vir ni v uporabi, brez javne koristi.

Končna vrednost je seštevek vseh pod-faktorjev, uteženih z ustrezno funkcijo uporabnosti in razdeljen v tri razrede pomembnosti (Sl. 8.4).

14.6.3 *Ocenjevanje tveganja za onesnaženje vodnega telesa*

Ocena tveganja za onesnaženje vodnega telesa identificira obstoječe in potencialne onesnaževalce, ki so potrebni obravnave, da bi zagotovili zadovoljivo varovanje voda (Daly in sod., 2004). Območja, označena z visokim tveganjem, zahtevajo takojšnje ukrepanje, bodisi z izboljšanjem razmer, odstranitvijo ali prilagajanjem obstoječih dejavnosti.

Intenzivnost tveganja nam posreduje pregled, na katerih območjih je velika verjetnost, da se bo onesnaženje pojavilo, in predvideva, kje bodo samoočiščevalni procesi učinkovito zmanjšali oziroma izničili onesnaženje. Hkrati izraža delež onesnaženja, ki bo dosegel podzemno vodo ali se pojavil na izvirih. Intenzivnost tveganja ocenimo na podlagi ocene naravne ranljivosti in obremenjevalcev (Hötzl, 2004).

Ob dodatnem upoštevanju pomena podzemne vode ali vodnega vira lahko ovrednotimo socialno, gospodarsko in ekološko škodo ob morebitnem onesnaženju. Na ta način ocenimo celotno tveganje za onesnaženje, ki lahko služi kot primerna podlaga za ustrezno upravljanje voda na krasu. Ocena celotnega tveganja je uporabna tudi pri vprašanjih povezanih z varovanjem kraških voda ter prostorskim planiranjem. Uporablja se lahko kot pomoč pri preprečevanju onesnaževanja.

14.7 APLIKACIJA NA PRIMERU IZVIROV PODSTENJŠKA

Slovenski pristop je bil prvič apliciran v zaledju vodnega vira Podstenjšek. Aplikacija je omogočila izpopolnjevanje in preizkus veljavnosti metode.

Podstenjšek izvira v petih manjših stalnih izvirih pri vasi Šembije pod Snežniško planoto v jugozahodni Sloveniji in se po treh kilometrih površinskega toka izliva v Reko. Eden izmed izvirov je od leta 1992 zajet za lokalno vodooskrbo (Sl. 11.1). Skupno oskrbuje 379 prebivalcev iz petih vasi.

14.7.1 *Naravne značilnosti zaledja*

Določitev zaledja vodnega vira temelji na podlagi poznavanja geoloških razmer, geomorfoloških opazovanj, izračunu vodne bilance, analize hidrografov in glede na rezultate, dosežene z opravljenimi sledilnimi poizkusi (Sl. 9.22).

Hidrografsko zaledje izvirov obsega 9,1 km^2 na jugozahodnem območju Zgornje Pivke, kjer skrajna severozahodna pobočja Snežnika prehajajo v dolino reke Reke. Obsega zakrasele paleocenske ter spodnjekredne apnence, dolomite in apnence in dolomitne breče cenomanijske starosti, ki so narinjeni na nepropustne eocenske flišne plasti.

Flišna zapora v podlagi narivnega območja preprečuje podzemni odtok kraške vode proti Reki. Le lokalno so na območju Podstenjška spodaj ležeče flišne kamnine prekinjene in del voda izvira kot Podstenjšek (Krivic in sod., 1983). Izviri se pojavljajo na stiku dveh geoloških enot, to je ob narivu spodnjekrednih apnencev na paleocenske plasti apnencev in na nepropustne eocenske flišne plasti. Na območju Šembijskega jezera in Narič apnence prekrivajo različno debeli kvartarni aluvialni nanosi, v suhi dolini Kamenščina pa se mestoma pojavljajo pleistocenski periglacialni sedimenti (Sl. 9.28).

Spodaj ležeče flišne kamnine vplivajo na obstoj plitvega kraškega vodonosnika, kar ob izjemno visokih vodah omogoča dvig kraške podzemne vode na površje in pojavljanje presihajočih jezer. Natančnih podatkov o gladini podzemne vode ni, vendar lahko iz opazovanj v Kozji luknji in občasnega Šembijskega jezera sklepamo na domnevne višine podzemne vode v različnih hidroloških stanjih (Sl. 9.3).

