Environ Geol (2006) 49: 804–813
DOI 10.1007/s00254-006-0174-8

ORIGINAL ARTICLE

Mihael Brencic

Groundwater and highways interaction: past and present experiences of highway construction in Slovenia

Received: 30 August 2005
Accepted: 29 November 2005
Published online: 25 February 2006

M. Brencic
Geological Survey of Slovenia,
Dimiceva 14, 1000 Ljubljana, Slovenia
E-mail: mbrencic@geo-zs.si
Tel.: +386-1-2809788
Fax: +386-1-2809753

Abstract During the planning, designing, construction, operation and maintenance of highways, groundwater can be of important environmental and constructional constraint that can significantly influence the safety operation of traffic and of big influence on the operational costs of highways. To classify and conceptualize the relation between groundwater and highways, three important groups of problems can be determined: groundwater protection from highway influences, protection of highway from groundwater and economic use of groundwater for highway operation. In the present study, groundwater management strategies are represented during all life cycles of highways. Greater emphasis is given to groundwater protection and field hydrogeological investigations for proper groundwater management related to the highway. The approach adopted in Slovenia and the role of hydrogeology is given as an illustration.

Keywords Groundwater protection · Groundwater management · Urban groundwater · Highways · Slovenia

Introduction

The transport industry is one of the fastest growing economic activities in the world. Growing transport has great influences on the environment and great care should be given to proper planning, designing, construction and operation of transport infrastructure. The effects of road traffic emissions on air quality (Schwela and Zali 1999) and on water environment are very well known, also to groundwater, the most important source of freshwater in several countries.

Vehicles are direct and indirect source of pollutants on roads. As a direct source, vehicles contribute pollutants from normal operation and wear of frictional parts. Indirect pollutants are solids that are acquired by the vehicle for later deposition. The runoff from daily traffic on roads can be a source of heavy metals, oil and grease, organic toxic compounds, particulate matter, nutrients and other materials deposited on road surface. In an incident pollution, various chemicals can be spilled.

During planning, construction, operation and maintenance of highways, groundwater can be an important constraint that can significantly influence the safety operation of traffic and the operational costs of highways. For the proper management of the groundwater constraints on highway, operational cycles interaction between groundwater and highways should be treated as a whole. Wrong solutions of an engineering problem at earlier operational stage can lead to environmental problems in later operational stages of the highway and vice versa.

Several authors studied the influences of road traffic and road infrastructure on water. They have studied the quality of runoff from pavement surface (Krein and Schorer 2000), the influence of pavement material type on runoff quality (Serrano-Belles and Leharne 1997; Faure et al. 2000), the influence of runoff treatment (Hvitved-Jacobsen et al. 1994) the influence of road salt contamination (Williams et al. 1999; Foos 2003), the first flush of runoff from pavement (Lee et al. 2002) and the interactions between road sediment and water (Rauch et al. 2000). Lacey and Cole (2003) studied accidents as water pollution risk. Several authors carefully studied the influence of groundwater on the road infrastructure, Reddi (2003) reviewed recent results of these studies.

In the present study groundwater management strategies during all life cycles of highways are represented. The approach adopted in Slovenia and the role of hydrogeology is given as an illustration.

General settings

In Slovenia, large highway construction works have been in progress since 1994. Parallel to highways construction, several local roads are being reconstructed or totally rebuilt and all these works greatly influence the water environment. As Slovenia is very rich in groundwater, aquifers are the main source of drinking water. The highways cross numerous groundwater catchment areas, which require great caution during their construction and operation. Several important questions about groundwater protection from highway runoff arose and various efforts have been made during planning, designing, construction and operation to protect groundwater resources. The abundance of water has its impact also on highway construction. Much attention was focused on the protection of highways from the negative impacts of water. This leads to the necessity for the involvement of hydrogeology into the design and construction of highways.

Geology and hydrogeology

The African and Eurasian tectonic plates played an important role in the geology of Slovenia. The territory is very compressed and dissected with numerous faults and napes. Rocks are predominantly carbonates of Mesozoic age, but Palaeozoic and Tertiary rocks are also present.

The aquifers of intergranular porosity comprise 22% of the country and are positioned in the tectonic depressions and valleys in the central and northeastern part of the country. They represent major water resources for the population living in larger cities. Karst aquifers in limestone rocks are also very important. They comprise 32% of the area and are mainly present in the southern and western part of the country. The characteristics of the aquifers with fissure porosity are very similar to those of the karst aquifers and cover about 15% of the area. Double porosity rocks cover 11% of the area. The rocks that can be classified as low permeable comprise only 20% of the country. (Brencic et al. 2001). Figure 1 is a basic hydrogeological map.

Road network

The public roads of the country are classified into state roads and local roads owned by communities. The total length of public roads in Slovenia is 6,255 km. The state roads are divided into seven categories. Highways are the highest standard of all roads. They are intended for long-distance traffic and are an integral part of motor-

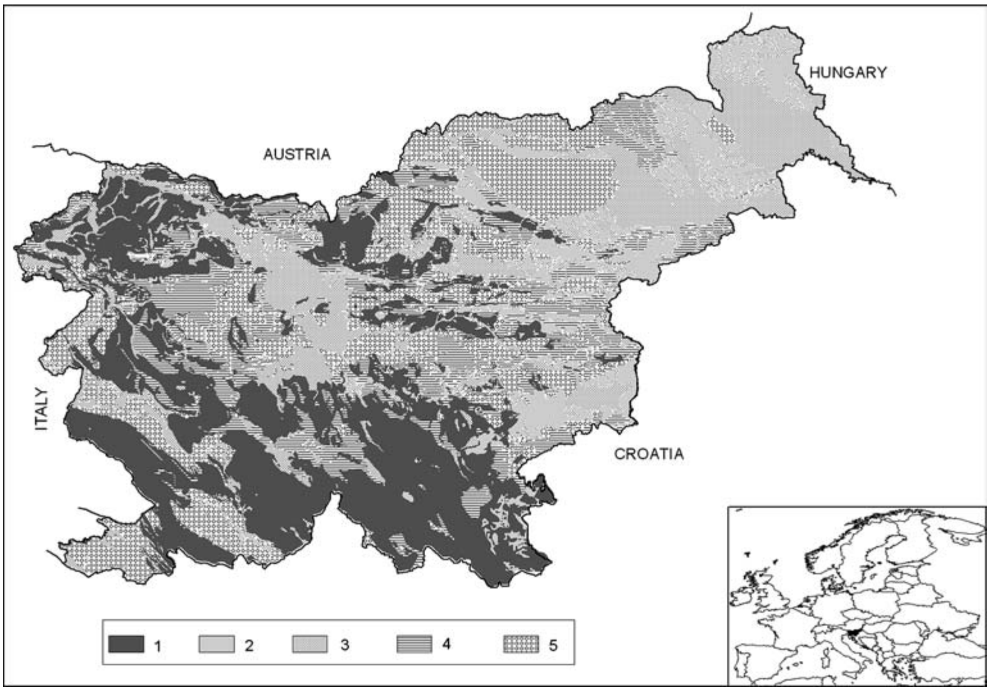

Fig. 1 Hydrogeological map of Slovenia *1* karstic rocks, *2* intergranular aquifers, *3* fissured aquifers, *4* double porosity rocks, *5* low permeability rocks

way connection with neighboring countries. All highways have a common length of 355 km. Expressways are reserved for traffic between the most important regional centers and the connections to motorways in the country and the road system of neighboring countries. They have the common length of 155 km. Main roads are divided into two categories and are intended for traffic connections between centers of regional importance. Their common length is 1,023 km. Regional roads are divided into three categories and are intended for traffic connections between important centers of local communities. All three categories of regional roads have the total length of 4,724 km. Local roads are divided into communal roads (over 13,500 km) and public paths (over 17,600 km). Figure 2 is a road network map.

Spatial relation between roads and aquifers

To investigate the spatial relation between roads and aquifers, several quantitative measures were introduced. The ratio of single road category lengths in a course above the single type of aquifer to the total length of all state roads is defined as the crossing ratio. According to the analogy with crossing ratio, impact potential was introduced. This ratio was introduced to estimate the potential impact of road pollution to the aquifers on the state level and is defined as the ratio between crossing ratio and share of the particular aquifer on the state level. Impact potential should be interpreted as the level of enlarged or reduced pollution risk according to the average pollution from roads on the state level. (Brencic and Rikanovic 2002) The crossing ratio and impact potential on the state level for particular road types are given in Table 1.

The crossing ratios and impact potential show that all state roads run mainly across intergranular aquifers. On average, 41% of all state roads cross intergranular aquifers. Impact potential of road pollution on intergranular aquifers is 1.86. Similar data can be found for particular type of roads. Supposing that traffic density is similar for each road group, the total input of pollutants from permanent traffic is much higher in intergranular aquifers than in other aquifers.