Ob nizkem vodostaju podzemna voda izvira v stalnih izvirih na nadmorski višini 510 m. Po intenzivnejšem deževju in/ali taljenju snega lahko naraste za 35 m, ko postane aktiven tudi občasni izvir iz Kozje luknje. Presihajoči jezeri Šembijsko jezero in Nariče z dni na nadmorskih višinah 559 in 571 m se napolnita z vodo, kadar je gladina podzemne vode dovolj visoko. Nižje ležeče Šembijsko jezero se pojavi približno vsaki dve leti, Nariče pa se je do sedaj pojavilo le dvakrat v zadnjih stotih letih. V Šembijskem jezeru gladina vode lahko naraste tudi za 11 m (Kovačič in Habič, 2005), medtem ko je v sušnem obdobju podzemna voda na nadmorski višini med 540 in 545 m (Krivic in sod., 1983).

Na obravnavanem območju letno pade med 1500 in 1600 mm padavin. Padavine so preko leta dokaj enakomerno porazdeljene in praktično noben mesec ni klimatsko sušen. Padavinski režim je submediteranski, saj je prvi višek padavin v jesenskih mesecih (novembra), kar je odraz morskih vplivov. Zaradi celinskih vplivov pa je na prehodu med pomladjo in poletjem (junija) opazen drugi, neizrazit padavinski višek. Najmanj padavin pade februarja, sekundarni nižek pa je meseca julija (Klimatografija Slovenije, Količina padavin, 1995; MOP ARSO, 2007).

Obravnavano območje pokrivata rjava pokarbonatna prst in rendzina (Pedologic map, 1988). Globina prsti se na razgibanem kraškem površju spreminja na kratke razdalje. Najdebelejše plasti prsti se nahajajo v konkavnih reliefnih oblikah, kjer dosežejo globino prek 1 m, medtem ko je ostalo površje precej kamnito, debelina prsti pa sega od 0-50 cm (Sl. 9.31 in 9.32).

14.7.2 *Fizikalno-kemične značilnosti izvirov*

Od maja 2005 zvezno spremljamo skupne pretoke vseh izvirov, temperaturo in specifično električno prevodnost izvirske vode. Izviri Podstenjška izkazujejo tipičen hidrološki režim s kratkotrajno zelo visokimi pretoki in podaljšanimi obdobji srednje visokih in nizkih pretokov. Do sedaj je bil najnižji zabeležen pretok 6 l/s, najvišji pa 1,6 m^3/s. Povprečni pretok znaša 140 l/s. Razmerje med najvišjim, srednjim in najnižjim pretokom pa znaša 1:26:267, kar je eno izmed najvišjih razmerij, zabeleženih med slovenskimi izviri. Za primerjavo je razmerje teh vrednosti na izviru Vipave 1:9:96 in Hublja 1:16:322 (Trišič, 1997).

Nasprotno pa temperatura izvirske vode skoraj ne niha in se giblje med 9,1 in 10,6°C. Glede na to, da je temperatura vode dokaj konstantna in skoraj identična povprečni letni temperaturi zraka na tem območju (9,6°C) lahko sklepamo na daljše zadrževalne čase vode v podzemlju.

Vrednosti specifične električne prevodnosti se gibljejo med 366 in 487 µS/cm. Na splošno hitrim porastom pretokov po obilnejših padavinah sledi znatna sprememba prevodnosti in manjša, toda opazna sprememba temperature vode, kar tudi označuje značilno kraško naravo izvirov Podstenjška (Sl. 9.6).

V času hidrološkega leta 2005/06 so bili najvišje povprečne vrednosti pretokov meseca decembra, najnižje pa julija. Najvišje povprečne vrednosti specifične električne prevodnosti so ravno tako bile decembra in najnižje julija. Najvišje povprečne vrednosti temperatur pa so bile meseca julija in septembra ter najnižje marca in decembra (Sl. 9.7).