The situation should be different in the case of incidental pollution. Karst aquifers are the most extensive and vulnerable aquifers in Slovenia. According to the

Table 1 Crossing ratios and impact potential for all state roads in Slovenia

Type of aquifer	Crossing ratio (%)	Impact potential
Intergranular	41	1.86
Karst	24	0.75
Fissured	11	0.73
Double porosity	11	1.00
Low permeable rocks	15	0.75

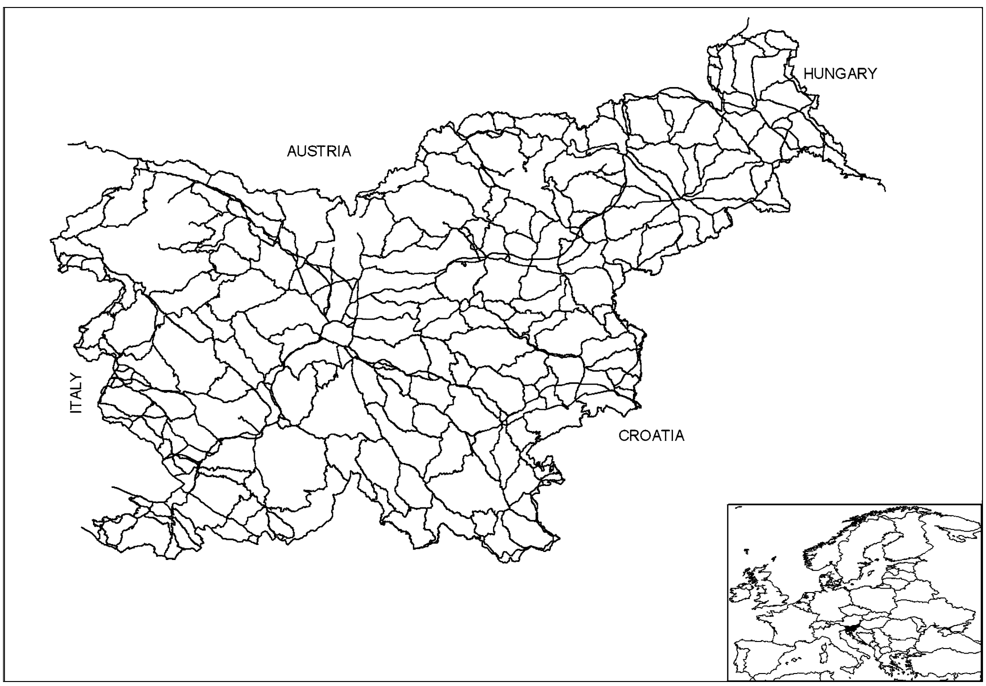

Fig. 2 Road network map of Slovenia

crossing ratio and impact potential they are loaded with values lesser than 1. But it is well known that the spreading of pollution in these aquifers is very fast and as a consequence, they must be protected from road impacts with high protection standards in spite of the fact that their potential traffic load is on the average lower than on intergranular aquifers.

Legal basis for groundwater protection from road influences

Groundwater protection from negative influence of roads represents a special topic. Nearly 20% of the state is covered with groundwater protection zones. Groundwater protection zones are represented in Fig. 3. Many of them are positioned in the big tectonic depressions and river valleys where main settlements and roads are also positioned. From this relationship several conflicts arose that must be solved during all life cycles of roads.

In the Slovene legislation, the Water Act and the Environmental Protection Act require the protection of groundwater resources. These primary legislations are very general about the requirements for groundwater protection from road traffic influences. The more precise measures for the protection of groundwater resources from the influences of roads are determined by regulations and governmental ordinances, and even more precisely by local drinking water resource protection acts. Brencic (2001) studied the present legislative status of groundwater protection from road influences in Slovenia.

A number of drinking water resource protection acts define restrictions and prohibitions of road construction. These restrictions are defined very diversely and refer to different categories of roads. A greater part of the ordinances includes prohibition of building a certain road type in the inner protected zone. In some cases where road construction is prohibited, exceptions are permitted. Those exceptions are permitted in accordance with spatial planning documents and regulations, taking into account preliminary regulations about groundwater protection. Measures for groundwater protection in outer protected areas are of a more general nature, prescribing road construction to prevent groundwater pollution. Some more recently passed local drinking water resource protection acts demand that newly constructed and reconstructed roads have a groundwater protection scheme and other projects dealing with road construction and maintenance.