Ob različnih priložnostih so bile narejene občasne kemične in biološke analize vode, ki kažejo na hidrokemično primernost izvirske vode za vodooskrbo, medtem ko bakteriološke analize kažejo na povečano vsebnost bakterij fekalnega izvora (Zavod za ..., 2001, 2002, 2003; Ur.l. RS 19/2004).

14.7.3 *Antropogene dejavnosti v zaledju*

V zaledju vodnega vira Podstenjšek ni resnejših dejanskih in potencialnih virov onesnaženja. Večji del zaledja je neposeljen, poraščen z gozdom, ali služi za ekstenzivne pašnike in travnike. Strnjena poselitev je le na območju spalnega naselja Šembije, kjer prebiva 209 prebivalcev (Popis …, 2002). Naselje ima urejeno kanalizacijsko omrežje, odpadne vode pa so speljane na manjšo čistilno napravo. V naselju in njegovi okolici ni pomembnejših gospodarskih dejavnosti in kmetijstvo je ekstenzivno.

Vodni vir dejansko in potencialno ogroža regionalna cesta Knežak – Ilirska Bistrica, ki razen skozi naselje Šembije nima urejenih obcestnih kanalov za odvajanje izcednih voda. Kakovost vodnega vira obremenjuje pokopališče, ki se nahaja neposredno nad izviri, sedem manjših divjih odlagališč odpadkov, potencialno nevarnost predstavljajo trije izkopi iz vrtač v zaledju. V skrajnem vzhodnem obrobju prispevnega območja izvirov Podstenjška je načrtovana gradnja vetrnih elektrarn (t.i. VE na Volovji rebri). Tveganje za onesnaženje podzemne vode je veliko v času gradnje, v času opravljanja rednih vzdrževalnih del (zamenjava olj) in v primeru nesreč.

14.7.4 *Karte naravne ranljivosti zaledja in tveganje za vodne vire*

Rezultati ocenjevanja ranljivosti podzemne vode na obravnavanem območju kažejo, da so ekstremno ranljiva območja goli izdanki karbonatnih kamnin (škraplje, jamski vhodi, zelo razpokana območja, kraški rob, suhe doline in tri vrtače, kjer je bil odstranjen zaščitni pokrov) ter estavela v Šembijskem jezeru (Sl. 10.18).

Večji del območja je ocenjenega kot visoko ranljivega (Sl. 10.17) in na splošno predstavlja golo kraško površje oziroma kraško površje pokrito s plitvimi prstmi. Območja, kjer debelina nezasičene cone preseže 250 m, ali kjer so apnenci pokriti z debelejšimi prstmi oziroma sedimenti, so označena kot srednje ranljiva. Glede na naklon pobočij in vegetacijski pokrov so manj ranljive vrtače v suhi dolini, prekrite z debelejšimi sloji sedimentov. Zelo nizka ranljivost je pripisana manjšim območjem grušča in fliša v neposredni bližini izvirov.

Upoštevajoč slovensko okoljsko zakonodajo, kjer je predvidena zaščita posameznega vodnega vira, smo izdelali karto ranljivosti vodnega vira. Na podlagi dobljenih rezultatov so visoko ranljiva območja nad Kozjo luknjo, estavela v Šembijskem jezeru, škraplje, jamski vhodi, zelo razpokana območja, kraški rob ter območja ob cestnih robovih. Kraško površje pokrito s plitvimi prstmi je srednje ranljivo. Vrtače, ki so prekrite z debelejšimi sloji prsti, ter ostali deli zunanje cone so nizko ranljivi. Glede na to, da se presihajoča jezera pojavljajo le ob izjemno visokih vodostajih, smo pri ocenjevanju naravne ranljivosti teh območij prvič upoštevali parameter hidrološke spremenljivosti in zato takšna območja niso zelo, temveč nizko ranljiva (Sl. 10.19).

V okviru kartiranja obremenjevalcev smo na obravnavanem območju identificirali točkovne, linijske in razpršene obremenjevalce. Točkovni viri onesnaženja so odlagališča odpadkov in izkopi. Linijski viri so prometnice, razpršeni pa pokopališče, kmetijska in pozidana zemljišča (Sl. 11.9).

Stopnja obremenitve je na splošno ocenjena kot nizka ali zelo nizka, več kot polovica območja pa ni izpostavljena obremenjevalcem (Sl. 11.10). Zelo nizko stopnjo obremenitve predstavljajo kmetijske površine, nizko pa urbana območja, prometnice, odlagališča odpadkov in izkopi.

Celotna ocena tveganja za onesnaženje je bila narejena za vodni vir, za katerega smo ocenili, da je srednjega pomena z vidika vodooskrbe in biotske raznovrstnosti. Končni rezultati ocenjevanja tveganja so močno odvisni od stopnje in razprostranjenosti obremenjevalcev (Sl. 11.11).

14.8 VELJAVNOST KART

Ranljivost je lastnost, ki se je ne da izmeriti ali neposredno pridobiti na terenu (Vrba in Cività, 1994). Za ocenjevanje ranljivosti so bile zato predlagane in testirane različne metode, izpostavljen pa je bil tudi pomen validacije dobljenih rezultatov. Karte ranljivosti so namreč konzervativne poenostavitve naravnih razmer in za potrditev njihove primernosti in ujemanja z dejanskim stanjem jih je potrebno ustrezno preizkusiti.

Čeprav preizkušanje veljavnosti različnih kart ranljivosti še ni povsem uveljavljeno, bi rezultati takšnih kart morali biti preverjeni. Do sedaj še ni bil predlagan enotni program preverjanja, vendar je jasno, da je ena najbolj učinkovitih metod t.i. validacije sledenje z umetnimi sledili.

Po injiciranju sledila v različnih točkah ranljivosti opazujemo pojavljanje sledila na izviru. Pomembne informacije so čas do prvega pojava sledila, njegova najvišja koncentracija in proces upadanja te koncentracije, ter celotno trajanje pojavljanja sledila. Od teh parametrov je namreč odvisno, kakšno stopnjo ranljivosti lahko pripišemo opazovanemu območju.

Predlagamo, da validacija kart ranljivosti temelji na dveh kriterijih, pridobljenih s sledilnimi poizkusi (Sl. 12.1). Prvi kriterij je čas do prvega pojava sledila ali čas do najvišje koncentracije sledila. Drugi kriterij pa je **normaliziran delež povrnjenega sledila** $\mathbf{R}_N$ (1), to je spremljanje pojavljanja sledila na izviru, neodvisno od višine pretokov.

Območje injiciranja sledila je visoko ranljivo, če se sledilo naglo infiltrira in se po razširjenih kraških kanalih hitro pretaka do izvira, kar zmanjšuje absorpcijo, degradacijo, kationsko izmenjavo, disperzijo in redčenje. Potovalni časi so zato zelo kratki, koncentracije ter relativna vrednost povrnjenega sledila pa visoke. Nasprotno pa je območje injiciranega sledila nizko ranljivo, če se sledilo absorbira v zaščitne sloje. Njegova infiltracija je zato zavrta in koncentracija pojavljanja na izvirih močno znižana. Sledilo se pojavi na izvirih z zamudo ali pa sploh ne.

Rezultate kart naravne ranljivosti v zaledju vodnega vira Podstenjšek smo preizkusili z dvema kombiniranima sledilnima poizkusoma, ob visokem in nizkem vodostaju. Marca 2006 smo izvedli sledilni poizkus ob visokem vodostaju (po izdatnejših padavinah in pred napovedanimi večjimi količinami padavin). S tem smo simulirali potencialno onesnaževanje v najslabši možni situaciji (to je ob visokih vodah, ko so hitrosti podzemnih voda najhitrejše).

V ta namen smo izbrali dve injicirni točki in uporabili dve različni umetni sledili. V estavelo na takrat praznem presihajočem Šembijskem jezeru, ki je po Slovenskem pristopu označena z visoko ranljivostjo, smo injicirali sulforodamin B, na golo kraško območje pod Volovjo rebrijo, označeno z nizko stopnjo ranljivosti, pa eozin (Sl. 12.12). Sledilni poizkus smo izvedeli 7. marca.