Interaction between highways and groundwater

Conceptual approach

The relation between highways and groundwater is diverse and complex. To classify and conceptualize the relation between groundwater and highways three important groups of problems can be determined:

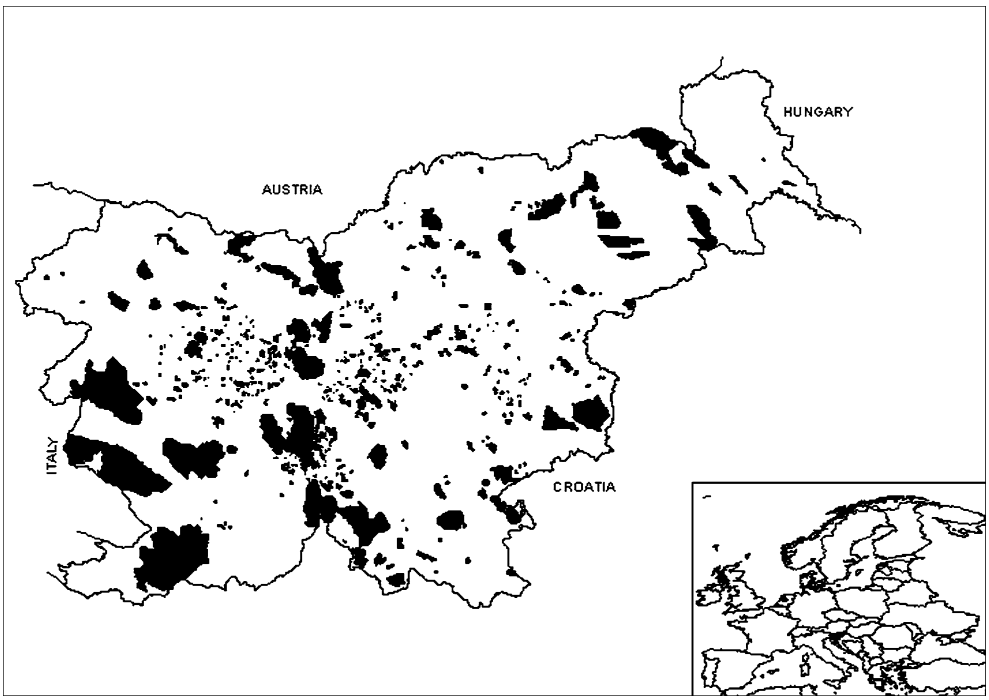

Fig. 3 Groundwater protection zones in Slovenia

(a) Groundwater protection from highway influences
(b) Protection of highway from groundwater
(c) Economic use of groundwater for highway operation.

Groundwater protection from highway influences

Groundwater protection from highway influences is performed according to the legislation demands and natural characteristics of water resource that must be protected. Legislation demands consist of general state valid requirements and prohibitions, and locally prescribed conditions. General requirements and prohibitions are defined in the laws. Locally prescribed conditions are defined in the local groundwater protection ordinances that are the responsibility of local communities, or in some other instances, in ordinances where groundwater protection is defined inside of some other nature protection demands. In every day practice it was experienced that these demands and requirements are very general and they do not present the exact guidelines that are needed for the construction and operation of highways. To prevent environmental damage and how to manage danger as a result of highway operation is the responsibility of highway owner and operator. Therefore, it is in their interest to establish precise technical and other measures to prevent pollution and environmental damage from highways.

To establish sound and cost-efficient measures for groundwater protection from negative highway influences, natural conditions must be well known to enable the proper planning and design of protection measures. To reach this goal, the classification scheme of highway course above the aquifer was defined and adopted in designing the technical measures for groundwater protection.

During the highway development scheme, existing hydrogeological situation in space crossed by highway, is classified on the basis of existing water protection zones and natural conditions. As a first step at the desk, studies of the demands and requirements from the groundwater protection ordinance are grouped together. At the second step, natural conditions are analyzed in the field with classical hydrogeological methods. Results of those investigations are used to determine the required level of groundwater protection. If the requirements defined in the existing groundwater protection ordinances are not so strict as it is supposed to be on the basis of the results of new field investigations performed during the highway development scheme, technical protection measurements are accommodated so that groundwater is protected according to the established natural conditions. If prescribed demands in the local groundwater ordinances are stricter than it is established by field investigations, the protection requirements are retained and usually the designer does not oppose them.

The classification scheme was defined in a way that makes further simple selection of technical preventive measures possible. The scheme is based on a simple conceptual model of an aquifer. According to this the model aquifer consists of an unsaturated and saturated part. In the model, the transit time of the probable pollutant that it takes its source on the highway through the unsaturated and saturated zone is estimated.