Po injiciranju smo opazovali vse kraške izvire v okolici in jih vzorčevali naslednjih 64 dni, vse dokler so bila sledila prisotna v nekaterih vzorcih. Po obilnem deževju 10. marca smo obe sledili zaznali v izvirih Podstenjška. Sulforodamin B je iz izvirov iztekal še štiri dni z največjo doseženo koncentracijo 1,65 ppb in se potem zopet pojavil v višjih koncentracijah med 23. in 26. marcem ter v manjših koncentracijah ob vsakem večjem deževju, ki je sledilo. V izvire Podstenjška je v celoti izteklo 52,5% injiciranega sulforodamina B, v drugih izvirih pa se ni pojavil (Sl. 9.22 – 9.25).

Praktično istočasno se je v izvirih Podstenjška pojavil tudi eozin, vendar v manjših koncentracijah z najvišjo vrednostjo 0,2 ppb. Eozin se je v Podstenjšku pojavil tudi v znatno manjših količinah. V obdobju vzorčevanja smo zaznali 0,95% od celotne injicirane količine.

Večji delež eozina, 81,2%, je odteklo v izvire Bistrice. Tam se je v primerjavi s Podstenjškom pojavil s časovnim zamikom, saj smo njegovo prisotnost določili šele v vzorcih, vzetih en teden po injiciranju – 13. marca. Vendar je bila v Bistrici največja zabeležena koncentracija sledila še enkrat večja, 0,43 ppb, sledilo pa je nepretrgoma iztekalo do 29. marca. V vzorcih, vzetih na ostalih izvirih, nismo določili prisotnosti umetnih sledil.

Vremenski pogoji jeseni in pozimi 2006/07 so nam omogočili opazovanje, kako bi se kraški vodonosnik odzval na morebitno onesnaženje v izredno suhem in dolgotrajnem obdobju. Tako smo naslednji kombinirani sledilni poizkus izvedli 23. novembra 2006.

Po ustrezni predhodni pripravi poskusa smo istočasno v izbrane štiri točke različnih ranljivosti injicirali štiri različna umetna sledila, na izvirih Pivke in Podstenjška pa nato opazovali krivulje pojavljanja teh sledil. Uranin smo razlili po dnu Šembijskega jezera, prekritega z več metri prsti in sedimentov, po Slovenskem pristopu označenega z nizko ranljivostjo (Sl. 12.12). Sulforodamin G smo razlili po dnu Narič, kjer se večje debeline prsti in sedimentov pojavljajo v žepih, karbonatne kamnine pa ponekod izdanjajo na površje. Tudi to območje je označeno kot nizko ranljivo. Litijev klorid (LiCl) smo razlili po golem kraškem površju na Pušlem hribu, ki je po Slovenskem pristopu označeno kot nizko ranljivo. Kalijev jodid (KI) smo razlili po kraškem površju prekritim z nekaj centimetri prsti in označenim s srednjo stopnjo ranljivosti.

Izvire Podstenjška smo opazovali 98 dni, izvir Pivke pa 60 dni. Dva dni po injiciranju smo v vzorcih, vzetih na izvirih Podstenjška zaznali prisotnost jodida. Jodid je iz izvirov iztekal še naslednja dva dneva, z največjo doseženo koncentracijo 3,2 ppb (Sl. 12.10). Sledilo se je ob nizkem vodostaju proti izvirom pretakalo z navidezno hitrostjo 18 m/h. Od celotne injicirane količine smo zaznali le 0,63% jodida.

Ravno tako dva dni po injiciranju smo v izviru Pivke zaznali litij, ki se je ob nizkem vodostaju podzemno pretakalo z navidezno hitrostjo 95 m/h. Sledilo je iztekalo 15 dni z najvišjo doseženo koncentracijo 2,6 ppb (Sl. 12.11).

Zaradi nezadostne zasičenosti prsti in epikraške cone z vodo, sta prst in kamnina vsrkala fluorescentna sledila in jih tudi po izdatnejšem deževju nismo zaznali v nobenem od izvirov.

Sledilni poizkus je potrdil povezavo območja severovzhodno od Šembij z izviri Podstenjška ter območje Pušlega hriba z izvirom Pivke ob nizkih vodah. Vendar je vprašanje ali se vode s tega območja ne stekajo k izvirom Podstenjška ob visokih vodah, saj ti kažejo izrazite lastnosti pretočnega tipa izvirov.