The spreading velocity of a pollutant through the unsaturated and saturated zone was described with two parameters. The vertical seepage of the pollutant in the unsaturated zone is defined as the specific vulnerability parameter. The higher the velocity of vertical transport, the higher the vulnerability of the water resource. The horizontal flow of the pollutant in the saturated zone is described with an exposure parameter. On the basis of the estimation of the pollutant spreading and progression into the direction of the water resource, the classification of arrival times from the spill off location or permanent pollution point due to the highway operation to the water resource is classified. Based on the cross-classification the combination of specific vulnerability and exposure parameters gives the estimation of the sensitivity of the water resource crossed with a highway. The estimation of the sensitivity of the water resources represents the guidelines for the selection of suitable technical protection measures from negative highway influences to the groundwater. Sanitation measurements are the essential part of the groundwater protection.

Parameters of specific vulnerability are determined on the basis of rock and/or soil hydraulic characteristic in the unsaturated zone and imposed contamination burden. Because sanitation measurements for the spill offs are consisting of digging out pollutant soil or rock, the measure of specific vulnerability is defined as the time needed for a pollutant to reach the deepest point within the reach of the arm of a hydraulic shovel used for excavation. This depth should be 6 m. The parameter of specific vulnerability divided into five categories according to the transport time to the depth of 6 m is represented in the Table 2.

Table 2 Classification of specific vulnerability parameter

Level of specific vulnerability	Specific vulnerability	Transport time of pollutant (day)
1	Very high	< 1
2	High	1–5
3	Medium	> 5–10
4	Small	> 10–50
5	Very small	> 50

Exposure parameter of the aquifer is determined by the hydrogeological characteristics of the recharge area of a water resource. Porosity and hydraulic conductivity of the aquifer are the most important among them. The parameter is determined on the basis of the proposed consequences of a pollutant spill, permanent pollution on the aquifer from traffic operation and the arrival time of the pollutant from the highway to the water resource. In the estimation of the exposure parameter, the significance and arrival time of the conservative pollutant to the body of water resource must be treated equally. The categories of exposure parameter are represented in Table 3.

Parameters of specific vulnerability and exposure of an aquifer together represents the sensitivity of the area that will be crossed by a highway. The sensitivity of the aquifer is determined by the cross-classification between levels of specific vulnerability and exposure categories (Tables 2 vs. 3). Arrangement of the highway influences on the groundwater are defined according to the following levels: highly sensitive (categories 1b, 2a), sensitive (categories 1c, 2b, 3a), moderately sensitive (categories 2c, 3b), lowly sensitive (categories 1d, 2d, 3c, 4a, 4b, 5a) and nonsensitive (the rest of the categories). If the area is classified as 1a, the construction of the highway is prohibited.

Protection of highway from groundwater

Protection of a highway and its surroundings from groundwater is needed when a highway is constructed below the groundwater table. These problems can be defined as classical dewatering problems in deep cuts, trenches, galleries and tunnels. Sudden appearance of groundwater during the construction can seriously raise expenditures and in the worst case causes the loss of material goods and human lives. Therefore, strong emphasis is given to the prediction of possible inflows or inrushes into the excavations during the planning stage. Great attention is also given to the proper prediction of chemical characteristics of groundwater that interact with highway infrastructures. Aggressiveness of the groundwater to the concrete is the most important property in the relation of the groundwater to the highway infrastructure. Precipitation of some minerals on drainage lines inside pavements and tunnels, usually calcite, should also be considered.

In the past during the highway construction in Slovenia some serious groundwater inrushes appeared. During the construction of the Karavanke highway tunnel that crossed the mountain ridge between Austria and Slovenia, a very large water inrush occurred (Mikos 1991). In other tunnels, groundwater was only a moderate constraint that slowed the advance of the tunnel front.

In some parts of the Alps aggressiveness of water to the concrete was experienced that is the consequence of sulfate presence. In the central part of the country some very soft waters are present and they caused the decarbonization of the concrete. Serious problems in some tunnels in Alps are experienced as a consequence of drainage clogging.

Economic use of groundwater for highway operation

Due to relatively well-developed water works systems in Slovenia, the economic use of groundwater for highway operation is to be an exception. In some highway routes, groundwater is captured as fire protection reserves in tunnels. At the very beginning of Slovenian highway construction in the mid-1990, the possibility to use groundwater as an independent source of water supply for some toll and maintenance stations was considered. The idea was later abandoned due to the public benefit. During highway construction, some new local water works and pipelines were built. Because the water supply in Slovenia is very crumbled with many small water works, this is also in accordance with the tendencies of new water legislation that tends to integrate the drinking water resources.