Rezultati sledilnih poizkusov so pokazali, da se je izmed petih apliciranih metod za kartiranje ranljivosti kraških vodnih virov Slovenski pristop izkazal kot najbolj verodostojna metoda (Sl. 12.13). Vendar če bi želeli bolje spoznati ranljivost obravnavanega vodonosnika, bi bilo potrebno kombinirani sledilni poizkus ponoviti še ob visokem vodostaju.

14.9 NUJNI UKREPI ZA ZAVAROVANJE IN NASVETI ZA PRIHODNJE NAČRTOVANJE

Za razvoj primerne strategije varovanja vodnega vira Podstenjšek je bila v njegovem zaledju izvedena celovita hidrogeološka raziskava ter kartiranje naravne ranljivosti vodnih virov in njihovega tveganja za onesnaženje.

V preteklosti so že bile narejene strokovne podlage za zaščito vodnega vira in izdelan predlog odloka o vodovarstvenih območjih (Petauer in sod., 2002). Vendar pa ustrezni odloki še niso bili sprejeti. Čeprav je kakovost izvirske vode razmeroma visoka, pa bi za njeno ohranitev nemudoma morali biti sprejeti primerni varnostni ukrepi.

Na podlagi naše raziskave smo ugotovili, da bi bilo potrebno spremeniti obstoječe predloge o vodovarstvenih območjih. Na osnovi ocenjene naravne ranljivosti vodnih virov bi bilo potrebno predlagana vodovarstvena območja povečati proti vzhodu in vključiti Kamenščino in vznožje Milanke (Sl. 10.19). Vendar pa bi lahko bil I. vodovarstveni pas občutno zmanjšan in bi se raztezal nad Kozjo luknjo, na območju estavele v Šembijskem jezeru, škrapelj, jamskih vhodov, kraškega roba, ob robovih cest ter na zelo razpokanih območjih.

Za zadovoljivo zaščito vodnega vira se je na omenjenih območjih potrebno izogniti kakršnemu koli onesnaženju. Zato morajo biti ta območja primerno označena ter zavarovana, kot je predpisano v *Pravilniku o kriterijih za določitev vodovarstvenega območja* (Ur.l. RS 64/2004). Omenjeni pravilnik predpisuje še zavarovanje območja, ki je od vodnega vira oddaljeno v 10 m radiju, kar prav tako še ni bilo storjenega.

Na območju I. vodovarstvenega pasu morajo biti predpisani primerni omejevalni ukrepi (t.j. prepoved gnojenja, uporaba pesticidov, prepoved golosečnje in novogradenj, spremembe obstoječe rabe tal, obvezna je primerna regulacija obstoječih prometnic, idr.).

V zaledju Podstenjška bi II. vodovarstveni pas moral biti na severnem, severovzhodnem in vzhodnem obrobju zmanjšan (t.j. območje notranje cone), ter razširjen na območje Kamenščine. Tudi to območje bi moralo biti ustrezno označeno. III. vodovarstveni pas bi moral obsegati predele na severu in severovzhodu, za katere nismo prepričani, če prispevajo k izviru oziroma prispevajo le ob visokih vodostajih, ter morfološko dvignjene predele, ki k izvirom prispevajo le v majhnih odstotkih in najverjetneje samo ob visokih vodah (t.j. območje zunanje cone).

Na podlagi ocen tveganja za onesnaženje (Sl. 11.12) bi prednostno morala biti sanirana divja odlagališča odpadkov in izkopov ter biti preprečeno nastajanje novih. Obstoječe prometnice bi morale biti primerno zaščitene in dovoljena hitrost znižana. Na območju vodovarstvenih pasov Podstenjška bi morale biti hitrostne dirke prepovedane. Širjenje poselitve ne bi smelo biti dovoljeno, spodbujati pa bi bilo potrebno obnavljanje starih (praznih) hiš in priklapljanje gospodinjstev na kanalizacijski sistem. Ohraniti bi bilo potrebno sedanji način kmetovanja, toda gnojišča bi morala biti urejena vsaj po obstoječih standardih (Ur.l. SRS 10/1985).

Bodoče antropogene aktivnosti bi morale biti načrtovane v skladu s *Pravilnikom* (Ur.l. RS 64/2004) in nadzor nad izvajanjem ukrepov bi moral biti zagotovljen.