Table 3 Classification of exposure parameter

Level of exposure	Exposure	Significance of aquifer	Arrival time of pollutant
a	Very high	Spill of the pollutant is fatal	< 5 days
b	High	Spill of the pollutant is not fatal Nonprotected recharge areas of water resources Potential water resources	5–60 days
c	Medium	Nonprotected recharge areas of water resources Recharge areas of potential water resources	> 60 days
d	Small	Other aquifers	1–10 years
e	Very small	Other aquifers	> 10 year

Assessment of groundwater and highways interaction

For solving the conflicts between highways and groundwater, characteristics of these relations should be precisely known. The assessment of the interaction between highways and groundwater, and research on problems that arose from this relation, are included in desk studies and field investigations. The investigations and studies are defined in steps in several phases that correspond to the main life cycles of the highway.

Highway life cycles

Life cycles of highways can be divided into two main parts: development scheme and operation period. During the development scheme, they are consecutively defined as the planning stage, designing stage and construction stage. During the highway operation, three phases exist: maintenance phase, operation phase and postoperation phase. The implementation of this scheme is experienced by highway operation in Slovenia. In general similar processes can be carried out in other countries.

During the planning stage, the preparation and implementation of a major highway proposal is performed by highway authorities. At the first phase, a scheme identification study is performed where the status of the existing highway infrastructure is identified (Boyle 2002). The improvement of the highway infrastructure is usually needed for economic reasons. In economies under the transition, environmental reasons for highway improvement, they are usually in the second plan. Possible alternative solutions at the next step, feasibility study, are investigated and the preferred route decision is subject to planning control. A designer is commissioned to provide a sufficient design to enable a decision where the highway will be located.

The designing stage is divided into two main steps: the preliminary design and the detailed design. The preliminary design is performed as an outline scheme where sufficiently a robust design is defined to enable efficient cost estimates. In the detailed design step, documentation is prepared for licensing, tendering and realization. During this process, bridges, road pavements, drains and other structures are designed (Boyle 2002).

Tendering construction of highway is a complex process that enables several parties to be involved. The client, contractor and supervising engineer coordinate the whole process, which ends with highway operation.

The operation period usually starts when ordinary highway traffic begins. During the first period of highway operational life that is usually short comparing to the whole operation phase, the contractor remains responsible for the highway structure. There will be a list of minor problems identified at the final inspection before release of the highway is accepted. This period of operational life is defined as the maintenance phase. During the operation period, highway traffic is fully under the operation. The density and type of traffic usually changes during the course of years and consequently the dynamic stress changes. These changing conditions very often cause some damage. Concurrently, the durability of some highway structures is limited due to the aging of materials, and they need repair with some frequency; very often these repairs are the consequence of water acting. The postoperation phase begins when the highway is abandoned. Roads are very rarely abandoned; older roads are usually reconstructed and modernized. Only rarely are the abandoned roads removed, usually during the course of years they are overgrown with plants. Very little is known about the abandoned roads and their influence on the environment.

Field investigation

To establish the relation between a highway and the environment, field investigations are needed in all life cycles of a highway. The complete life of a highway is very long and each life cycle often requires information of a different type, quality and quantity. The sequence of field investigations can be divided into the following classical phases: preliminary investigations, main investigations and additional investigations (O'Flaherty 2002). Together with these main phases, some other types of field investigations can be performed. Among them are: preparative investigations, concurrent investigations and quality control investigations.

Preliminary investigations are mainly desk-based studies that search out and gather as much known technical information as possible regarding the conditions likely to be met along the alternative routes being considered for the proposed highway. The desk studies are normally supplemented by short-site reconnaissance trips. During this phase, the plan for site investigation during the main phase is prepared. These investigations are carried out during the feasibility studies.

The purpose of the main ground investigations is to obtain all sufficient additional geological and geotechnical information from on-site field research that consists of a wide spectrum of geological methods. The influencing factors of main investigations are the nature of the highway being examined, the anticipated design of the proposed highway, and the location of its structures. These investigations are carried out during the preliminary design scheme and detailed design scheme. Emphasis of the field investigations is given on the preliminary design scheme.

Additional investigations are usually carried out when the basic design or location of the structure is changed or conditions on the field are in consequence of changes during the designing process. They are performed during the design phase of the construction.

The public official invitation should be properly prepared for site investigation by client who usually carries out preparative investigations that consist mainly of short reconnaissance trips and basic desk studies. Concurrent investigations are performed with the contractor, which are usually specified in the design documentation as a support for proper construction procedures. They are usually performed during tunnel, deep cuts constructions, deep foundations or other geotechnical structures of great pretension. Design presumptions and quality of realized structures is controlled by quality control investigations also performed during the construction.

Hydrogeological research

Hydrogeological investigations are performed to fulfill the knowledge required for groundwater protection from negative influences of highway traffic and other activities connected by highway to protect highway space from groundwater influences or to enable groundwater exploitation for highway operation. These investigations have to be performed during all life cycles of the highway.

During the feasibility study, hydrogeological investigations begin with desk-based studies where regional characterization shows the main groundwater characteristics in the area crossed by alternative highway routes. Main groundwater flow directions in the area, and the position of highway and its objects according to the groundwater flow are defined. Concurrently, drinking water resources and groundwater protection zones are identified together with the prescriptions defined in the groundwater protection ordinances. The alternative routes of highways are preliminary classified according to the sensitivity model. The comparison of highways based on the sensitivity model is usually included in matrix decision models very often performed during feasibility studies.

During the main investigation phase that is performed at the preliminary design, a majority of field- and desk-based hydrogeological investigations are made. At this investigation phase the highway route is usually exactly known; only some minor changes in the course of median strip can occur. Again, investigations begin with regional characterization; according to the results of previous investigations performed during the feasibility study, more specific missing information is obtained. Defined are nonprotected drinking groundwater resources and potential resources in a downgradient direction of a highway. For each of the drinking groundwater resources basic characteristics, such as pumping rate and number of wells or other capture structures, are given. After the field investigation, when hydrogeological parameters are known, simple relation between recharge area of the particular groundwater resource and highway is established. The width of the recharge area that occupies the highway line is calculated and arrival times of conservative pollutant from a highway to a particular well are estimated.

The amount of subsurface boring depends on geotechnical conditions. During these activities a groundwater observation network is established. In this network groundwater observation is usually started immediately after the construction of observation boreholes. The frequency of observations depends on the type of aquifer. Also, older observation boreholes from some other investigations are included in the network. On the basis of these observations, actual piezometric maps are constructed.

Important parts of hydrogeological investigations are hydrogeological measurements. They consist of in situ tests and laboratory measurements. In the laboratory, measurements of permeability and porosity are performed on selected borehole cores and also in sediment sieve analyses. During in situ investigations pumping tests in highly permeable materials are performed and in the lower permeability environment usually inflow tests are performed. In special cases when sensitive karstic areas are crossed, tracing experiments are also integral parts of the field investigations.

During regional hydrogeological characterization, maps of groundwater appearances together with piezometric surface are given. Usually they are represented in ground plans of scale 1:25,000 and 1:5,000. On the longitudinal highway profiles, the depth of the saturated and unsaturated zones are given and when highways cross the important intergranular aquifers, also maps of the depths of these zones are presented. Based on the quantitative hydrogeological measurements, hydrogeological maps and additional calculations of some basic groundwater balance parameters are also established.

As a final stage of hydrogeological investigations, hydrogeological prognosis during the construction and operation of highway is given. The prognosis consists of the exact definition of hydrogeological phenomena according to the intervals of the designed highway. In a condensed manner these conditions are given on prognostic hydrogeological longitudinal profiles as strips with different content. In these strips the quantitative hydrogeological characteristics (e.g. groundwater level, transmissivities and permeability) are given together with drinking water recharge areas that cross a highway route. In a separated strip the classification according to the sensitivity model is also presented. Together with this information, predictions about quantity and the nature of inflow into the earthworks are also calculated.

During the detailed designing scheme, groundwater problems are dealt with in relation to particular structures. In the case where higher groundwater inflows are expected during earthworks, a hydrogeologist purposes the solutions for groundwater dewatering and this is included into the construction plan. At this phase the exact design of groundwater protection is defined. Sometimes when problems of groundwater protection are detected additional observation boreholes for groundwater monitoring are constructed.

Hydrogeological investigations in other investigation phases are usually site-specific problems. During the construction groundwater, investigations are part of the monitoring procedure. In deep cuts and tunnels, it appears that some additional observation boreholes are needed during the construction. During the operation of a highway the monitoring of the highway influences is a paramount role. Sometimes during the later stages overflooding of tunnels or deep cuts, additional investigations with drilling are needed.

Conclusions and discussion

Very often groundwater is the most important source of fresh drinking water. This is the reason why groundwater must be protected from the urbanization influences. Among them highways and highway traffic represent a heavy burden.

Relation between highways and groundwater must be treated as a whole in spite of the case that the spectrum of problems appearing from this relation is very broad. The problems connected with this relation can be separated into three main groups. In the first group there are problems related to groundwater protection from negative highway influences. In the second group there are problems related to groundwater influences on the highway and its vicinity; and in the third group there are problems related to the economic exploitation for highway operation.