Med možnimi lokacijami za postavitev vetrnih elektrarn v Sloveniji je izvedba projekta najbližje na lokaciji Volovje rebri. Sleme Volovje rebri leži na skrajnih severovzhodnih obronkih zaledja Podstenjška (Sl. 9.22), ki pa je v tistem predelu bolj podobna širši coni kot pa liniji, narisani na karti.

Predvidena je postavitev 33 vetrnih turbin tipa G52-850kW, z rotorji na višini 55 m (Gamesa, 2006). Vsaka od njih za nemoteno delovanje potrebuje približno 200 l različnih olj. Ob normalnem delovanju vetrnih turbin vplivov na onesnaženje kraške podzemne vode sicer ni pričakovati, vendar pa je tveganje za onesnaženje veliko v času gradnje, v času opravljanja rednih vzdrževalnih del, to je zamenjava olj, in v primeru nepredvidenih dogodkov oziroma nesreč, ki bi lahko pomenile porušitev stolpov vetrnih turbin (Ravbar in Kovačič, 2006b).

Potencialno nevarnost za pitno vodo predstavlja tudi gradnja temeljev za vetrne turbine in ostalo infrastrukturo ter adaptacija in izgradnja novih prometnic, saj omenjeni posegi zahtevajo odstranitev zgornjega zaščitnega sloja prsti, katerega samočistilna sposobnost je že tako minimalna. V času gradnje se bo zelo povečal tudi promet ter emisije iz transportne in gradbene dejavnosti, obstoječe prometnice pa niso urejene v skladu z okoljevarstvenimi standardi (Ravbar in Kovačič, 2006b).

Na podlagi opravljenih raziskav smo ugotovili, da bi v primeru namernega ali nenamernega kemičnega oziroma biološkega onesnaženja na širšem območju Volovje rebri bila ogrožena vodna vira Bistrica in Podstenjšek. Sledilo eozin se je proti Podstenjšku ob visokih vodah pretakalo z navidezno hitrostjo 52,7 m/h, proti Bistrici pa z navidezno hitrostjo 25,7 m/h, računano glede na pojav sledila v izvirih. Te dokaj velike hitrosti pretakanja vode nakazujejo tudi na hiter prenos morebitnega onesnaženja s širšega območja Volovje rebri proti vodnima viroma. Glede na pojavljanje sledila v izvirih bi bila vodna vira lahko ogrožena od nekaj dni do nekaj mesecev, možnost onesnaženja pa bi povečalo vsako večje deževje.

Injicirna točka pod Volovjo rebrijo je manj kot kilometer zračne razdalje in 220 višinskih metrov oddaljena od vrha slemena, vendar je na razvodnem območju. Z opravljenim sledilnim poizkusom smo vsaj deloma ugotovili, kako se pretakajo vode na širšem območju Volovje rebri, vendar pa bi bilo v fazi načrtovanja in preverjanja ustreznosti lokacije Volovje rebri za postavitev vetrnih elektrarn z vidika varovanja vodnih virov potrebno za popolnejšo sliko ugotoviti, kam natančno se stekajo vode s predvidene lokacije. Pričakujemo lahko namreč drugačne rezultate. Poleg tega bi bilo potrebno ugotoviti, kakšno je podzemno raztekanje vode v odvisnosti od različnih hidroloških razmer.

14.10 SKLEPI IN IZZIVI ZA RAZISKOVANJE

Slovenski pristop se je izkazal za uspešnega in rezultati kart naravne ranljivosti, obremenjevalcev in tveganja v izbranem zaledju so verodostojni. Slovenski pristop bo apliciran še na drugih kraških pokrajinah v Sloveniji in pokazalo se je, da je sprejemljiv tako na strokovni ravni in kot vsestransko pomagalo za varovanje podzemne vode, vodnih virov, primernega gospodarjenja in na splošno načrtovanja v prihodnosti.

Pogosto nam pri kartiranju težave povzroča ustrezno merilo, ki je največkrat pogojeno z razsežnostjo proučevanega območja. Težave nam povzročajo kakovost prvotnih informacij različnega izvora, ki močno vplivajo na kakovost končnih rezultatov. V nekaterih primerih pa dejanska velikost objektov ne more biti prikazana zaradi premajhnih dimenzij in je tako obstoječa prostorska informacija izgubljena.

Zato mora biti merilo kartiranih objektov enako končnemu izdelku ali celo natančnejše. Posameznik pa je kljub temu pogosto prisiljen k določenim poenostavitvam. V odvisnosti od velikosti proučevanega območja in merila končnega izdelka je posploševanje nujno, da bi bile karte dejansko uporabne. Pri tem pa je potrebno poudariti, da majhna neranljiva območja lahko izbrišemo, medtem ko visoko ranljivih ne smemo. Takšna območja moramo narediti še bolj opazna in jih, če so premajhnih dimenzij, povečati. Priložen izsek takšnih območij v natančnejšem merilu je nujen, da lahko uporabniki takoj dobijo vpogled v situacijo. Navedeno velja tudi pri kartiranju obremenjevalcev in tveganja (Sl. 13.2).

Že v mnogih primerih se je izkazalo, da je obnašanje vodonosnika močno odvisno od trenutnih hidroloških razmer in se s časom bistveno spreminja, ter da je mehanizem toka in prenosa snovi odvisen od zasičenosti prsti in kamnin z vodo. Kjer imajo hidrološke spremembe pomemben vpliv na ranljivost podzemne vode ali vodnega vira smo pripravili predlog, kako se lotiti takšnih primerov. Seveda pa ocenjena vrednost stopnje ranljivosti določenega kraškega okolja ne more dati odgovora na to, kako se bo hidrološki sistem odzval v različnih možnih hidroloških situacijah.

V prihodnje je na tem področju potrebno natančneje raziskati dinamiko toka podzemne vode skozi različne cone kraškega vodonosnika ter vlogo razlik v načinu takšnega pretakanja in transportu škodljivih snovi v zaledju posameznega vodnega vira. Za primerno varovanje je na podlagi ocen ranljivosti potrebno izdelati še sezonsko prilagojena opravila in dejavnosti ter pripraviti ustrezna navodila za monitoring kakovosti voda.

Dodatne raziskave je potrebno posvetiti še razvoju celostnih validacijskih tehnik preverjanja rezultatov kartiranja ranljivosti in tveganja ter postavitvi enotne validacijske sheme. Temelji naj na kombinaciji različnih spektrov fizičnega preverjanja na posreden ali neposreden način, kot so izvedba sledilnih poizkusov z naravnimi in umetnimi sledili, matematični in statistični modeli, ipd.

Raba vode za različne namene tako v gospodarstvu kot v gospodinjstvih nenehno narašča, koncept ranljivosti in tveganja za onesnaženje pa se ne dotika problematike pretiranega izrabljanja podzemne vode in vodnih virov. Da bi preprečili čezmerno črpanje, bi države morale imeti sprejemljivo strategijo izrabe in uporabe pitne vode, ki bi ga lahko vključili v obstoječ koncept ranljivosti in tveganja.

Slovenija ima edinstveno priložnost ohraniti zadovoljive količine kraške podzemne vode visoke kakovosti, da jih bo lahko izkoriščala tudi v prihodnje. Vendar je za zagotavljanje primerne kakovosti tega naravnega vira nujno osnovati ustrezen strateški načrt zaščite, ki naj temelji na določevanju optimalnih vodovarstvenih pasov s pripadajočimi omejevalnimi ukrepi. Obstoječa zakonodaja ne upošteva posebnosti pretakanja voda v krasu v zadostni meri, zadovoljive rezultate pa lahko pridobimo z aplikacijo Slovenskega pristopa za ocenjevanje naravne ranljivosti in tveganja za onesnaženje.

Vendar pa se moramo zavedati, da obstoječih problemov v zvezi z onesnaževanjem in varovanjem kraške podzemne vode ne bomo rešili zgolj z zakonskimi zahtevami in prepovedmi tehnične narave. Predvsem je potrebna kooperacija med znanstveniki, zakonodajalci, načrtovalci in odločevalci, da bi se izognili konfliktom pri načrtovanju rabe tal in sodelovali v skupnem interesu varovanja kraških voda. Spremeniti je potrebno človekov odnos do narave in naravnih virov ter izobraževati ljudi o pomenu varovanja pitne vode.

15
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Diamonds and pearls of the Hades' land.
K R A S