The whole life cycle of a highway is divided into several phases: planning, designing, construction and operation. Each of these phases requires a unique approach for the solution; however, these solutions come from a step-by-step approach. Problems that are solved at the time of the earlier phases do not appear later. Negation of the step-by-step approach can lead to the crumbling of the solutions and consequently into non-transparent situations that have a consequence in the later operational phases of a highway. Late solutions to these problems are not time and cost effective, and can have serious effects; even resulting in loses of human lives. This is the reason problems related to groundwater highway relations must be treated seriously from the very beginning of the designing phase of the highway. Results of these investigations must provide an answer mainly to all hydrogeological problems.

Due to the prevailing part of groundwater in the drinking water supply of Slovenia, groundwater protection from highway influences plays an important role in all life cycles of highways. During the construction of highways, hydrogeology has played an important role, especially during the investigation period when basis for highway routing and planning were performed. During the construction period itself, hydrogeology was involved mainly in larger geological engineering works, such as tunneling, deep cuts and deep foundations. Along the highway operation, hydrogeology is involved mainly in monitoring and sometimes in reconstruction works when due to complicated geological conditions some constructions must be redesigned or repaired. The experiences from Slovenian case studies showed that groundwater investigations are an integral part of geotechnical investigations and design. Proper solution of problems that are the consequence of groundwater influence on the highway or pollution of groundwater from a highway should be solved at very beginning. A delay in solving these questions can lead to higher costs in later stages.

Acknowledgements The work presented in the paper was carried out within the project Urban Hydrogeology the Impact of Infrastructure Objects on Groundwater, financed by The Ministry of Education, Science and Sport of RS (project no. L-1-3107-0215-01). The support of Slovene highway authorities and their technical staff, especially Andrej Locniskar, during the years of hydrogeological investigations is greatly acknowledged.

References

Boyle A (2002) Plans, specifications and contracts. In: O'Flaherty CA (eds) Highways the location, design, construction and maintenance of road pavements. Butterworth Heinmann, Oxford, pp 53–67

Brencic M (2001) Analysis of standardized measures for the protection of drinking water resources from negative impacts of roads. Acta Hydrotech 19:137–153

Brencic M, Prestor J, Locniskar A (2001) The analysis of the influence of highways construction on groundwater in Slovenia. In: Seiler KP, Wonlich S (eds) New approaches characterizing groundwater flow. Balkema, Lisse, pp 467–471

Brencic M, Rikanovic R (2002) Groundwater and road network interactions—case study from Slovenia. Geologija 45:325–330

Faure P, Landais P, Schlepp L, Michels R (2000) Evidence for diffuse contamination of river sediments by road asphalt particles. Environ Sci Technol 34:1174–1181

Foos A (2003) Spatial distribution of road salt contamination of natural springs and seeps, Cuyahoga Falls, Ohio, USA. Environ Geol 44:14–19

Hvitved-Jacobsen T, Johansen NB, Yousef YA (1994) Treatment systems for urban and highway run-off in Denmark. Sci Total Environ 146/147:499–506

Krein A, Schorer M (2000) Road runoff pollution by polycyclic aromatic hydrocarbons and its contribution to river sediments. Water Res 34:4110–4115

Lacey RF, Cole JA (2003) Estimating water pollution risk arising from road and railways accidents. Q J Eng Geol Hydrogeol 36:185–192

Lee JH, Bang KW, Ketchum LH, Choe JS, Yu MJ (2002) First flush an analysis of urban storm runoff. Sci Tot Environ 293:163–175

Mikos B (1991) Predor Karavanke—geologija—geotehnika. Cestni inzeniring, Ljubljana, pp 134

O'Flaherty CA (2002) Subsurface investigations. In: O'Flaherty CA (eds) Highways the location, design, construction and maintenance of road pavements. Butterworth Heinmann, Oxford, pp 34–52

Rauch S, Morrison G, Motelica-Heino M, Donard OFX, Muris M (2000) Elemental association and fingerprinting of traffic-related metals in road sediments. Environ Sci Technol 34:3119–3123

Reddi LN (2003) Seepage in soils—principles and applications. Wiley, Hoboken, 402 p

Schwela D, Zali O (1999) Urban traffic pollution. E & FN Spon, London, pp 249

Serrano-Belles C, Leharne S (1997) Assessing the potential lead release from road dusts and soils. Environ Geochem Health 19:89–100

Williams DD, Williams NE, Cao Y (1999) Road salt contamination of groundwater in a major metropolitan area and development of biological index to monitor its impact. Wat Res 34:127–138